Chimaera Modelling – when the modellers must reconcile inconsistent elements or purposes

Bruce Edmonds[1*], Gert Jan Hofstede[2], Jennifer Koch[3], Christophe le Page[4], Theo Lim[5], Melvin Lippe[6], Beatrice Nöldeke[7] and Hedwig van Delden[8]

[1] Centre for Policy Modelling, United Kingdom
[2] Dept of Social Sciences, Urban Economics Group, Wageningen University, The Netherlands & UARM, North-West University, Potchefstroom, South Africa
[3] Geography & Environmental Sustainability, The University of Oklahoma, Norman, OK, USA
[4] UMR Knowledge Environment and Societies, CIRAD, Montpellier, France
[5] School of Community and Regional Planning, University of British Columbia, Vancouver, Canada
[6] Johann Heinrich von Thünen Institute, Institute of Forestry, Hamburg, Germany
7 Institute for Environmental Economics and World Trade, Leibniz University of Hanover, Germany
[8] Research Institute for Knowledge Systems (RIKS), Maastricht, The Netherlands

Abstract

Socio-Ecological System modelling projects are becoming increasingly complicated, with multiple actors and aspects being the norm. Such projects can cause problems for the modellers when this involves different elements, goals, philosophies, etc., all pulling in different directions – we call this "Chimaera Modelling." Although such situations are common when you talk to modellers, they do not seem to be explicitly discussed in the literature. In this paper, we attempt to turn this perceived "inside" phenomenon into an "outside" phenomenon and to start a debate to increase transparency among the modelling community. We discuss the different aspects which may be relevant to this problem to start this debate, including: the underlying philosophy, modelling goals, extent of choice the modellers have, different stages of modelling, and kinds of actors that are involved. We further map out some of the dimensions with which Chimaera Modelling connects. We briefly discuss these and propose to the community as a whole to work on their methodological development, feasibility, risks and applicability as their resolution is far beyond the scope of this paper. We end with a brief description of the broad possible approaches to such situations. Our main message is a call for recognition of Chimaera Modelling as a likely side-effect of multi-stakeholder, multi-purpose projects, and to take this into account proactively at the project team level and be transparent about the tensions and contradictions that underly such modelling.

Keywords

participation; inter-subjectivity; multi-actor; complex projects; project management

1. Introduction

A large and increasing variety of models is used to support policy. This leads to new challenges. Here, we concentrate on our area of experience: agent-based models of socio-ecological systems. Agent-based models are being used increasingly within large and complex projects that address issues of policy relevance. The models

Correspondence:
Contact B. Edmonds at bruce@edmonds.name

Cite this article as:
Edmonds, B., Hofstede, G.J., Koch, J., le Page, C., Lim, T., Lippe, M., Nöldeke, B., & van Delden, H.
Chimaera Modelling – when the modellers must reconcile inconsistent elements or purposes
Socio-Environmental Systems Modelling, vol. 6, 18593, 2024, doi:10.18174/sesmo.18593

Socio-Environmental Systems Modelling
An Open-Access Scholarly Journal
http://www.sesmo.org

often play an integrative role – aiming to bring together a variety of kinds of input within a single representation framework (the simulation itself). Typically, these models are then used to help evaluate or explore possible policies or outcomes and thus aim to inform the subsequent decision making.

To make the context clearer we list some of the properties such models often have. They:

a) are both complicated in terms of their composition, as well as complex in terms of their behaviour, and as a result they are hard to understand, by those involved in the modelling exercise or by others;
b) use and synthesise a variety of sources to inform the specification of the model (existing theories, stakeholder/expert opinion, survey data, time series, interviews, other models, traditional assumptions, secondary data etc.);
c) are embedded within several other processes (policy formation, consultation, science, contingency analysis, etc.) that involve several other actors;
d) take a while to develop, with the modelling stages alternating over a period of time with consultation, calibration, discussion, etc. allowing the objective and/or focus to be changed as this happens (Voinov & Bousquet, 2010);
e) attempt to incorporate, within the model, multiple kinds of observed structures and processes: geographic, ecological, social, political, behavioural etc.; and
f) lack a complete consensus from project partners concerning how to evaluate or validate them, because of their different interests, goals and perspectives and because nobody has full knowledge of all the constituents of the target system.

These properties are common when modelling Socio-Ecological Systems (SES). An example is the U.S. Geological Survey funded project aimed at developing policy support for the transboundary Rio Grande/Bravo basin (U.S./MX), a basin whose scarce water resources face increasing urban development, population growth, and frequent, severe droughts. An interdisciplinary team of hydrologists, land systems scientists, anthropologists, and integrated modellers developed first a conceptual and then an agent-based simulation model, based on the ENVISION modelling framework (Bolte et al., 2007, Inouye et al., 2017, Spies et al., 2017) drawing heavily on semi-structured interviews with water managers (Koch et al., 2019; Plassin et al., 2020; Sandoval-Solis et al., 2022).

Another example is the agent-based model that was developed to simulate the emergence of alternative long-term management strategies for the sheep farms and the woodlands in the Causse Méjean (France), a rare grassland-dominated ecosystem endangered by pine invasion. In a first step, foresters, farmers and the National Park of Cévennes rangers proposed individual scenarios and specific indicators to assess their impact on the main productive and environmental stakes. Later on, new scenarios were collectively designed to explore alternative sylvo-pastoral management based on innovative practices (Etienne & Balandier 2003).

This paper's authors have themselves been involved in these kinds of modelling processes, and have experienced first-hand many of the issues we discuss. These and other examples are the target for this article and provided its motivation. The goal of this paper is to raise the issue which seems to be solely an "inside" phenomenon, with the consequences in terms of external traces only known to those involved in the project. The purpose of this paper is to start a debate and motivate a move to make this an "outside" phenomenon for increasing transparency and for enabling methodological discussion. We have heard of this issue from many other modellers, but it does not seem to be explicitly discussed in the literature. Here, we want to name the beast and expose it to scrutiny.

The problem is introduced in the next section, followed by a number of sections that sketch some of the dimensions that this interacts with, including (in turn): the underlying philosophy, modelling goals, modelling choices, kinds of data used, different stages of modelling, and different kinds of actor that may be involved in the modelling process. We conclude with a classification of the different kinds of approach that may be used in such situations, but a detailed consideration of strategies or interaction between the dimensions listed is far beyond the scope of this paper and requires further debates for the community as a whole to address.

2. The Problem – *Chimaera Models*

The difficulty here is managing this complicated mixture of elements and ensuring a model can achieve all of what is wanted of it. This puts the modellers on the spot, since they (or the persons in charge of the modelling project) are the people responsible for ensuring the quality of the relationship between the model inputs and its results, and often their interpretation as well. Such modellers are often pulled in lots of different directions at once, trying to keep the modelling process honest (in the sense of ensuring the model achieves what is claimed for it) and trying to satisfy what the other project partners (and funding agencies) want of the model.

Models in this context can have a mixture of what might be characterised as subjective and objective elements, e.g., as a result of integrating qualitative and quantitative data. While working with qualitative data in the modelling and synthesis contexts has its own set of challenges (see An et al., 2021; Robinson et al., 2007), the integration of subjective and objective elements is a complex endeavour that is not frequently discussed in the modelling literature (see also Lim et al., 2023 this special issue). For example, the wider project might well have significant levels of stakeholder engagement which the model is expected to consider (for model specification) while simultaneously desired as a reliable means of assessing the future impact of policies. These demands on the model having both subjective and objective aspects make life difficult for the modellers, who have an obligation to keep the modelling "honest" (that is, make sure the model supports the conclusions drawn given all its inputs). We call such models, 'Chimaera models' because they are composite beasts, having a mixture of different aspects and goals within the same model (Figure 1).

Figure 1: Chimaeras are mythical beasts made up of parts from different animals. The various heads and limbs may point in different directions and have different goals. Attributed to Jacopo Ligozzi, Museo del Prado, Madrid, Spain. https://commons.wikimedia.org/wiki/File:Ligozzi_(Una_quimera).jpg.

Chimaera models do not have a clear, single purpose in the sense of Edmonds et al. (2019), which is what is trying to be achieved from the model and thus how it should be judged. For example, stakeholder input that affects the specification of a model implies a kind of model-mediated interaction between stakeholders and the users of the model output (e.g., policy actors) might be the purpose. However, if the model is considered as a reliable way of assessing the impact of possible policies, then this implies that the model needs to be able to predict, which relies on it sufficiently corresponding with empirical evidence. The absence of a single, well-defined modelling purpose is obviously problematic, with the danger being that no one goal is reliably achieved.

Describing these types of models as Chimaera models pays tribute to that other monster of the modelling world – the "Integronster" (Voinov & Shugart, 2013), however those beasts are different from each other. Integronsters are what can transpire when different sub-models are carelessly joined into one, whilst Chimaera models may be constructed as a single model but one trying to pull in different directions at once or trying to integrate inconsistent elements. Of course, some constructions might be both!

To be clear, we do not think Chimaera modelling is a new problem but rather an existing one that has not been explicitly discussed in the academic literature. The authors have had informal conversations with other modellers where these kinds of difficulty are talked about. However, one could not have told this from the papers that result from the corresponding research projects, which tend to present a more 'polished', positivist and consistent account (e.g. by only reporting on consistent sub-parts of the project).

Chimaera models seem to have become more common. Maybe this reflects a transitional phase in SES model development, as the scientific/modelling community pushes for interdisciplinary approaches and uses more stakeholder participation to identify actionable solutions for complex problems. Moving away from modeller-driven research toward integrating a variety of disciplinary angles and perspectives as well as practitioner input, can result in compromises that go against strict single-disciplinary methods – leading to the trade-offs and ambiguities that can be useful in social learning situations (Brugnach & Ingram 2012) but may also lead to confusion. Here, we acknowledge the importance of these models as synthesis and knowledge generation tools, while also discussing ideas to improve their handling.

This paper reviews the problems Chimaera models present from various points of view and modelling aspects, including: underlying philosophy, modelling goals, kinds of data input, choice in model specification and the nature of the project members. The bulk of this paper reviews these before making some tentative suggestions as to ways to approach Chimaera models. This is more a case of mapping out the territory of Chimaera models and the role that modellers play in this process rather than presenting a definitive analysis or set of solutions.

3. Underlying Philosophy

Identifying where the problem lies might depend on one's philosophical outlook – how one thinks of the models. In this section we look at the three positions of realism, social constructionism and pragmatism to illustrate the issue (other philosophical stances are available).

If one is a positivist (or realist), then one would expect a model to correspond in some well-defined sense with reality, so either it is a good representation or not; either the stakeholders provided correct input or were mistaken. In this case, although one might be open to suggestions and input from a variety of sources, the final arbiter would be comprehensive validation against trusted data. Policy actors often want a model that is a faithful reflection of reality so it can be used to test or optimise possible policies before they are made.

If one is a social constructivist, one might be quite happy with the model reflecting the view of the stakeholders and indeed all those involved but would not necessarily expect the model to correspond to some part of reality and thus would not necessarily believe any assessments concerning the outcomes of possible policies. One might use such a case to explore the internal structure and "logic" of each view but accept there would never be a final or definitive view that would take precedence over other views. Social researchers often take this stance because they are very aware of the very different viewpoints that are involved in any joint endeavour.

If one is a pragmatist, one might think of the model not as a representation at all, but rather as a knowledge tool, but in this case one would need a clear idea of what the tool was designed for in order to know how to judge it (as well as how to mitigate against possible sources of failure). Edmonds et al. (2019) for example take this approach. However, this implies one has agreement over the purpose of the model and hence how to assess it. Technical modellers often take this stance, maybe because having clear and feasible goals for each model makes their life easier.

The philosophical view one takes is deeply intertwined with many other aspects of modelling, including: modelling purpose, method, interpretation, documentation and application. It is thus hard to untangle the philosophy from all these other aspects. Sometimes the philosophical view is explicit and underlies the rest, but other times it is implicit and seems to emerge from practice, being more of a connecting narrative than logical account. We map out a few of the connections in Table 1 below.

A significant meta-problem is that different actors involved in the modelling project might well have different philosophical perspectives, and often it is the designated modeller's responsibility to reconcile or negotiate between these. The modellers themselves might be one of these actors that have a view rather than just being a passive consultant for the others involved. The diverging philosophies might put the modeller on the spot when bringing philosophies that differ between the involved stakeholders together or when they unilaterally adopt one. It can also be a source of tension if the stakeholders' views do not align. There are various strategies for trying to reconcile these situations, which we discuss at the end of this paper.

Table 1: The connection of philosophical stance with some other modelling aspects that can be important in Chimaera modelling.

Modelling Aspect	Positivist	Social Constructivist	Pragmatist
Model purpose and multiplicity of goals	Models are to explain observed data, to predict unknown data or better understand theory.	There may be multiple purposes that a model may fulfil reflecting different views and roles. Any declared purpose (e.g., reflecting a collective viewpoint) is a result of negotiation between involved actors.	There may be multiple models, each with a different purpose (e.g., one focussed on data and another more on social and political factors). Model spaces, purposes, how they fit together and are evaluated are worked out in practice.
Approach to ambiguity and uncertainty	Uncertainty is not desirable and so decreased through additional data collection and appropriate model specification and structure.	Ambiguity and uncertainty serve useful social functions in collective decision-making and model exploration – useful for fostering dialogical learning and to clarify: the types of knowledge used, how and by whom it is created, what values are incorporated and how values are weighted.	Sources of ambiguity and uncertainty are identified, documented and assessed for each component model.
Documentation	Protocols such as ODD+ and TRACE can be used to properly document all aspects of the model.	In addition to protocols such as ODD+, reflexive practices, such as records of engagement and path tracing of model development are recorded to illuminate reasons for modelling choices and how the project develops.	Document and assess modelling exercises for different purposes separately. Different elements/purposes are traced through the model to assess the model for different purposes and document each of these.
Modelling process	Process follows established scientific methods, e.g., for prediction, apply the principles of uncertainty reduction.	The modelling process is a socio-political process, in which subjective values are not completely separable from scientific/technical decisions.	The modelling process is a distributed process, in which participants have defined responsibilities; acknowledge and document any intersubjectivity.
Responsibility and role of modellers	Modellers are "honest brokers" of science and have responsibility for all technical considerations.	Modellers are embedded actors with subjective interests in the outcomes of the model and the modelling process (Barnaud & Van Paassen, 2013).	Modellers are facilitators of a distributed process of knowledge and tool development.

The underlying philosophy guiding the modellers in their integration approach affects all stages of the modelling process, and ultimately also the modelling outcomes. This may become more relevant with an increase in inter- and transdisciplinary modelling effort that brings together collaborators from different disciplines applying various philosophies in their respective disciplinary research. At the least, the issue of underlying philosophies merits attention during a modelling project. It is quite plausible that without such clarification a project with, say, positivist financers, pragmatist modellers, and social constructionist stakeholders could run into Chimaera issues linked with confusion about model aims and tension emerging during model development and validation.

4. Modelling Goals

People who are assessing reports on modelling projects, whether they be other researchers, interested stakeholders or policy actors, need to know how to judge the success of that project. To do this, they need to know what the model was intended to achieve, in other words to be clear about the modelling goal or purpose of that exercise in the relevant context. Although, to an outsider, models may look as if they have a fixed purpose in the scheme of things, there are many possible reasons to do modelling – Epstein (2008) lists 15 in addition to prediction. As discussed elsewhere (Edmonds et al., 2019), different modelling purposes imply different model requirements, assessment and dangers. Just as "cancer" is a label for many different diseases each with very different causes, symptoms, progression and cures, so is the label of "models". Part of the difficulty of Chimaera modelling is that different actors may have different goals for the same process or model. This can over-constrain the process, meaning that it may not be able to satisfy all the goals wanted of it simultaneously.

For example, the 1972 'Limits to Growth' book (Meadows et al., 1972), which was centred around a system dynamics model of the interaction between global variables such as economy, pollution, population etc., was not explicit about the purpose of their model. It might be interpreted as being: (a) an exploration of theory showing what the effect of time lags between different factors could be, (b) a model to predict what will happen in the future, or (c) an illustration or story of what might happen if we continue with an unlimited growth approach to economic development. From our perspective, we might well decide that the modelling achieved (a) but the main message of the book was (c). The need for scientific credibility seemed to motivate (b) since that was what economic models were supposed to do, following Friedman (1953). The model was probably attacked due to others not liking the story that was propounded under (c) but did so on the grounds of (b), for example, by showing that the results were very sensitive to some of the parameters and so any noise in these would make this difficult to use for prediction (e.g., De Jongh, 1978).

A clash of modelling goals that often appears in grant applications describing projects is to say it will include the views of stakeholders, incorporating them in a model, (thus acting to mediate between these views) whilst also claiming that a model will be able to assess the extent to which policy options will work (which implies it can usefully predict their effects). One can understand why such proposals say both of these things but are usually somewhat opaque as to how both of these will be achieved without compromising one or both of them. In practice, within a project, modellers often spend a lot of time trying to moderate the wishes of other project partners to something that is achievable, whilst the implications of the compromises made are not so clear to those not participating in the model development process as this is not always reported on explicitly.

5. Choice in the Modelling Process

As said in the introduction, a model is a representation of something, e.g., a part of reality, a theory or a set of ideas. This means it reflects the choices made during the modelling process. What is selected and developed may be more or less objective, but which model is developed for which process is a result of a choice process. Different views, concerns and interests are almost always at stake. Sometimes factors and actors external to the modellers determine these choices, but not always all of them, the rest being made by the modelling team. These non-constrained choices may reflect the competing pressures or be attempts to reconcile the outside pressures and norms. In complex simulations there are many unconstrained or only partially constrained choices and these seem to be a source of the modelling tensions within complex projects. For this reason, we briefly discuss this here.

In this section we focus on those elements that make it into the model. These elements may be based on widely accepted knowledge and count as "objective". Unfortunately, we see that where there is a difference in interest between societal groups, even knowledge that is quite solid from a scientific point of view may be contested and labelled as biased by those with a vested interest in an opposing viewpoint (the health effects of smoking, or the climate effects of fossil fuels, being cases in point). Lim et al. (2023) for example discussed how "gaming" can lead to unintended or negative outcomes in participatory SES modelling. This intersubjectivity can be important for SES and multi-stakeholder modelling projects. Achieving consensus about the ontological status of key model components early on in a project, especially those involving potentially "difficult" stakeholders, can head off later confusion and conflict. If everyone accepts the point of departure, they are more likely to accept the outcomes.

The modeller picks selected components, feedback and other mechanisms from the profusion of all those that are observed or imagined. They can make the model go beyond developing/testing dry knowledge to tell a particular story that imparts meaning to that universe. The creative role of modellers runs deeper than only choosing which data sources to use, and which parameters. Even if solid, well-tested theories with large nomological networks are chosen (i.e., having proven their descriptive or predictive values on many domains), those theories tend to be underspecified compared to the demands of modelling environments. For example, modellers may need to determine which real-world values can act as proxies for theoretical concepts; which threshold values to obtain; which calibration parameters are required; and so on. This becomes especially relevant since components can be selected and discussed in isolation, but then must be tested and adjusted once combined, representing and producing complex interactions.

The modeller might be required to fill in logical gaps when implementing a theoretical framework into the model. Even when an established/accepted approach has been chosen to be implemented in the model, several conceptualisations or alternative formalisations of one theory may be possible. As one example, consider the alternative concepts for bounded rationality for an agent in a simulation (e.g., An, 2012; Gigerenzer & Goldstein, 1996; Gigerenzer & Selten, 2001; Muelder & Filatova 2018; Schilirò, 2018; Simon, 1972). In addition, the modelling team is also responsible for resolving issues emerging when working on the technical integration of model components. This may include data processing to align spatial and temporal scales (upscaling or downscaling of data) or the delineation of model representations of decision-making units (e.g., Martín-López et al., 2017).

5.1 Documenting Modelling Choices

Protocols such as the Overview, Design concepts and Details (ODD+) protocol for describing Individual-and Agent-Based Models (ABMs) (Grimm et al., 2020) or guidelines such as TRACE for keeping modelling notebooks to document the modelling process (Ayllón et al., 2021) are useful and now widely accepted for documenting models in journal articles. While being very useful for increasing transparency and documentation (especially when it comes to keeping track of decisions related to model integration as they focus on the technical aspects of the modelling process) both ODD+ or TRACE tend not to mention the social or political context/dynamics in their descriptions. While not directly relevant to the wider issues we are discussing, these protocols still provide clear descriptions of the outcomes of modellers' decision making, and as such, provide an important starting point for documenting the issues/modelling choices discussed here. However, not all kind of modelling choices might be covered by these protocols. Different stakeholders not only bring their own tools and backgrounds, but can also contribute with different kinds of (mental) models, perceptions, attitudes and interests (Voinov & Bousquet, 2010). Such mental models and prior experiences can impact the modelling process in a non-objective way (Voinov et al., 2016), potentially not even obvious to the stakeholder themselves, leading to hidden choices during the modelling process.

6. Kinds of Data Used

Agent-based modelling is often used for integrating a variety of inputs. Integrating empirical data can not only provide a way to link the model with its modelled world, but also strengthen stakeholders' confidence in the model (Achter et al., 2022; Filatova, 2015). There are different ways to generate data that may be useful for ABMs such as: sample surveys, participant observation, field and laboratory experiments, companion modelling, GIS and remotely sensed spatial data (Robinson et al., 2007). The corresponding data collection approaches differ regarding measurement type (quantitative or qualitative), the extent to which they are based on theory and the level of social, behavioural, and biophysical data collected among others (Robinson et al., 2007). Also, the purposes of integrating data in the model can differ, and data can be integrated at different stages of model development (Achter et al., 2022). For example, Diouf et al. (2022) use data from field monitoring to compare simulated population dynamics for validating their model. In contrast, Naivinit et al. (2010) implement the Companion Modelling approach to co-design a model of a social-agro-ecological system in Thailand to integrate indigenous and academic knowledge in an iterative modelling process. In general, data input can be used for model design, abstraction processes, initialization, or validation (Achter et al., 2022; Hassan et al., 2010). Different model purposes may, at different times, drive the choice of which kind of data to include in the model development.

The variety of input types and ways of integrating data at different stages in the modelling process are associated with certain challenges, adding another layer to the Chimaera problem. Most importantly, the modellers need to decide what kind of input to include at what stage of the modelling process. Experts from distinct disciplines may not only implement different methods to collect different kind of inputs, but also interpret data differently and have opposing views on the data's quality, validity, and suitability for integrating it into the model (Achter et al., 2022; Elsawah et al., 2020; Verburg et al., 2016). For example, anthropologists commonly rely on qualitative inputs such as narratives, whereas natural scientists may perceive quantitative data as more valuable (Elsawah et al., 2020). In the context of socio-ecological models, these challenges become particularly relevant (Verburg et al., 2016): differences in the involved stakeholders' expertise, desires, and needs regarding data can determine which kind of input is chosen and integrated into the ABM (Elsawah et al., 2020). In multidisciplinary teams, this diversity can be a necessity to represent and include a variety of perspectives through their disciplinary lenses, but this can cause tension.

In an ideal case, the use of data in empirical ABMs should be aligned with the overall research goal (Laatabi et al., 2018) and the philosophy guiding the modelling process. Data collection specifically for multi-agent modelling and simulation can make data translation easier by connecting data with the multi-agent model ontology (Geller, 2014). The co-design process should involve those who conducted the data collection and create room for discussion to develop a common understanding and interpretation of the inputs (Verburg et al., 2016). The modeller should document the modelling process and clarify the reasons for their decision concerning what kind of data was included and at what stage and how these choices influence the modelling process and results (Achter et al., 2022). All of these help ensure the consistency and reliability of modelling, but presume that there is an agreement on the modelling goals and the different viewpoints involved can be reconciled.

7. Different Modelling Stages

Different challenges pertaining to Chimaera models arise across different modelling stages. It is important to point out that socio-ecological model development is typically an iterative process, where different modelling phases are revisited frequently, based on the outcomes of the individual phases and that social learning is an important part of this process (Van Delden et al., 2011 a, Badham et al., 2019, Iwanaga et al., 2021). Below, we discuss the modelling phases planning and development.

7.1 Planning

The planning phase of the modelling process comprises problem definition and scoping, stakeholder planning, project management planning, and conceptual modelling (Badham et al., 2019). The overarching goals of this phase are to decide on: the modelling objectives, the function the model is expected to perform, the scope and boundary conditions of the socio-ecological system to be studied with the model, the participants of the modelling effort, and the resources necessary to successfully conduct the modelling effort. Moreover, the planning phase also entails the development of a conceptual model outlining the components (and their relationships) of the system under study (Badham et al., 2019).

While some modelling exercises are guided by a single objective or purpose, others – e.g., integrated modelling (Jakeman et al., 2006) or system-of-systems modelling exercises – may have multiple modelling purposes (Iwanaga et al., 2021). Different modelling purposes are often related to different philosophical stances (Table 1) resulting in additional complications when aiming to reconcile differences. Deciding on more than one modelling purpose and incorporating different philosophical stances may be a key factor for resulting in a Chimaera model, as it might lead to increasing complexity of the model and making it more difficult to keep the modelling consistent and users and modellers aware of the different purposes and related decisions made.

In participatory modelling the modelling process includes, to a varying degree, the participation of different interested parties, rights holders, and decision makers. This has become an established way of modelling socio-ecological systems (Voinov et al., 2016). While these partnerships and collaborations play a crucial role for informing and guiding the model development process on the one hand, and the use(fulness) and application of the resulting simulation model on the other hand, the involvement of a variety of interested parties, may also result in a Chimaera model. A heterogeneous group discussing the direction of the modelling exercise and expectations for the outcomes of the model application, brings together various perspectives and ideas (which may be the result of different philosophies). While this may make the model planning phase more complex to manage, this engagement can enrich the modelling process (e.g., Lippe et al., 2011; Voinov et al., 2016), making a potential increase in model complexity and internal contradictions a worthwhile compromise.

Modelling often starts by determining a conceptual model. The conceptual model development starts to spell out the details to be included in the simulation model in terms of system components and processes to be represented. During the development process of the conceptual model, as the complexity grows, discussions on the integrity of model structure regarding scale (Iwanaga et al., 2021) and other important system characteristics may be a starting point for reducing planned model complexity. This may also help to consolidate the expectations towards the model purpose and objectives.

The step of aligning the model objectives with the resources available to implement the model may lead to revisiting and prioritising what the model can realistically include and achieve. This may lead to a consolidation and reduction of planned model complexity – a natural point in the modelling process to think about possible clarification and focussing.

7.2 Development

The development phase of the modelling process comprises data collection, construction, calibration, uncertainty analysis, and model testing (Badham et al., 2019). The goals of this second phase of modelling comprise assembling quantitative, categorical, or qualitative data and other knowledge necessary for model development and testing, working from the conceptual model to develop a quantitative model, using data and other knowledge to adjust model parameters to best reproduce observations of the system under study, and exploring and quantifying the uncertainties present in model simulations (Badham et al., 2019). In this context a Chimaera model might result in extra developmental complexity due the to the lack of one clear single purpose and the integration of socio-economic and biophysical processes and the complicatedness this brings to the modelling process as the model developers, model users and stakeholders have different backgrounds, understandings, objectives, and approaches.

Data collected for informing the model development can be derived from a variety of sources such as literature reviews or fieldwork, participatory methods, or data analysis (Iwanaga et al., 2021), maybe including both objective and subjective information (see above). Decisions regarding what constitutes relevant information and which epistemologies to apply for guiding the data collection (e.g., Snapp, 2022) considerably affect the outcome of the model development. Since SES model development often requires the collection (and integration) of data across multiple disciplines, systems, and scales, metadata becomes central for documentation purposes (Iwanaga et al., 2021) and forms a crucial part for dealing with Chimaera models during the data collection step. As individual components of the Chimaera model often have a background in a specific discipline, the type, spatial, temporal and thematic resolution of the data for the individual components may not match those of other components. In these cases, approaches should be developed that are conceptually sound, provide model inputs that are sufficient for supporting the modelling goals, and can work with the data that is available (Van Delden et al., 2011b). In aligning the data, various conceptual decisions are made that often remain undocumented and hence unavailable to those not involved in the process. One example is the mismatch of agricultural (area, yield) data on crop yields from mandatory or voluntary reporting versus quantification through remote sensing approaches, with the former being frequently used in economic modelling approaches and the latter playing an important role in spatiotemporal land-use modelling.

Constructing and implementing computer models requires technical expertise. Hence, the modellers frequently work in separation from other disciplinary project partners or the stakeholders during this step. To ensure good communication between technical modellers and other aspects of the project (e.g. goal setting or data collection) model implementation should be an iterative process (Jakeman et al., 2006), providing opportunities to solicit feedback and enable social learning (Sargent, 2013; Van Delden et al., 2011a) from stakeholders and other collaborators, on the model drafts. During the implementation process, it can help to revisit the model purpose and manage expectations about what a computer model using a certain modelling approach can realistically deliver. In Chimaera models, the conceptual integration (how to integrate across scales, disciplines, model types, purposes etc.) remains a challenge (Iwanaga et al., 2021; Robinson et al., 2007; Van Delden et al., 2011a). Although good software solutions can help with the technical integration of components and the usability of the modelling systems, these do not solve many integration problems: research, information technology and user friendliness have to go hand in hand to manage Chimaera models (Van Delden et al., 2011a) due to the importance of good communication between the parts.

Model calibration describes the adjustment of model parameters to achieve a certain accuracy in the simulation outcomes (van Vliet, 2016). Model calibration requires the existence of sufficient data (Iwanaga et al., 2021), which can often be a limiting factor for agent-based simulation models and other complex socio-ecological systems models. Here, the combination of statistical and map data together with the use of qualitative information, narratives, and expert knowledge can be important to inform the parameterisation (Badham et al., 2019). When done in a participatory setting, calibration can also help build a sense of ownership for those involved (Hewitt et al., 2014). A challenge for Chimaera models is to deal with the various calibration approaches that are deemed appropriate in the various disciplines involved. A better understanding of the data sources and their limitations and a focus on the plausibility of the parameters as well as the numerical fit between the modelled results and the target data can help to overcome model challenges, but, again, the different modelling goals and viewpoints in Chimaera modelling might mean determining the appropriate approach is hard.

Model testing and assessment is an important part of model development and involves assessing if the developed model is fit for purpose. There may be a range of different ways model testing and assessment can be carried out, dependent, amongst other factors, on the disciplines involved and the practical limitations. It can involve an independent check on the reliability of the model results, usually done by comparing these results to new data (or data unknown to the modellers). Whether one does such a validation step might depend upon one's philosophical stance – for example it is necessary if one is aiming for realism, but maybe less important from a social constructivist stance. Furthermore, the kind of validation may depend upon the model purpose (Edmonds et al., 2019). Another way to better understand the developed model is to carry out a sensitivity analysis (Ligmann-Zielinska, 2020). A specific challenge for Chimaera modelling in the testing and assessment modelling phase is the system complexity and the involvement of modellers and users from different backgrounds and disciplines, each bringing to the table their own understanding and approaches. Navigating this complicated process requires all involved to engage in social learning and to create a common understanding on critical aspects together with respects for the different contributors and their viewpoints. However, with a *Chimaera model* many of the understandings involved might not be explicit making a common agreement on them difficult.

8. Kinds of Participants in the Modelling Process

Typically, SES modelling projects involve a variety of kinds of non-modeller (Checkland & Scholes, 1990). Indeed, the modellers are often the only common factor between different modelling stages and the only people who interact with all the different parties involved, so it is them that have to decide how to adapt to the different pressures. For brevity, we consider three kinds of participants in the Chimaera modelling process: stakeholders (those who might be affected by model outcomes), analysts and policy actors. Within a research context, public funders often play a role different from the user, which may create an extra difficulty as what these funders want to fund might not be what the users are interested in. Client-funded projects, on the contrary, might be an exception, as in this case the user can be the one arranging the funding – the funding is there to support their purposes in developing a model.

From a modelling perspective different kind of participants can influence the modelling process and their representation within a model. Participants may be further composed of sub-groups, for example, where a policy actor or analyst is part of a larger group such as a ministry or government. They can influence one another throughout a network of relationships, including collective cultures and other forms of norms and beliefs. There is a view that stakeholders should be engaged in all stages of the modelling process, however the degree to which this is be done in practice is often distinguished in terms of different intensities and depths of participation. Technology advances make it nowadays easier to incorporate information in interactive formats via visualisation or serious games to augment participatory experiences. However, stakeholders are also increasingly demanding to be engaged in planning decisions that affect them and their communities, at scales from local to global. How people interact with and access models and data is rapidly evolving. In turn, this requires changes in how models are built, packaged, and disseminated. In particular, stakeholders are becoming increasingly aware of their own capabilities to provide inputs to planning processes, including models (Voinov et al., 2016). This can also lead to negative aspects such as power plays or gaming, again pushing the modeller towards a Chimaera modelling situation. Funders can play an important role in such participatory exercises, as they can require research projects to pay particular attention to stakeholders, including their values and beliefs which the modellers then have to take into consideration, even if this is not entirely consistent with the main purpose of modelling (e.g., evaluation of policies). The important and diverse roles models can play in guiding decision processes are a feature of stakeholder participation today and increases societal knowledge in general. While being useful for increasing transparency of the modelling process as such, it is often better that participation is not done haphazardly during the modelling process, or given lip service. This can be challenging and adds another dimension to Chimaera modelling.

9. A Sketch of Some Strategies for Dealing with Chimaera Models

The point of this paper is principally to raise an issue for further debate rather than suggest approaches to mitigate the problems that Chimaera models pose. However, there seems to us to be five broad approaches for dealing with such situations, not all mutually exclusive. We briefly discuss these, to highlight the methodological development, feasibility, risks and applicability that will be needed in future research, however their resolution is beyond the scope of this paper. The approaches are as follows.

1. Relax and not worry about the issue, simply accept the contradictions and ambiguities – e.g., by emphasising that a model is the result of a creative process. This might take off the pressure and its flexibility might facilitate relationships with stakeholders, but it may lead to no clear results, it opens up the modelling to criticism and may deceive those outside the team that want to assess it or use it for other purposes (e.g., predict the result of a possible policy). Instead of resolving the contradictions and ambiguities, emphasis might be on developing a mutual understanding of these – why and where they occur. This may be part of a process to resolve the difficulties, but it may be that some take the resulting model too seriously and its outcomes (or implications) too authoritative.

2. Have an explicit agreement about the model scope and purpose (e.g., Checkland, 1981). Either this involves achieving agreement before the modelling starts or a post-hoc summary of what it turned out to do. These presume that a single, satisfactory account of model scope and purpose is possible. This approach has many advantages in terms of clarity. Agreeing on clear modelling goals can help bring all those involved to the same page (modellers, stakeholders, etc.) and thus reduce misunderstandings and conflict. This approach also makes it more likely that the agreed goal will be achieved and reduces the stress on the modellers as they will not be pulled in different directions. Such clarity might pave the way for future work that might aim at different or extended goals and so inform what steps might be needed to achieve them. However, such an explicit agreement can also be the focus of tension between parties and might delay the modelling – in some cases preventing it ever happening or resulting in parties dropping out.

3. Keep modelling exercises for different purposes and aspects completely separate (separate model versions, separate documentation versions etc.). This approach has the advantage of clarity, but at the expense of effort. Developing models takes time and effort, and demands on time and effort are greatly increased if there are lots of separate modelling sub-projects, each with their own purpose and processes. Furthermore, there is still the problem of integrating the results of the different sub-projects (e.g., comparing different models of the same phenomena). Modelling projects often run out of time, so well-intentioned attempts at such multiple modelling might flounder after the first is achieved – resulting in a more arbitrary resolution of the issues according to what was easiest or happened first.

4. Document and assess modelling exercises for different purposes separately, even though the modelling activities and model versions overlap. This is theoretically more efficient than the previous approach in the sense that it uses the same models and many of the same modelling processes for multiple purposes etc. with only the documentation and assessment occurring separately. However, this is difficult to achieve honestly, as different purposes, philosophies, data,

involved actors etc. almost always imply different kinds of model development, so one ends up with different processes and model versions at the end. It may help to inspire confidence by the transparency of the processes and increase others' understanding by making the different uses clear. However, it will require more time, risks confusion between the different uses and may encourage sloppy modelling (e.g., we have a model for purpose A let us simply assume it is also good for purpose B).

5. Track and trace the different elements and purposes through the models and modelling processes so one can assess the model for different purposes as needed each time. This is hard to do in practice, due to its complexity and so risks causing confusion. The methodology and tools to support this have not been sufficiently developed though one can envisage that this might happen, e.g., tools to support model decision provenance as in Lotzmann et al. (2015). It might be hard to detect how a change in one element (e.g., data or goal) might affect the others. Thus, at the moment, this is an approach that might work in theory but is yet to be realised in practice for complex projects.

Of course, there are many different ways of achieving any of these. For example, when the modeller detects tensions or compromises (for example in modelling goals or between stakeholders) they might seek to ensure that this is reflected to others for discussion and decision making and should be in the documentation (e.g., limitations). Such processes can increase transparency, inform the interpretation of the results and promote dialogue between involved actors but can also put off some actors from participating and can be time-consuming to do.

The modelling processes might be inherently collaborative between the actors involved, with a variety of disciplines being represented, as well as stakeholders, implying a shared responsibility. Such a deep collaborative approach will need compromises to balance and facilitate multi-disciplinary input but might increase feelings of project ownership among actors especially if compromises can be agreed that are satisfactory to all involved. Such sharing of responsibility is not easy however, it is more time efficient to have one "model manager" and the collaborative process might be the source of conflict within the project.

The modelling may exist in a policy context, where the models may embody political interests and power-determined values. In this case, model managers need to anticipate potential unintended consequences of participatory processes at different stages of model implementation/improvement. Whilst an awareness and sensitivity to such a context is always useful, bringing out these interests and power relations and making them explicit does not always help the processes and can increase polarisation and conflict. It takes some patience and skill to navigate such interests and power relations.

10. Conclusion

This paper is a diagnosis, rather than a therapy. Multi-stakeholder projects of socio-ecological systems, with multiple goals that evolve over time, easily lead to Chimaera models. We may not be able to do much about this, but we can acknowledge it and seek to mitigate the effects. Although we have outlined and given a name to a problem, we have no easy solutions – most require a lot of work and/or have risks. For some all that is required is a little humility and transparency. For example, instead of implying that the 'Limits to growth' model was a realistic representation and actually predicted the future, the authors of the study could have claimed that the model established a counterexample to the existing equilibrium economic models, revealing what might happen when there are significant time lags between processes. In other cases, those involved could simply accept that they were not going to agree and develop different models of the same phenomenon in parallel, with the bonus that they could later compare the resulting models with each other.

We have been motivated by the occasional difficulties of being the "modellers in the middle", with the responsibility to ensure the modelling is rigorous, despite all the difficulties and contradictions. We call for more recognition of these problems, but more than anything else, we advocate for a diffusion of the responsibility of modelling decisions to the wider project team. This includes stakeholders and policy actors where these have an input in shaping or informing the project.

Our most important recommendation is that modellers should not be the only ones who are forced to reconcile the different aspects and goals of a complex project, but this should be done collectively. Furthermore, this should be done from the beginning, built into the fundamental project plan. As with all integrative efforts this cannot be left until the end. Modellers cannot simply integrate previous results towards the end of the project (Bammer, 2013) – the infamous "workpackage 5" in many projects.

It takes a team to raise a model!

Acknowledgements

This paper builds on discussions from the Lorentz workshop "Participatory and Cross-scale Modelling of Social Ecological System" at Lorentz Centre, Leiden, the Netherlands in June 2022. The authors acknowledge the Lorentz Center, Leiden University and NWO for hosting and providing financial support.

References

Achter, S., Borit, M., Chattoe-Brown, E., & Siebers, P.O., (2022). RAT-RS: a reporting standard for improving the documentation of data use in agent-based modelling. International Journal of Social Research Methodology, 25(4), 517-540. https://doi.org/10.1080/13645579.2022.2049511

An, L. (2012). Modeling human decisions in coupled human and natural systems: Review of agent-based models. Ecological Modelling, 229, 25-36. https://doi.org/10.1016/j.ecolmodel.2011.07.010

An, L., Grimm, V., Sullivan, A., Turner Ii, B. L., Malleson, N., Heppenstall, A., Vincenot, C., Robinson, D., Ye, X., Liu, J., Lindkvist, E., & Tang, W. (2021). Challenges, tasks, and opportunities in modeling agent-based complex systems. Ecological Modelling, 457, 109685. https://doi.org/10.1016/j.ecolmodel.2021.109685

Ayllón, D., Railsback, S. F., Gallagher, C., Augusiak, J., Baveco, H., Berger, U., Charles, S., Martin, R., Focks, A., Galic, N., Liu, C., van Loon, E., Nabe-Nielsen, J., Piou, C., Polhill, G., Preuss, T.G., Radchuck, V., Schmolke, A., Stadnicka-Michalak, J., Thorbek, P.,, Grimm, V. (2021) Keeping modelling notebooks with TRACE: Good for you and good for environmental research and management support. Environmental Modelling & Software, 136, 104932, https://dx.doi.org/10.1016/j.envsoft.2020.104932

Badham, J., Elsawah, S., Guillaume, J. H., Hamilton, S. H., Hunt, R. J., Jakeman, A. J., Pierce, S., Snow, V., Babbar-Sebens, M., Fu, B., Gober, P., Hill, M.C., Iwanga, T., Loucks, D. P., Merritt, W. S., Peckham, S.D., Richmond, A. K., Zare, F., Ames, D., & Bammer, G. (2019). Effective modeling for Integrated Water Resource Management: A guide to contextual practices by phases and steps and future opportunities. Environmental Modelling & Software, 116, 40-56. https://doi.org/10.1016/j.envsoft.2019.02.013

Bammer, G. (2013). Disciplining Interdisciplinarity. ANU E Press. https://library.oapen.org/bitstream/handle/20.500.12657/33556/459901.pdf

Barnaud, C. & Van Paassen, A. (2013). Equity, Power Games, and Legitimacy: Dilemmas of Participatory Natural Resource Management. Ecology and Society, 18(2). http://dx.doi.org/10.5751/ES-05459-180221

Bolte, J. P., Hulse, D. W., Gregory, S. V., & Smith, C. (2007). Modeling biocomplexity–actors, landscapes and alternative futures. Environmental Modelling & Software, 22(5), 570-579. https://doi.org/10.1016/j.envsoft.2005.12.033

Brugnach, M., & Ingram, H. (2012). Ambiguity: the challenge of knowing and deciding together. Environmental Science & Policy 15(1), 60-71. http://dx.doi.org/10.1016/j.envsci.2011.10.005

Checkland, P. B. (1981). Systems Thinking, Systems Practice, John Wiley & Sons Ltd, London.

Checkland, P. B. & Scholes, J. (1990). Soft Systems Methodology in Action, John Wiley & Sons Ltd, London.

De Jongh, D. C. J. (1978). Structural parameter sensitivity of the 'limits to growth' world model. Applied Mathematical Modelling, 2(2), 77-80.

Diouf, E.G., Brévault, T., Ndiaye, S., Faye, E., Chailleux, A., Diatta, P., & Piou, C. (2022). An agent-based model to simulate the boosted Sterile Insect Technique for fruit fly management. Ecological Modelling, 468, 109951. https://doi.org/10.1016/j.ecolmodel.2022.109951

Edmonds, B., le Page, C., Bithell, M., Chattoe-Brown, E., Grimm, V., Meyer, R., Montañola-Sales, C., Ormerod, P., Root H. & Squazzoni. F. (2019) Different Modelling Purposes. Journal of Artificial Societies & Social Simulation, 22(3), 6. http://doi.org/10.18564/jasss.3993

Elsawah, S., Filatova, T., Jakeman, A. J., Kettner, A. J., Zellner, M. L., Athanasiadis, I. N., Hamilton, S. H., Axtell, R. L., Brown, D. G., Gilligan, J. M., Janssen, M. A., Robinson, D. T., Rozenberg, J., Ullah, I. I. T., & Lade, S. J. (2020). Eight grand challenges in socio-environmental systems modeling. Socio-Environmental Systems Modelling, 2, 16226. https://doi.org/10.18174/sesmo.2020a16226

Epstein, J. M. (2008). Why model? Journal of Artificial Societies & Social Simulation, 11(4), 12. https://jasss.soc.surrey.ac.uk/11/4/12.html

Etienne, M., & Balandier, P. (2003). Interactions bétail-végétation dans les systèmes sylvo-pastoraux en France| Livestock-vegetation interactions in silvopastoral systems in France. Schweizerische Zeitschrift fur Forstwesen, 154(5), 161-168.

Filatova, T. (2015). Empirical agent-based land market: Integrating adaptive economic behavior in urban land-use models. Computers, Environment and Urban Systems, 54, 397–413. https://doi.org/10.1016/j.compenvurbsys.2014.06.007

Friedman, M. (1953). Essays in positive economics. University of Chicago press.

Geller, A. (2014). Building Empirical Multiagent Models from First Principles When Fieldwork Is Difficult or Impossible. In: Smajgl, A., Barreteau, O. (Eds.), Empirical Agent-Based Modelling – Challenges and Solutions Volume 1: The Characterisation and Parameterisation of Empirical Agent-Based Models. Springer, New York, pp. 223–237. http://doi.org/10.1007/978-1-4614-6134-0_12

Gigerenzer, G., & Goldstein, D. G. (1996). Reasoning the Fast and Frugal Way: Models of Bounded Rationality. Psychological Review, 103, 650–669. https://doi.org/10.1093/acprof:oso/9780199744282.003.0002

Gigerenzer, G., & Selten, R. (2001). Rethinking Rationality. In: Bounded Rationality. The Adaptive Toolbox. MIT Press, Cambridge, London.

Grimm, V., Railsback, S. F., Vincenot, C. E., Berger, U., Gallagher, C., DeAngelis, D. L., Edmonds, B., Ge, J. Giske, J., Groeneveld, J., Johnston, A. S.A., Milles, A., Nabe-Nielsen, J. Polhill, J. G., Radchuk, V., Rohwäder, M., Stillman, R. A., Thiele, J. C., & Ayllón, D. (2020). The ODD Protocol for Describing Agent-Based and Other Simulation Models: A Second Update to Improve Clarity, Replication, and Structural Realism. Journal of Artificial Societies & Social Simulation, 23(2), 7. http://doi.org/10.18564/jasss.4259

Hassan, S., Pavón, J., Antunes, L., & Gilbert, N. (2010). Injecting Data into Agent-Based Simulation. In: Takadama, K., Cioffi-Revilla, C., Deffuant, G. (Eds.), Simulating Interacting Agents and Social Phenomena. Springer, Tokyo, pp. 179–191. http://doi.org/10.1007/978-4-431-99781-8_13

Hewitt, R., Van Delden, H., & Escobar, F. (2014). Participatory land use modelling, pathways to an integrated approach. Environmental Modelling & Software, 52, 149-165. http://doi.org/10.1016/j.envsoft.2013.10.019

Inouye, A. M., Lach, D. H., Stevenson, J. R., Bolte, J. P., & Koch, J. (2017). Participatory modeling to assess climate impacts on water resources in the Big Wood Basin, Idaho. Environmental Modeling with Stakeholders: Theory, Methods, and Applications, 289-306. http://doi.org/10.1007/978-3-319-25053-3_14

Iwanaga, T., Wang, H., Hamilton, S. H., Grimm, V. Koralewski, T. E., Salado, A. Elsawah, S., Razavi, S., Yang,J., Glynn, P., Badham, J., Voinov, A., Chen, M., Grant, W. E., Peterson, T. R., Frank, K. Shenk, G. Barton, C. M. Jakeman, A. J., & Little, J. C. (2021). Socio-technical scales in socio-environmental modelling: Managing a system-of-systems modelling approach, Environmental Modelling & Software, 135, 104885. http://doi.org/10.1016/j.envsoft.2020.104885

Jakeman, A. J., Letcher, R. A., & Norton, J. P. (2006). Ten iterative steps in development and evaluation of environmental models. Environmental Modelling & Software, 21(5), 602-614. https://doi.org/10.1016/j.envsoft.2006.01.004.

Koch, J., Friedman, J. R., Paladino, S., Plassin, S., & Spencer, K. (2019) Conceptual modeling for improved understanding of the Rio Grande/Río Bravo socio-environmental system. Socio-Environmental Systems Modeling, 1, 16127. https://doi.org/10.18174/sesmo.2019a16127.

Laatabi, A., Marilleau, N., Nguyen-Huu, T., Hbid, H., & Babram, M. A., (2018). ODD+2D: An ODD based protocol for mapping data to empirical ABMs. Journal of Artificial Societies and Social Simulation, 21. https://doi.org/10.18564/jasss.3646

Ligmann-Zielinska, A., Siebers, P. O., Magliocca, N., Parker, D. C., Grimm, V., Du, J., V. & Ye, X. (2020). 'One size does not fit all': a roadmap of purpose-driven mixed-method pathways for sensitivity analysis of agent-based models. Journal of Artificial Societies & Social Simulation, 23(1), 6. http://doi.org/10.18564/jasss.4201

Lim, T. C., Glynn, P. D., Shenk, G. W., Bitterman, P., Guillaume, J. H. A., Little, J. C., & Webster, D. G. (2023). Recognizing political influences in participatory social-ecological systems modeling. Socio-Environmental Systems Modelling, 5, 18509. https://doi.org/10.18174/sesmo.18509

Lippe, M., Minh, T. T., Neef, A., Hilger, T., Hoffmann, V., Lam, N. T., & Cadisch, G. (2011). Building on qualitative datasets and participatory processes to simulate land use change in a mountain watershed of Northwest Vietnam. Environmental Modelling & Software, 26(12), 1454-1466. https://doi.org/10.1111/gcbb.12176

Lotzmann, U., Neumann, M., & Möhring, M. (2015). From Text To Agents-Process Of Developing Evidence-Based Simulation Models. In European Conference on Modelling and Simulation, (pp. 71-77). https://www.scs-europe.net/dlib/2015/ecms2015acceptedpapers/0071-abs_ECMS2015_0104.pdf

Martín-López, B., Palomo, I., García-Llorente, M., Iniesta-Arandia, I., Castro, A. J., Del Amo, D. G., Gómez-Baggethun, E., & Montes, C. (2017). Delineating boundaries of social-ecological systems for landscape planning: A comprehensive spatial approach. Land Use Policy, 66, 90-104.

Meadows, D. H., Meadows, D. L., Randers, J., & Behrens III, W. W. (1972). The limits to growth. Club of Rome.

Muelder H., & Filatova T. (2018). One Theory - Many Formalizations: Testing Different Code Implementations of the Theory of Planned Behaviour in Energy Agent-Based Models. Journal of Artificial Societies & Social Simulation, 21(4), 5. https://doi.org/10.18564/jasss.3855

Naivinit, W., le Page, C., Trébuil, G., & Gajaseni, N., (2010). Participatory agent-based modelling and simulation of rice production and labor migrations in Northeast Thailand. Environmental Modelling & Software 25, 1345–1358. https://doi.org/10.1016/j.envsoft.2010.01.012

Plassin, S., Koch, J., Paladino, S., Friedman, J. R., Spencer, K., & Vaché, K. B. (2020). A socio-environmental geodatabase for integrative research in the transboundary Rio Grande/Río Bravo basin. Scientific Data, 7(1), 80. https://doi.org/10.1038/s41597-020-0410-1

Robinson, D.T., Brown, D.G., Parker, D.C., Schreinemachers, P., Janssen, M.A., Huigen, M., Wittmer, H., Gotts, N., Promburom, P., Irwin, E., Berger, T., Gatzweiler, F., & Barnaud, C., (2007). Comparison of empirical methods for building agent-based models in land use science. Journal of Land Use Science 2(1), 31–55. https://doi.org/10.1080/17474230701201349

Sandoval-Solis, S., Paladino, S., Garza-Diaz, L., Nava, L., Friedman, J., Ortiz-Partida, J. P., Plassin, S., Gomez-Quiroga, G., Koch, J., Fleming, J., Lane, B. A., Wineland, S., Mirchi, A., Saiz-Rodriguez, R., & Neeson, T. (2022). Environmental flows in the rio grande-rio bravo basin. Ecology & Society, 27(1), art20. https://doi.org/10.5751/ES-12944-270120

Sargent, R. G. (2013). Verification and Validation of Simulation Models. Journal of Simulation, 7, 12-24. https://doi.org/10.1109/WSC.2013.6721430

Schilirò, D. (2018). Economic Decisions and Simon's Notion of Bounded Rationality. International Business Research, 11, 64. https://doi.org/10.5539/ibr.v11n7p64

Simon, H.A. (1972). Theories of Bounded Rationality. In: McGuire, C.B., Radner, R. (Eds.), Decision and Organization. Elsevier, Amsterdam, pp. 161–176.

Snapp, S. (2022). Modeling futurity: examining epistemological assumptions and political context in urbanization modeling. https://shareok.org/handle/11244/335643

Spies, T. A., White, E., Ager, A., Kline, J. D., Bolte, J. P., Platt, E. K., Olsen, K. A., Pabst, R. J., Barrons, A. M. G., Bailey, J. D., Charnley, S., Morzillo, A. T., Koch, J., Steen-Adams, M. M., Singleton, P. H., Sulzman, J., Schwartz, C., & Csuti, B. (2017). Using an agent-based model to examine forest management outcomes in a fire-prone landscape in Oregon, USA. Ecology & Society, 22(1), 25. https://www.jstor.org/stable/26270069

Van Delden, H., Van Vliet, J., Rutledge, D. T. & Kirkby, M. J. (2011a). Comparison of scale and scaling issues in integrated land-use models for policy support. Agriculture, Ecosystems & Environment, 142(1-2), 18-28. https://doi.org/10.1016/j.agee.2011.03.005

Van Delden, H., Seppelt, R., White, R. & Jakeman, A. J. (2011b). A methodology for the design and development of integrated models for policy support. Environmental Modelling & Software, 26, 266-279. https://doi.org/10.1016/j.envsoft.2010.03.021

van Vliet, J., Bregt, A. K., Brown, D. G., van Delden, H., Heckbert, S., & Verburg, P. H. (2016). A review of current calibration and validation practices in land-change modeling. Environmental Modelling & Software, 82, 174-182. https://doi.org/10.1016/j.envsoft.2016.04.017

Verburg, P. H., Dearing, J. A., Dyke, J. G., Leeuw, S. van der, Seitzinger, S., Steffen, W., & Syvitski, J., (2016). Methods and approaches to modelling the Anthropocene. Global Environmental Change, 39, 328–340. https://doi.org/10.1016/j.gloenvcha.2015.08.007

Voinov, A., Bousquet, F. (2010). Modelling with stakeholders. Environmental Modelling & Software, 25(11), 1268-1281. https://doi.org/10.1016/j.envsoft.2010.03.007

Voinov, A., Shugart, H.H., (2013). 'Integronsters', integral and integrated modeling. Environmental Modelling & Software, 39, 149-158. https://doi.org/10.1016/j.envsoft.2012.05.014

Voinov, A., Kolagani, N., McCall, M. K., Glynn, P. D., Kragt, M. E., Ostermann, F. O., Pierce, S. A., & Ramu, P. (2016). Modelling with stakeholders – Next generation. Environmental Modelling & Software, 77, 196-220, https://doi.org/10.1016/j.envsoft.2015.11.016