How to operationalise the social in social-ecological models and simulations: Two mutually linked perspectives

Ronald Bialozyt[1,2,*], Martina Roß-Nickoll[3], Richard Ottermanns[3], Jens Jetzkowitz[4,5]

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[1] Northwest German Forest Research Institute, Göttingen, Germany
[2] Georg-August-University, Department of Ecosystem Modelling, Göttingen, Germany
[3] RWTH Aachen University, Institute for Environmental Research, Aachen, Germany
[4] Thünen-Institute for Rural Studies, Braunschweig, Germany
[5] Helmut-Schmidt-University, Faculty of Humanities and Social Sciences, Hamburg, Germany
[*] Presenting author

Abstract

Research on sustainability and co-evolution often uses models and simulations to develop knowledge on social-ecological problems. This usually involves the knowledge produced by several scientific disciplines which deal with different aspects of reality and in which scientists work on the basis of different narratives. In exploring the question of how to properly integrate social aspects in interdisciplinary models and simulations of sustainability science and co-evolutionary research, we have found that two perspectives need to be distinguished, namely a structural and a procedural one. Both reflect the documented but scattered efforts in the literature to incorporate the social into models and simulations. In a structural perspective, various approaches have developed to model interactions and feedbacks between ecological and social aspects of a sustainability problem. Among the best known is the concept of the social-ecological system, which makes it possible to grasp the complexity of reality in ecological and social subsystems that are nested within each other. From a procedural perspective, various approaches to protocols for model documentation have been developed in the professional discussion in order to take into account the fact that every model formation is a social, communicative process.

We have explored the different approaches to incorporate the social aspects into the modelling with reference to sociological knowledge and have gained new insights into the path dependency of model structures. We have also identified an extended hierarchical structure of modelling. Most importantly, we describe how the interactions between these two perspectives can be used to improve an active modelling process. In the process, fundamental considerations emerge that can be used for a working guide of SES models in the future.

Keywords:

SES framework; modelling process; procedural perspective; structural perspective; nested structure; social components

1 Introduction

Mathematical and simulation models are a well-established research strategies in natural and social sciences (Arnold 2010). They provide answers to research questions on causal relations and are able to reveal missing links in the understanding of our world. In the current need to get more insights into the interplay between social and environmental issues, social-ecological[1] models have been developed. There are two important reasons, why scientists follow this interdisciplinary approach.

First, modelling and simulation studies are able to relate different aspects of reality and study their interdependencies, feedback loops and emergent properties. This allows to tackle problems and knowledge gaps that emerge in interdisciplinary research. Modelling approaches are able to integrate what is usually studied in isolation in different academic disciplines, based on their own conceptual frameworks and methodologies (Grant and Thompson 1997; Liu 2001).

Second, modelling and simulation studies can offer predictions of the likely outcome of processes started with known independent variables (Harris 2002; Kelly et al. 2013). The traditional way to gain such insights is through experimental studies, which are considered the silver bullet of scientific research (Ivanova 2021). Models and simulations are used to project systems behaviour into the future and are used to guide decision makers in environmental consulting.

In sustainability science, most scholars agree that environmental concerns should be closely linked to social issues, although there is no consensus on how this should be done in research. Including social factors in ecological models and simulations is complex, involving value judgements and norms more so than in natural and technical sciences. Various fields have developed different approaches to incorporate social aspects into models, each based on their specific understanding. This has led to a range of paradigms in sustainability science. These paradigms include complex adaptive systems (Arthur et al. 1997; Filatova et al. 2016), coupled human-natural systems (Hull and Liu 2018), Earth System Governance (Burch et al. 2018), and issues of justice (Menton et al. 2020), all of which examine the interactions between societies and their environments.

Given the diversity of approaches to incorporating social factors into ecological models, it's reasonable to ask if these methods can be unified. This question is central to our reflections, but we are not aiming to create a single framework that integrates all modelling approaches. Instead, we seek to encourage discussion on developing a guide for good modelling practices to support the appropriate development and communication of concrete models.

To achieve this, we draw on sociological insights, examining various discussions on including social aspects in social-ecological modelling. We will highlight two essential perspectives for integrating social aspects into these models: a structural and a procedural one. We aim to synthesise what can be learned from different approaches to operationalise social aspects for sustainability science and co-evolutionary research. This synthesis can help scientists develop good modelling practices and ensure high quality scientific knowledge production through the modelling of Social-Ecological Systems (SES).

[1]We use the term "social-ecological" instead of "socio-ecological" (or "socioecological") following Berkes, because "social-ecological emphasises that the two subsystems are equally important, whereas socio- is a modifier, implying a less than equal status of the social subsystem" (Berkes 2017).

2 Good modelling practise

Our aim was to integrate social aspects into social-ecological models. Although our ideas originate from concepts outside System Dynamics, we believe that our ideas about the modelling process are so universal that they apply to all modelling exercises dealing with societal problems. This is particularly true in the case of System Dynamics. Here the policy derived from the model is clearly a focus of the modelling exercise and a truly societal issue.

Forrester (2007) devoted five points of his nine criteria for quality in System Dynamics to the policy issue. He concluded his analysis by saying that the only way to improve quality is to demand higher standards of work. Our approach, if rigorously applied, would produce such higher modelling standards which Forrester demands.

Since Forrester's speech in 2007, there has been a debate in the System Dynamics Society about how to achieve higher standards and what direction to take. Clancy et al. (2023) analysed the different strands of this debate and identified four distinct schools in System Thinking. They emphasise that these schools are not mutually exclusive and that the structure of this classification arises from the different mental models.

Often these mental models are not clear to an outsider, and sometimes not even to the modellers themselves. This is where we want to make our contribution, to help modellers and laypeople to become more aware of the shortcomings of not adequately dealing with different mental models as one aspect of how the social enters into the modelling process.

3 The social in social-ecological modelling

Our analysis of the incorporation of social factors into the development of social-ecological models reveals the existence of at least two distinct perspectives. From one perspective, the social is conceptualised as a component of the model, representing a social subsystem within a larger social-ecological system. Conversely, the social is seen as a process within the modelling framework. This second aspect is not exclusive to the development of social-ecological models; it is applicable to any modelling exercise.

In light of the above, we propose to call these two perspectives structural and procedural, respectively. The first perspective, that of structural analysis, integrates the two basic structural concepts of social and ecological subsystems, thereby facilitating a systematic correlation between ecological and sociological knowledge.

The second perspective is concerned with the modelling process, the generating system. In this context, special attention is given to the social aspects, as these significantly extend the understanding of the classical modelling process and capture the process more appropriately. An awareness of this process and of all the decisions that have to be made along the modelling chain will support the development of an effective modelling practice.

3.1 Structural perspective

The structural perspective (Fig. 1) gives us an idea of how to select appropriate components and processes to include in the model. We start with the discipline-specific structures of the object under study. These often do not include ideas or structures from other disciplines. But both domains, here ecology and society, are part of the same model, so we need to identify processes that link them. These are shown in the Figure 1 as black arrows going from one domain to the other. In selecting such processes, feedback loops may be identified, indicated by the red dashed arrows. The components and processes to be selected will depend on the 'impact parameter' defined by the objective of the study.

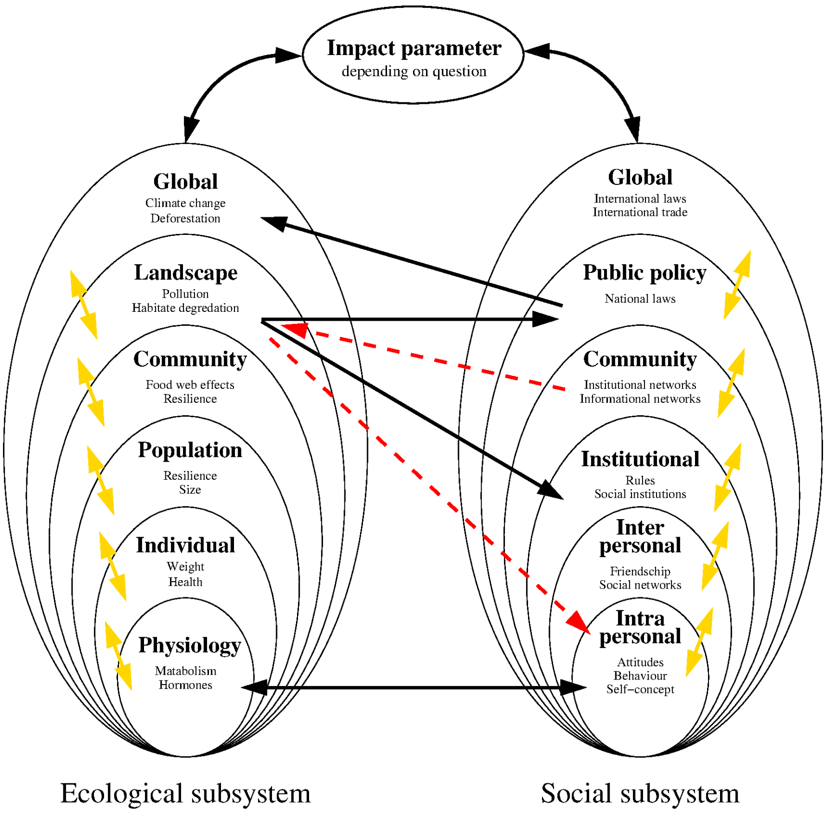

Fig. 1: A framework of nested ecological (left) and social subsystems (right) with hierarchies formed by internal processes (yellow arrows). Black arrows represent processes connecting both subsystems across hierarchical levels, creating feedback loops (red dashed arrows). The impact parameter guides the selection of suitable processes based on the research question.

3.2 Procedural perspective

The procedural perspective is concerned with the process of modelling. Figure 2 shows our identified social components of this process as blue circles. They indicate important aspects in the development of a model, both temporally and structurally. These social components are connected by processes, green arrows, and feedback loops, blue arrows. The subject of these processes is indicated along these arrows.

Decisions have to be made along these processes. These decisions are made by the experts involved, and different experts make different decisions for the same issue. Once a decision is made, the structure of the model is fixed in that aspect and it will be difficult to change it later. This phenomenon is known as path dependency, as described by Hämäläinen and Lahtinen (2016) in operational research. It can lead to a completely different model that behaves similarly in some areas or questions, but completely differently in others.

3.2.1 An outline of the model-building process

Every modelling process begins with a social impulse, namely a demand (Kelly et al. 2013). This arises either from mere curiosity or, in more specific cases, it may be a societal problem that needs to be solved. The initial problem definition is commonly diffuse and does only trigger the process in the first place.

According to our scheme, the development of the exact research question results from the combination of the experts involved in modelling and what they already know or believe ("Expert knowledge"). We call this process "Genesis" because in this process the specific "Research question" is generated (Fig. 2). Thus, the research question is shaped by the prior knowledge of the experts involved. Both components, "Expert knowledge" and "Research question", are social components and each part of feedback loops within the modelling process, which we call "Refinement" and "Learning". These loops arise during the modelling cycle (Grimm and Railsback 2005) improving the research question.

It must be emphasised in this context that the selection of experts involved in the definition of the research question is an important aspect for the process of "Genesis" as well as that of "Learning". In the current best practice recommendations for the documentation of models, a detailed description of these social aspects is not mandatory, but would contribute significantly to the clarification of included as well as excluded components of the developed model. It would also be useful if the various experiences from qualitative social research with non-probability or information-based sampling (Gentles et al. 2015) were taken into account in the composition of expert groups, thus making the process transparent.

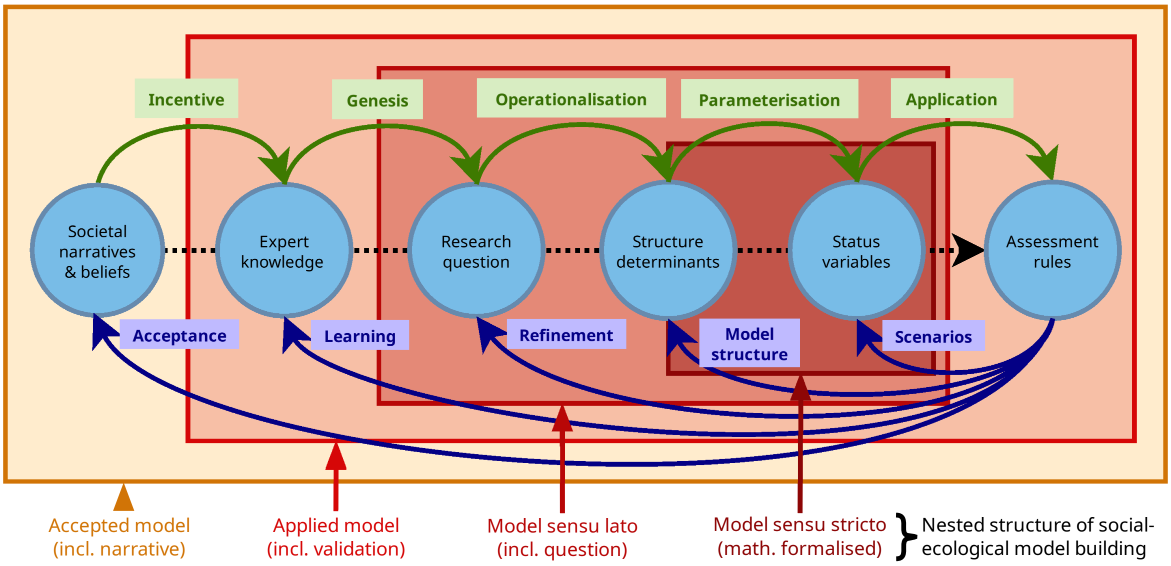

Fig. 2: Outline of the nested model-building process showing key social components (blue circles) and their generating processes (green arrows), along with feedback loops (blue arrows) that shape the model structure. The process includes emergent structural levels (orange/reddish rectangles). See text for details.

The "Expert knowledge" in modelling is shaped by "Societal narratives and beliefs' that are communicated in everyday interactions, making it a social component. This knowledge influences model-building incentives and feedback loops, such as "Acceptance", which either confirm or change societal beliefs. Experts are involved in all steps, making path-dependent decisions about "Structural determinants" and "Status variables" that shape the model's boundary conditions and dynamics. These choices are refined through feedback loops to ensure that the model meets "Assessment rules".

These "Assessment rules" define when a model is considered a good representation of the system, balancing conflicting interests and establishing evaluation standards. The iterative process of modelling, involving scenario simulations and expert feedback, ensures the validity of the model. If these rules aren't met, the research question may need to be refined, possibly requiring sub-models. Throughout, experts "Learning" to refine the research question and model components, leading to better models.

A model is good if it is able to change users' understanding and behaviour. Documenting assumptions clearly helps to achieve this. Standardised protocols such as ODD and TRACE overlook the social aspects of modelling, so there is no clear requirement to describe them. Overall, social components and feedback loops are crucial in SES modelling and addressing them improves the modelling process and documentation.

3.2.2 Hierarchical structure of modelling concepts

Looking at Figure 2, we identify key elements of the hierarchical modelling process. Each level influences the levels below it. The social components can be summarised as follows: "Status variables" and "Structure determinants" form the core of the mathematically formalised model ("Model sensu stricto"), which generates predictions that are evaluated on the basis of "Assessment rules".

This model level is part of a broader structure ("Model sensu lato") which includes the "Research question" as a new social level. The purpose of the model is the opening statement in the ODD protocol (Grimm et al. 2010). This is because Grimm and Railsback (2005) define a model as an abstract representation of reality with a purpose, communicated in scientific literature. So they have already recognised the social aspect of modelling. This is the level at which most modelling work is done.

The "Applied model" level introduces "Expert knowledge" and "Assessment rules" along with the "Learning" feedback loop essential for model development. When a model is validated, the expert knowledge is modified and can be applied to new scenarios, extending the learning to all scientists and stakeholders involved, thus evolving the "Assessment rules" and contributing to validation.

The final structure, the "Accepted model", becomes a new paradigm if it is able to change "Societal narratives and beliefs". It contains all the feedback loops. The acceptance loop critically evaluates the indicators, potentially changing the research question, structure determinants and status variables, leading to a revised model structure.

4 Combining both perspectives

While there is certainly no silver bullet for creating a good SES model, we recognise the question of appropriateness to a research problem as an essential element of good modelling practice. Although we are far from proposing a working guide as an answer to this question, we do suggest that the two perspectives should be used alternately and iteratively in model development.

Components and processes are chosen to address the specific problem being modelled. Emphasis is placed on the social dimension, without neglecting theoretical aspects. Each model should include only the necessary aspects determined by the research question and the experts and backgrounds involved. These social dimensions shape the model structure to reflect real system components and feedback loops.

Using our proceduralö perspective helps to decide which decisions should be documented. For example, changes in the system structure, especially during feedback processes, should be recorded. While the motivation for modelling is only briefly discussed in a paper, the research question often undergoes continuous refinement. This should be documented, especially if it is hindered by data limitations. Extensive discussions also occur during the "Operationalisation" and "Parameterisation" processes and could be documented through model versioning, using tools such as GitHub. The "Assessment rules" evolve during modelling and the final version should be part of the documentation.

Unlike other best practice recommendations for modelling, we emphasise the critical importance of social aspects in the modelling process. Individual choices made during model development affect the outcome, similar to the findings of Hämäläinen and Lahtinen (2016). We argue that the selection of experts and prevailing ideas about the system also have a profound influence on the model structure. Although not all social aspects can be documented, they should be taken into account when interpreting model results.

Treating social aspects in SES models as dynamic processes rather than fixed agents or entities, leads to new model structures. Processes drive model dynamics, and the inclusion of social processes creates a new class of models. Our structural perspective helps to select appropriate social levels and processes based on the research question. Previous approaches, such as adding people as agents or including formal institutions, lack social system dynamics. Our approach identifies when dynamic treatment of agents or institutions is needed. Using our guide, researchers can build a comprehensive picture and identify appropriate processes and feedback loops, which is not common in current SES models (Filatova et al. 2016).

Dealing with the structure of the two perspectives combined will increase modellers' awareness of how to improve the quality and documentation of their models, as requested by Forrester (2007).

5 Conclusion

To understand and address societal challenges, we need to model not only external mechanisms such as nature or climate change, but also the side effects and feedback loops within society. This is the core of the SES approach. Given the diversity of perspectives in society, it is impractical to seek a universal approach to integrating social aspects into ecological models. However, we believe it is important to establish standards to distinguish good models from less effective ones. The two perspectives on social aspects in SES models provide fundamental considerations for this.

We suggest that rules for good modelling practice can be developed through scientific discussion and summarised in a working guide. Our reflections on the procedural perspective contribute to this by helping modellers, experts and laypersons to understand the social dynamics in the modelling process. This understanding can lead to better expert selection, more appropriate research questions, and improved model structures and results. Incorporating "Assessment rules" extends the understanding of the model and defines its limits of validity. Expert decisions are crucial in determining the areas of application of the model.

Modellers who are aware of these social implications will produce better models and documentation. This will improve the understanding of theoretical and simulation models in societal discussions and help to identify tipping points to find leverage for interventions in "social-ecological" and other systems (Meadows 1997).

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