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# The different ways to operationalise the social in applied models and simulations of sustainability science: A contribution for the enhancement of good modelling practices

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A B S T R A C T

There are several concepts out there, which describe modelling as a circular process with several rounds of iteration. The aim of these concepts is to structure the process and gain insights into the various steps carried out during a modelling project. It is common to all these concepts that they are created by modellers themselves, hence the focus is on generating a good modelling practice (GMP) in standardising technical aspect. However, modelling must also be considered as a social process, which have so far only been marginally considered in these GMP protocols.

Therefore, we explored the different approaches to incorporate the social aspects into GMP of interdisciplinary applied modelling projects in sustainability science with reference to sociological knowledge. While discussing the social dimensions in the modelling process, we found that two perspectives need to be distinguished, namely a structural and a procedural one. From 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 intertwined within each other. From a procedural perspective, several components describing decision points and feedback processes along the modelling pathway have been identified. This forms a new GMP scheme different from the so far published ones as it incorporates all the feedback loops active during the modelling process. It therefore breaks the so far common circular approach. The new scheme emphasises the fact that every model formation is a social, communicative process at all phases of a modelling project.

Additionally, we have gained new insights into the path dependency of model structures and identified an extended hierarchical structure of social modelling steps. Most importantly, we describe how the iterative application of these two perspectives should be used to improve the GMP of an active modelling project.

## 1. Introduction

Modelling and simulation studies are well-reputed research strategies in natural and social sciences which provide answers to research questions on causal relations (Arnold, 2010). In sustainability science these strategies have gained attention for two important reasons. First, their potential to relate different aspects of reality and to study their interdependencies, feedback loops and emergent properties makes them attractive to tackle problems and knowledge gaps that emerge in interdisciplinary fields. Used properly, modelling approaches promise to integrate what is usually studied in isolation in academic disciplines, based on their own conceptual frameworks and methodologies (Grant and Thompson, 1997; Liu, 2001).

Second, modelling and simulation studies offer predictions of the likely outcome of processes started with known independent variables (Harris, 2002; Kelly et al., 2013). This can otherwise only be achieved

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through experimental studies, which are considered the silver bullet of scientific research to investigate causal relationships under controlled changing (ceteris paribus) conditions (Ivanova, 2021). Knowledge about what might happen in the future is desperately sought by decision makers and scientists engaged in applied research and environmental consulting.

In sustainability science most scholars agree upon the idea that environmental concerns must be recognised in close interaction with social issues (e.g., Anderies et al. 2022), but there is no consensus on how this should be addressed in research. Modellers in particular are regularly in a challenging situation here. While their main focus is on the calculations and ensuring that there are no errors on this side, they also act as gate keepers due to their expert knowledge. They determine which aspects of the world can (or cannot) be taken into account in a model and how this can be done. If they include social issues in models and simulation studies, they inevitably become entangled in value judgements and other normative patterns in a far more complex way than is usual in the natural and technical sciences (Diekmann, 2013; Diekmann and Peterson, 2013).

However, it is not only modellers who are confronted with the particularities of the social as a subject area. Overall, it can be said for sustainability science that various approaches and research paradigms have developed in order to investigate the interfaces between societies and their environment (Hurt et al., 2020). These include, for example, complex adaptive systems (Arthur et al., 1997; Filatova et al., 2016; Folke, 2006; Preiser et al., 2018), coupled human-natural systems (Hull and Liu, 2018) or coupled human-environment systems (Moran, 2010), approaches that address issues from an Earth System Governance perspective (Earth System Governance Project, 2018) and also of intra- and intergenerational justice (Menton et al., 2020).

With this diversity in mind, it is reasonable to ask whether the various approaches to incorporating the social into ecological models can be unified. This question is at the centre of our reflections. However, we do not attempt to answer it by designing some kind of generic framework that integrates all other modelling approaches. Our concern is neither to reduce the variety of concrete models nor to unify the different approaches of social-ecological modelling and model types. Rather, we want to contribute to an expanded concept of good modelling practice (GMP) and support applied modellers in sustainability science in incorporating the social into their models.

We assume that all modellers working on social-ecological, socio-technical or other sustainability problems have to deal with the question of how the social is incorporated into their models and simulations (see, Gotts et al. 2019). They are confronted with this question regardless of whether they use agent-based, equation-based or statistical modelling, and ultimately they have to answer this question, even if they are advised by experts or - in the context of participatory modelling - by stakeholders. As experts on the model (of whatever type), they act as information regulators who ultimately determine what goes into it and how. Therefore, in our view, they need to be supported with knowledge about the social aspects relevant to modelling so that they can perform this role appropriately.

To stimulate this discussion, we draw on sociological understandings, through which we first examine the various strands of discussion in which social aspects are discussed in the context of social-ecological modelling. Then, we will highlight two different perspectives we consider as essential for the integration of social aspects into applied models in sustainability science, namely a procedural and a structural perspective. We thereby present what we believe can be synthesised from the various approaches to operationalising social aspects for models of sustainability science and co-evolutionary research. In our view, this synthesis contributes to GMP by ensuring the quality of scientific knowledge production from a previously less illuminated vantage point.

## 2. Sociological perspectives on modelling

Modelling is an individual cognitive process that is socially embedded. It is a process that everyone does at all times in order to make sense of our complex world (Little, 1993). Sense-making, however, is not only a mental, but also a social and communicative process (Weick, 1995). People give meaning to their experiences on the basis of their inevitable involvement in conventions, habits, customs, explicit rules, discourses, and other components of culture in which earlier sense-making has already been inherited. Because people are socialised in sociocultural contexts, everyone develops their own personal mental model of how the world works. This is always and everywhere done in relation to what is sociocultural mediated and can take place affirmatively, adversely or ambivalently.

Communicating a mental model to someone else is difficult and can lead to misunderstandings. Most of the modeller's beliefs and assumptions are taken for granted from the modeller's point of view and are therefore not explicitly explained in the model presentation. Communicating models to others therefore requires either that the recipient uses a similar mental model or that all these beliefs or assumptions are presented in a form that can be understood by recipients. This aspect is often overlooked by the person presenting the model.

Therefore, we pay attention not only to the question of how 'the social' can be adequately included, but also consider the communication that takes place in the modelling process as a social process itself. We focus here on the modelling of social-ecological systems (SESs),[1] but we find no convincing reasons why our considerations should not apply to other models of sustainability science in which social aspects are considered.

### *2.1. How to introduce "the social" in applied models of sustainability science?*

While the social is a fuzzy concept, it must nonetheless be seen as fundamental. It is so fundamental, in fact, that it is mostly assumed in accounts of essential concepts in sociology (Giddens and Sutton, 2021; Ryan, 2018; Stolley, 2005; an exception is Little 2016). As a matter of fact, "the social" denotes nothing other than the in-relation-standing of individuals (Smith, 1999). This being-in-relation is an inescapable fact of human life that people constantly interpret and reinterpret. As people refer to traditional interpretations and sense-making, social systems gain stability and develop the capacity for self-perpetuation as sociocultural systems or "societies" (e.g., Giddens and Sutton 2021).

Fuzzy terms are problematic in model building not only because they cannot be operationalised and parameterised unambiguously, but above all because they open up completely different interpretations of a research object. This applies not just to the various models and simulations of sustainability research discussed earlier, but also to models for engineering questions that address the "human factor" through the physical or cognitive characteristics of the user (Duffy, 2016; Stanton et al., 2017; Woodson et al., 1992). In economic models, the fuzzy concept of the social is replaced by that of utility, which can be sharpened via the utility function and grasped as a preference/difference relationship of (economic) subjects. However, this comes at the price of not being able to capture those aspects of decision-making that cannot be explained by economic utility considerations. They have to be classified and treated as "soft factors" (Jankelová et al., 2019; Mercan and Halıcı, 2005), which equals reading tea leaves.

Game-theoretic models of the social struggle with a similar problem. They can yield general assumptions about the rationality of agents in

[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).

various constellations of decision situations, which can be empirically investigated as hypotheses (Raub et al., 2013). Yet, in these models, the purposes and goals of concrete actors, their motivations, and overall the social as well as non-social contexts of their actions remain unconsidered. Insofar as the questions of sustainability research are concrete and capture specific social and ecological circumstances, it is appropriate to explicate the notion of the social in social-ecological models in terms of sociocultural premises (Elwell, 2013), in which the components of sense-making are implicit.

In the social sciences, the term "culture" serves as an umbrella concept for all manifestations of meaning-structured behaviour. Everything that people create in the world on the basis of meaning, as well as the creation itself, belongs under this heading. In this sense, the term also functions as an expression in opposition to the concept of nature, which comprises what is neither created by humans, nor has been affected by them. To understand how different ways of living and doing business by humans affect biophysical systems, it is these aspects that need to be considered, not general principles of decision-making. Furthermore, the emergence of meaning structures is always linked to confirmation or rejection in communities, and meaning is conveyed between people. This does not mean that humans only reproduce what they have learned, but that they also create new interpretations, rules and behavioural options. However, it is insufficient to focus on actors only as moral agents equipped with a free will and capable of making the right choice for a sustainable path.

The significance of an objectively appropriate conceptualisation of the social is evident in sustainability science through the example of modelling SES. The concept of a SES provides a widely accepted framework that underlines the interconnectedness of sociocultural and biophysical systems and emphasises the need to develop interdisciplinary research approaches supporting sustainable development through adequate knowledge of the co-evolution of nature and society. However, what is "adequate knowledge" in this context? Brown and Rounsevell (2021) recognise that most of the complexity and uncertainties in SES arise from the social part of the system, which is still poorly understood. Therefore, SES scholars run into danger of underestimating the complex interaction patterns of social factors in SES. Other modellers of SES put the focus on modelling the interactions between the social and the ecological subsystems (Polhill et al., 2016; Schlüter et al., 2019a; 2019b). Lade et al. (2013) were able to show in their theoretical model that explicit modelling of social dynamics in an SES can lead to regime shifts that do not occur when the social component is treated only as an exogenous factor. All these papers emphasise that modelling the internal dynamics of the social system and the interaction with the biophysical counterpart is crucial for developing adequate SES models.

According to what has been said above and to the state of the recent discussion in social theory (e.g., Shove 2010), a residual concept of the social should be avoided at this point. Operationalising human embeddedness in ecological systems primarily in terms of individual behaviour, consciousness and decisions is an inappropriate reduction of social complexity (Binder et al., 2013; Nassl and Löffler, 2015; Partelow and Winkler, 2016). Other levels of the social – institutions, community ties, aspects of public policy, global contexts – that constitute meaningful human behaviour and binds it to factors that contribute to the self-organisation quality of the social (such as habits, traditions, laws and the requirements of organisations and specialised subdivisions of society) must not be systematically ignored. Otherwise, modellers run the risk of developing supposedly convincing models of SES or of socio-technical systems (STS) for specific problems that answer inappropriate questions.

### 2.2. How to support the communication of models by documenting them?

Several efforts have been made in the literature to describe and establish schemes for good modelling practise (see Section 3 in Jakeman et al. 2024). They deal with different aspects of the modelling process. These include design, model selection, evaluation and sensitivity analysis, to name but a few. In addition, we consider the scientifically sound communication of modelling results, including the documentation of their development, to be an important aspect of the modelling process. Consequently, we do not only focus on the description of the model components, but also include the communication of the background, the explanatory goal of the model and the decisions made during the modelling process.

For social-ecological models, especially in individual-based modelling, there exists already a standard for their documentation using the ODD protocol (Grimm et al., 2020; 2010; 2006). This protocol takes the developed model as reference and provides guidance on which aspects should be included in the documentation and in what order. For this protocol scientists have agreed on common aspects and concepts that are used in modelling approaches and selected the most important ones to include in a model documentation. Although not all of the items listed have to be included in the model documentation, the scientists are free to make their own decisions on the importance of each item in the model. The use of this protocol has the effect of reducing the effort required by other modellers to assess the model structure and purpose.

An extended approach to document modelling efforts is to ask modellers to keep modelling notebooks as developed in the TRACE concept (Ayllón et al., 2021; Grimm et al., 2014; Schmolke et al., 2010). This builds on the recognition that the individual expertise and choices of stakeholders and scientists play an important role in formulating the final model. Therefore, TRACE demands that all significant steps during the model development should be documented very closely. However, aspects such as which scientists and stakeholders were involved in the process, which narratives they pursued or what expertise they brought to the project are subsumed under the category of problem formulation. The TRACE concept focuses on the documentation of the model development phase in order to increase the fault tolerance during modelling. It keeps track of the most important conceptual and technical changes of the model during its genesis. TRACE can therefore be seen as an extension of the ODD protocol.

Decisions by scientists at certain points during model development, which could also be made differently, are crucial for the outcome of the resulting model (Lahtinen et al., 2017). A different decision at such a point would not lead to a wrong model, but only to a different model. Whether both models would still produce to the same result is unclear, but not relevant here. This phenomenon is called "path dependency", since decisions during model development steer the model developed along a certain path and thus closes others (Grimm and Berger, 2016; Hämäläinen and Lahtinen, 2016; Lahtinen and Hämäläinen, 2016). Such different decisions can enter the modelling process at several stages such as the model aim, data availability, expert knowledge, etc. (Thiele and Grimm, 2015). Path dependency emphasises the need to document the individual steps in the modelling process, similar to the TRACE concept, but places an additional emphasis on documenting the key decisions.

In the context of the COVID-19 pandemic, Barton et al. (2020) argue, that good documentation of the models is crucial in order to building confidence in the policies derived from them. Since these models need to be reviewed by many eyes, they stress that there is need to document all their model assumptions, parameterisations and algorithms. In their call for greater transparency they generally address all scientists involved in the model development but focus on sharing only the technical implementation of the model. The disciplines the experts involved belong to and the type of narratives pursued are neither demanded in this work, nor in the ODD protocol or the TRACE concept.

Considering the classical structure of a paper, the experts involved should be mentioned in the list of authors or in the acknowledgements, and the current narratives should be addressed in the introduction. However, in all these efforts to increase transparency the narratives used and the individuals involved (modellers, stakeholders or laypersons) are not described in such a detail, that their different social status and position is visible to the reader. In the following we will refer to these non-technical factors influencing modelling as social aspects. It is therefore reasonable to assume that their varying influence on the modelled results is not adequately accounted for.

For example, deciding which scientist should be involved in the modelling process and at which stage is complex and may change the model structure because of the different interests and ideas these actors may have (Lippe et al., 2019). Typically, modellers focus on the technical implementation of the model in the documentation, but overlook the social aspects of the modelling process. Not only does the path dependency require documentation of the decisions made during modelling, but also the different narratives and beliefs of the experts involved are also important to understand the model structure. These aspects are not documented in the same detail as the technical aspects, hence a very important aspect for explaining the model structure and consequently also for interpreting the model results is missing. Thus, we agree with Gotts et al. (2019) in their demand to pay more attention to social aspects in social-ecological modelling. Here, we extend this call to the documentation of social aspects.

### 2.3. The ambiguity of the social in social-ecological modelling

Analysing sociologically how the social is taken into account while developing a model in sustainability science, we recognise at least two different perspectives. On the one hand, the social is represented as a model component, as a social subsystem of a superordinate socio-ecological system. On the other hand, the social is definitely seen as part of the modelling process, namely in the communication of decisions when building models and the involvement of experts. Accordingly, we define these two viewpoints as the structural and the procedural perspective respectively, which are explained in more detail below. The first, the structural perspective, combines the two basic structural concepts of social and ecological domains and thus systematically relates ecological and sociological knowledge. The second perspective focuses on the process of model building, the generating system. Here, we pay particular attention to the social aspects, as these significantly expand the understanding of the classical model-building. An understanding of this process, and an awareness of all the contingent – technical like social - decisions which could lead to a different model, will support GMP.

As a preliminary point, we would like to emphasise that protocols are already being discussed to document modelling efforts. However, the current protocols for documenting modelling efforts focus on the technical documentation of the model itself to ensure reproducibility (see Jakeman et al. 2024). By considering social aspects and especially feedback loops, we have been able to identify additional social structures that operate during the modelling process to generate the model. Hence, social aspects need to enter the model descriptions to enhance the communication between modellers and stakeholders (Baumgärtner et al., 2008).

## 3. The procedural perspective: model-building as a social process

The development of a model, including a SES model, takes place in a social process. As we will show in below, this process itself must be understood as a hierarchical dynamic process, the course of which is determined by various social aspects[2] (Fig. 1). We will first explain the process of model building and then discuss our thesis that the structure in fact includes hierarchical relationships between superordinate and subordinate systems and therefore can be considered as nested.

### 3.1. 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 will usually be diffuse and will only primarily trigger the process in the first place. In current research, for example, the problem of reducing greenhouse gas (GHG) emissions is an open question and only the starting point for several different modelling efforts. Depending on the experts involved, each of these addresses a more specific research question.

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. 1). 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". This is particularly taken up in participatory modelling approaches (see, e.g., Robinson 2008). However, in the current best practice recommendations for the description of models, the description of these social aspects is not mandatory, although it would contribute significantly to the clarification of the included as well as the excluded components of a 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.

In our model of the modelling process, we also emphasize that the "Expert knowledge" applied in this process is generated in a sociocultural context (Antonyuk et al., 2023). It is shaped by "Societal narratives & beliefs" already present in society and shared through communication and education during everyday interactions. We consider this to be clearly a social component of the modelling process. Since sociocultural contexts create various incentives for model building, we call the process of raising these issues with the experts as "Incentive". This creates another feedback loop called "Acceptance". Communicating the expert knowledge gained from modelling processes to society can confirm "Societal narratives & beliefs" or change them. Knowing of these aspects leads to a better understanding of the modelling process itself. This is where participatory modelling comes into its own, as it relies on the participation of stakeholders and lay people not only in the use of the model, but also in its construction (Lee et al., 2022). In this way, the flow of information from "Societal narratives & beliefs" to "Expert knowledge" is intensified.

[2] In addition to social aspects, cognitive aspects naturally also play a significant role in the construction and development of models. The identification of a social-ecological problem and the social and ecological components involved in it naturally requires cognitive capacities. However, we emphasise here that these cognitive aspects always unfold in social contexts, e.g. by finding a problem definition that is shared by modellers and the involved domain scientists. When we focus on the social aspects in the following, we presuppose the existence of cognitive capacities for model building.

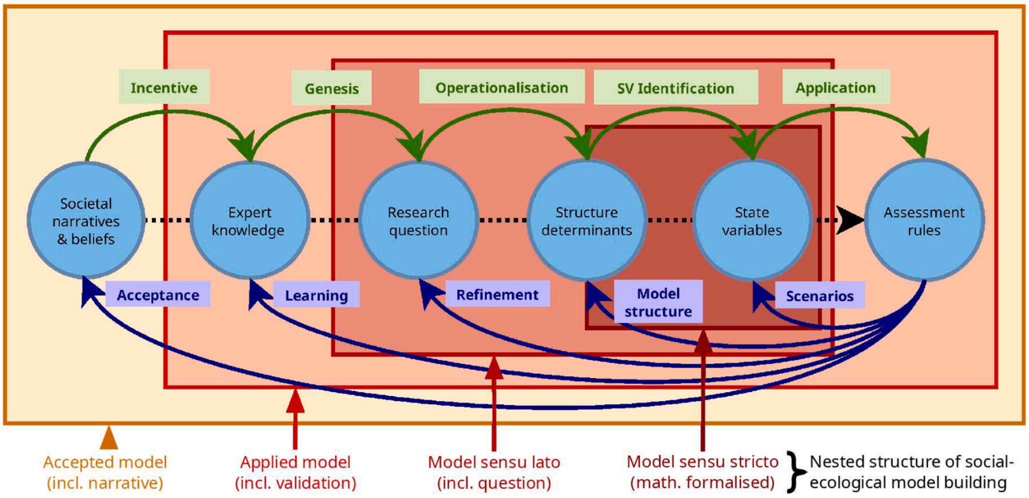


**Fig. 1.** Outline of the nested process of model building describing important social components (blue circles) and their generating processes (green arrows) as well as feedback loops (blue arrows) influencing the resulting model structure. Within this concept there are emergent structural levels of the model building process (yellow/orange/red rectangles). SV = State variables. For further information see text.

In the recommended standardised protocol for the documentation of individual-based models (ODD; Grimm et al., 2006, 2010) as well as in the TRACE concept (Ayllón et al., 2021; Grimm et al., 2014; Schmolke et al., 2010) the research question is the starting point. From this, the model is derived. Although not appreciated explicitly by the recommended ODD protocol, the social aspects of the modelling process described so far are already part of the formulation in a modelling paper. The expert's involved in the modelling process can be taken from the author's list and the acknowledgements. The current "Societal narratives & beliefs" are outlined in the introduction of such a paper but mostly from a scientific point of view of a single discipline. Thus these protocols lack the first two social components and therefore are, in our perspective, not sufficient to explain the model structure in full detail. The next components in our concept of the model building process follow the well-established steps of model development.

We would like to emphasise that experts, and in participatory modelling also stakeholders and lay people, are involved in all steps of the modelling process. On this basis, we can identify further social components within the modelling process that shape the structure of the model. Hence, there are path-dependent decisions by these experts in all steps (Hämäläinen and Lahtinen, 2016). Starting from the research question, modelling experts together with their colleagues and collaborators, who contribute specific scientific expertise and presumably have all different background knowledge, decide which parameters might serve as "Structure determinants" to describe the essence of the system in general. "Structure determinants" define also the boundary conditions given by the intended model application. They depend on the specific purpose of the model and have executive character in the definition of the "Assessment rules". Thus, we suppose that the premises are translated into practice through the process of "Operationalisation", which in turn is influenced by a feedback loop that can correct the model structure. We call this feedback simply "Model structure". The model is defined by structural determinants, and these determinants may need to be changed if unacceptable results arise from the application of the "Assessment rules" – a feedback process that is often called the modelling cycle (Grimm and Railsback, 2005).

According to our understanding of the process, the experts involved are not only decisive in selecting "Structural determinants". They also choose "State variables" which define mathematical model components and contain accepted process-oriented expert knowledge. The process of "SV Identification" (state variable identification) defines these "State variables" from already negotiated "Structure determinants". They describe the dynamics within the model, which allows to identify unintended side effects or structural flaws. In the case that such a variable changes to values out of reasonable boundaries from an empirical point of view, the structure of the model needs to get changed.

As the social component that concludes the process of model building, we consider the "Assessment rules". These must be formulated to determine when the model will be accepted as a good representation of the system under study. Certainly, in its basic form, it must provide answers to the research question. Going beyond this basic criterion, "Assessment rules", in our view, implement a common standard of evaluation that should be negotiated at the beginning of the modelling process by all actors involved.

Modelling is often viewed as an iterative process (e.g., Gotts et al. 2019, Grimm and Railsback 2005, Iwanaga et al. 2021, Schulze et al. 2017) and that it goes through several cycles until it meets the criteria defined in the "Assessment rules". To test the range of conditions under which the model produces sensible results, scenario simulation seems to us to be the most widely used. Whether a simulation is accepted as a valid scenario, should, according to our understanding, depend on the "Assessment rules". If these rules are not met for all scenarios, the assessed "State variables" can be changed until a satisfactory and interpretable result is achieved. This extremely robust feedback loop usually takes most of the time and involves all experts and stakeholders. If necessary, the "Assessment rules" can be re-negotiated.

If the "Assessment rules" cannot be satisfied by either changes in the "State variables" or the model structure, the research question could be too broad and had to be refined to make it more specific. In our experience, there is often a need to develop several submodels before a more general model is able to answer the original research question. What kind of submodels are needed is not always clear from the beginning of the modelling process but they are an outcome of the modelling attempts using premature models including "Structure determinants" and "State variables".

During the modelling process, we consider expert's "Learning" as a key feedback loop that enables experts to formulate a refined or even new research question and - subsequently - to select new "Structural determinants" and "State variables". Although learning is ubiquitous during the modelling process and sometimes the main reason for starting the process, we emphasise this loop here because the discrepancy between the self-generated assessment rules and the model outcome is the main transmission belt for learning processes.

However, the most comprehensive feedback loop we would like to point out is based on our belief that a model is only a good one if it convinces users and changes the way they think about the system in question. It needs to change understanding about this system in a more general way so that other experts, decision makers and even the general public can adjust their decisions and behaviour based on the conclusions drawn from the simulation results. Such a change is most likely to occur if the underlying assumptions are well documented and plain. This feedback processes may lead to an adjustment of initial framing.

There are more feedback processes during all stages of model development, which are not explicitly pictured in Fig. 1, but act all the time (e.g. during the discussion of the research question, in evaluating the structure determinants and also during the state variable identification process). These are fast processes and cannot be documented with the same accuracy as the other processes during model development. However, this is, in our experience, not necessary since the resulting conclusions are already part of the model structure and the overall feedback loops.

To sum up, all of the social components mentioned above are key decision points for applied modellers of, e.g., SESs, whether or not they are thoroughly addressed. In our experience, feedback loops define hidden layers in the construction of models. Explicitly addressing them and naming them in their various functions will support modellers in appropriately fulfilling their role as facilitators in the construction of models, documenting decisions and contributing to GMP. Ultimately, the success of a model depends on the beliefs and expectations of the stakeholders involved, and their satisfaction with both the model itself and its results (Hamilton et al., 2019).

### 3.2. Hierarchical structure of modelling concepts

Looking at Fig. 1 in more detail, we can identify governing aspects in the hierarchical structure of the modelling process. We therefore assume a hierarchical structure in which a superordinate structural level prefigures what can happen at a subordinate structural level. The social components of the process perspective described so far can be aggregated as follows. The “State variables” together with the “Structure determinants” form the core of each modelling project, the mathematically formalised model. It describes the system using some kind of modelling technique (actor network, agent-based, differential equations etc.). We define this structure, which is the model in a more narrow sense, as “Model sensu stricto”. In the modelling process this structure is used to generate predictions about “State variables”. Their values are judged on the basis of the "Assessment rules" and are variable during the different scenarios.

This mathematically formalised model is embedded within a model in a wider sense (“Model sensu lato”) which adds the “Research question” as a new social level into the modelling process. As defined by Grimm and Railsback (2005) a model is an abstract representation of reality that has a purpose. The purpose is included into this structure by the formulation of the research question. This structure defines the common approach to communicate a model in the scientific literature and is also covered in the ODD protocol (Grimm et al., 2010).

The next governing level in this structure of modelling is defined by the term “Applied model”. This level adds the social components of “Expert knowledge” and “Assessment rules” to the hierarchy. The “Learning” feedback loop is part of this modelling level too. All components together are the logical next step in model development. A model is fully usable if it provides valid results for the selected scenarios. It is already changing the knowledge of the experts involved in the modelling process. Applying this model to new environments and different settings by other scientists extends this learning loop to all scientists or stakeholders working with this model. In this step, the “Assessment rules” might become changed as well, especially if new scenarios are tested which could theoretically be represented by this model. Such a step is widely regarded as validation, which is an important aspect of model development. This variant of the validation process greatly increases the number of people who learn through the application of the model.

The final structure, which includes all defined components and processes, is called the “Accepted model”. This structure becomes effective if the learning extends to the whole society and is accepted as a new paradigm. This structure includes all feedback loops within the entire process of model development. These feedback loops act all the time unconsciously but are relevant to understand the final structure of the model. The modelling feedback loop (“Acceptance”) can be conceived as a critical appraisal of indicators and is, therefore, responsible for a different framing of the “Expert knowledge”. This might in its consequence change the formulation of the “Research question”, alters the selected “Structure determinants”, which results in different “State variables” and therefore leads to a changed model structure.

The hierarchical structure of the modelling levels reflects not only the social structure of an applied model, but ultimately of any modelling process (Fig. 1). All feedback loops which are at work during the development of the model should also be considered as social components. The part of the world that is to be captured and simulated in its interrelationships of effects, such as a social-ecological context, is represented by the “Model sensu stricto”. But of course, the research question, the experts involved in the modelling process, and the socio-cultural narratives, etc. can also be included. In this way, the modelling process is represented as a discrete structure that flows back into itself. As a result, it is hierarchical in such a way that each substructure can be considered as an independent entity that fully includes the level below it.

The extension of the model boundaries from the “Model sensu lato” into ever wider spheres of society reflects the hierarchical structure. In this process of including ever larger groups of societal members new levels in either subsystem are identified which should become part of the developed model. At the next level, the “Applied model”, we emphasise the clear formulation of “Assessment rules” and the description of the process of selecting experts. Both components are not explicitly part of any recommended model documentation protocol so far (e.g. ODD, TRACE). If we extend the boundary further to include society as a whole, we arrive at the “Accepted model”, which claims that a good model is one that is accepted by society. In fact, we would go so far as to say that a truly good model is one that contributes to change “Societal narratives & beliefs”.

## 4. The structural perspective: intertwined structures exemplified by social-ecological systems

Studying ecological and social aspects separately has a long tradition in the history of Western science (Bunge, 1983; Lovejoy, 1955; Quinones, 2007). In the course of this tradition, specialised sciences have emerged, each with its own methods and conceptual frame of reference. Thus, knowledge about differentiated aspects of the intertwined and interlocking orders of the world emerges, but no overall picture, which has long been criticises in the philosophy of science (e.g., Husserl 1988). The integration of different bodies of knowledge emerging from particular sciences and the triangulation of different data accessed through these particular sciences at least open up possibilities to see more than through the lens of a single science alone.

Inspiration is needed for this process, as it is generated, for example, by the concept of ecology. Ernst Haeckel, who invented the term, conceived of “ecology” as a science “of the relations of the organism to the surrounding external world, into which we may reckon, in a broader sense, all ‘conditions of existence’ …” (Haeckel, 1866, p. 286, translation by the authors). Nominally, this already includes the conditions generated by societies, although a conception of how human societies are placed and evolve in ecological systems has long been undeveloped. To be sure, the concept of ecology and insights from ecological research were received and developed early in the so-called human ecology of the Chicago School, a social science research tradition (Park, 1952). However, this and other approaches did not translate these suggestions conceptually or methodologically into research concepts and strategies with which human societies, plus their internal dynamics, were studied in their interactions with ecological systems. Indeed, this did not occur until researchers such as Holling (1973), Berkes and Folke (1994), Janssen and Ostrom (2006) began to blend systems theory and ecology with simulation modelling and policy analysis, coining the term social-ecological system.

As a result of the public discussions about environmental problems in general and about global warming and the mass extinction of species in particular, it has become a matter of course to consider humans with their societies as an impact factor of natural interrelationships. Problem solving requires an adequate understanding of the complexities of the problem, for which the approaches previously cultivated in the various disciplines of the social and natural sciences must be synthesised (Schlüter et al., 2012). How SES are formed from the coupling of subsystems, which in turn are intertwined and feedback with each other, can be analysed from the intersection of knowledge from the natural and social sciences (Schlüter et al., 2014). It can be assumed that these feedback's determine the nature of certain SES (Schlüter et al., 2019a).

There are actually two technical approaches currently used to integrating the social and the ecological systems reflecting their intertwined structure. First, as was often the case in earlier attempts to conceptualise social-ecological models, the social system is only included in the model at the level of an external parameter or as a variable. Second, the integration of the social into ecological models is conceptualised at the level of individuals or collectives, using the individual-based approach (e.g., Schlüter and Pahl-Wostl 2007). However, this method limits the choice of the interacting processes and focuses exclusively on the processes of the current level of analysis. In addition, this method makes it difficult to model the dynamics within the nested structure of the social sub-system. An extension of this idea is to model human society and its components as agents (e.g., groups, institutions) or in a more general notion as agent functional types (Rounsevell et al., 2012). This expands the possibilities enormously, but the dynamics within the social subsystem are limited to the structures already specified in the original model concept. New social structures (e.g., new group structures or institutions) cannot emerge from the dynamics within the partial model (see discussion in Conte et al. 2001). The important question using this approach is therefore how to select the appropriate level to include into the model structure.

To support this process, we suggest building on the so far accepted knowledge of nested structures within the relevant disciplines of the social and natural sciences (see Fig. 2)[3]. Within the two subsystems processes link the nested structural levels. More precisely, levels are an emergent property that arises from the processes at work. In our concept the system boundary is expanded to include both subsystems. Thus, not only processes within these subsystems can become components of the model but also processes between the two intertwined structures. Here only these processes are included, which are considered important for answering the current research question (see black and red arrows in Fig. 2 as examples). Thus, our scheme captures the different types of processes considered essential to SES in recent research (see Radosavljevic et al. 2024), which are not purely social, economic or ecological but social-ecological in nature.

It is important to note that the dynamics within the two subsystems are visible on different timescales as described in Radosavljevic et al. (2024). While the nested structure in ecology is stable on ecological timescales, changing only through the slow forces of evolution, the nested structure in social systems is much more dynamic, operating on the basis of the influence of knowledge and other cultural aspects. In unfolding the direct and indirect impacts on social change, it is important to remember that social systems are much more dynamic than ecological systems. They are subject to changes in model application and problem solving (Lippe et al., 2019), which ideally lead to sustainable relationships of the real social and ecological subsystems.

We illustrate the notions of SES as intertwined ecological and social subsystems using the example of a current research question that arises in the course of research to reduce greenhouse gas (GHG) emissions. Because peatland soils emit significant amounts of $CO_2$ when drained, agricultural peatland soils should be rewetted (Günther et al., 2020). How rewetting measures affect biodiversity is an open question. Rare and endangered plant and animal species have settled on some drained moor soils. What will become of these and how will biodiversity develop at all if the rewetted soils are used for agriculture? In order to be able to assess the effects of the upcoming social-ecological transformation on species diversity, it is of course necessary to take into account how the populations of specific plant and animal species develop on the rewetted soils (population level with the embedded level of individuals). However, with regard to soils, a distinction must at least be made as to whether these were formerly raised bogs or fens (landscape level), because they provide different conditions for species. Which methods are used depends not only on the soil type (former raised bog or fen) but also on the specific social conditions in which a change in farming methods is carried out. In addition to the economic incentives that a state may provide for such a conversion and the sales opportunities for the new agricultural products, aspects of social acceptance are particularly decisive in determining whether and, if so, how a new land management system is established. If there is a favourable interaction between conditional factors at the landscape level of the ecological subsystem and at the social levels of farms, political economic support, appropriate buyers for the new products, and local acceptance, new structures in the social subsystem can emerge, which we refer to as a regional innovation cluster as described from a business management perspective by Porter (1990). It can be assumed that this will also have an influence on how biodiversity develops.

The processes described above can give rise to new governing structures in the social subsystem quite quickly, while the structures in the ecological subsystem remain relatively constant within the same time frame. It is precisely this difference in temporal dynamics makes it so difficult to develop a single framework that applies to different subsystems at different stages of development. The interactions between the subsystems affect the dynamics of the other system not only in its direction and strength, but also in its temporal dynamics. Thereby, both subsystems of this SES develop co-evolutionary on the basis of self-organising processes with external control factors that intervene in parallel on different structural levels and objects (e.g., Horcea-Milcu et al. 2018). The two subsystemic structures build a complex adaptive system (Filatova et al., 2016) in which indirect effects are generated by the interconnection at different levels.

Interactions between both subsystems arise from interdependencies of both subsystems realised by processes (observation, communication) and feedback loops (e.g. GHG emission, land use change). During model development, for each identified important level within one subsystem, a dependent level within the other subsystem must be considered (Fig. 2). If such a level exists, the relevant process connecting these levels has to be identified and modelled explicitly. This results in the intertwined structure outlines in Fig. 3. Which processes to include is dependent on the question asked and on the educational background of the involved modellers, similar to selecting processes and variables in Schlüter et al. (2014). Through understanding that nested and interwoven structures are to be expected in the subject area of the ecological and the social, they are put in a position to inquire with the experts who contribute the knowledge of a particular scientific discipline to the modelling process and to successively guide the model construction in a critical dialogue. The more actors (scientists, stakeholders, policy makers) involved in the model-building process, the more of these connections are usually selected. However, the resulting model will always reflect the foreknowledge of the actors and the underlying model-building process.

[3] A similar divide in a social and an ecological subsystem was already presented by Folke and Berkes (1998), cited in Colding and Barthel (2019).

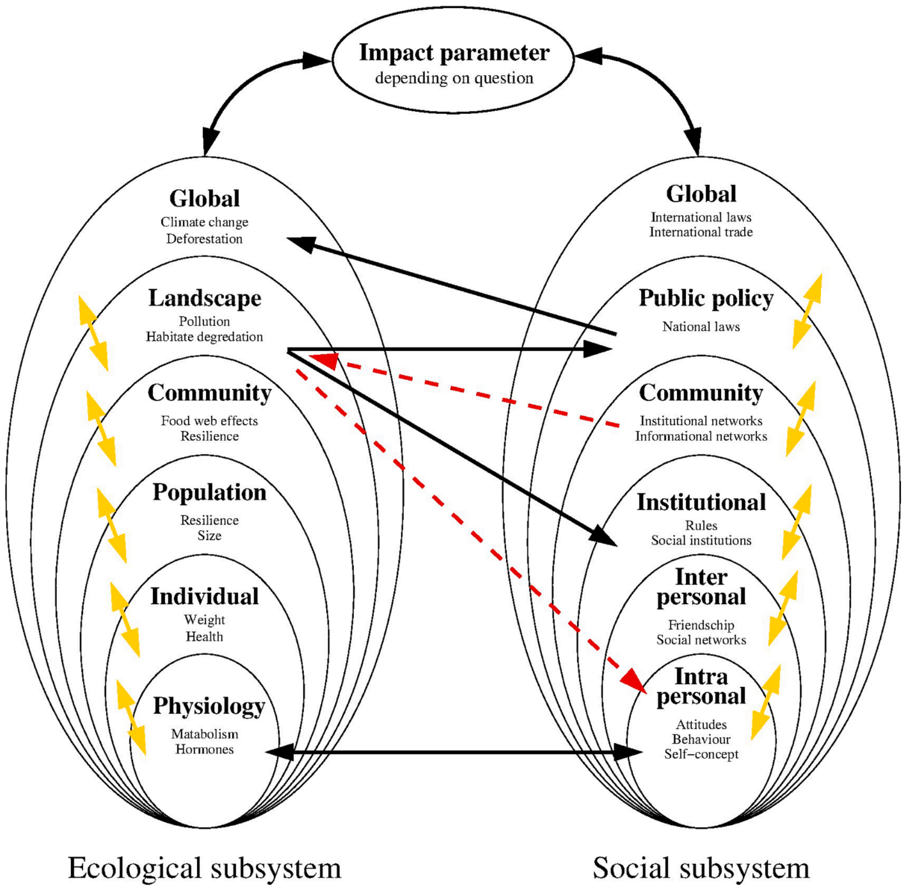


**Fig. 2.** A framework of intertwined structures of ecological (left) and social subsystems (right). In both subsystems, hierarchies arise through processes within their own domain (yellow arrows). In addition, there are processes that connect both subsystems (black arrows). These operate from a specific hierarchical level of one domain to one or more levels of the other domain. In combination, they can create feedback loops (red dashed arrows). The impact parameter motivates the selection of suitable processes depending on the research question.

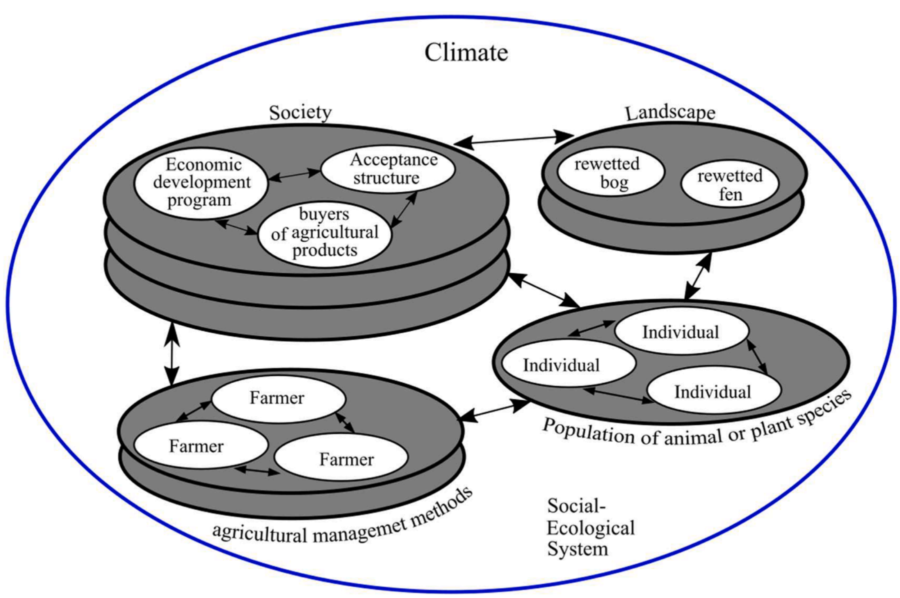


**Fig. 3.** Illustration of the intertwined structure of ecological and social components in a SES about rewetting peat bogs. The displayed structures represent only some basic elements. Depending on the research question and experts involved several other structures may emerge.

## 5. Synthesis: towards a broader understanding of GMP that includes social aspects

Through the preceding sections, we discuss what it means for modellers in applied areas of sustainability science to “step out of their comfort zone, by not only reflecting on the technical, but also the social aspects of modelling” (Jakeman et al., 2024). We presented two different perspectives on social aspects in applied modelling, especially of SES. The first focuses on the modelling process itself and the second on the structure of the model. Both perspectives address the social in different ways. However, combining these two perspectives, can support modeller in sustainability science to perform their role as gatekeepers of a modelling process appropriately and to lead it responsibly as a knowledge generation process. This is something we recognise when we consider the practical benefits of these perspectives.

Looking at a sustainability problem through the lens of two-folded structure of, e.g., a SES can help researchers to develop ideas about the levels, interactions and processes needed to model and explain it. This is necessarily accompanied by the selection of expertise’s needed for the construction and development of a specific problem. If the discussion between modellers and experts is open-ended about necessary and sufficient components of the model, new aspects may emerge that change the perspectives on the intertwined structures of the specific system, which in turn may lead to the selection of new levels in the model and the inclusion of further expertise. Using SES as an example, the basal ideas of intertwined ecological and social structures can serve as a roadmap for the selection of necessary levels, interactions and processes when the feedback loops of “Refinement”, “Learning” and “Acceptance” presented above in the procedural perspective are taken into account in the process of model building.

In this context, it is important to emphasise that the various structural levels named in Fig. 2 are to be read here only as placeholders that illustrate the intertwined and nested order of forces at work in reality. Even if the levels represented here can be well justified, different levels of the social can be relevant, especially for a social subsystem of a SES, depending on the social sub-area and the issue under investigation. The structures presented here are primarily intended to encourage modellers to ask problem-related questions about the multifaceted and complex structure of the relevant section of reality to be modelled and to include the different levels appropriately.

While there is certainly no silver bullet for creating a good model of a SES, we identify the inclusion of social aspects, not only in the model itself, but especially during the modelling process, as an essential element of GMPs. We, therefore, suggest that in model development the two perspectives should be used alternately and iteratively in model development. This way, those components and processes are selected that are necessary to understand the problem to be modelled. In both perspectives presented, emphasis was placed on addressing the social dimensions without sacrificing the model-theoretical aspects. As mentioned earlier, each model should include only those aspects that are important for the problem under consideration, but no more. Which levels are important depends on the research question derived by the experts and stakeholders involved, their interests and their individual educational background. The selection of components and decisions made are all purely social dimensions of modelling. We therefore assume that using both perspectives will lead to a model structure that maps the necessary components of the real system. At the same time, it leads to map the important aspects from the discussion of the feedback loops between the social components mentioned in the procedural perspective.

For the communication of the modelling results, the explicit use of the procedural structure should make it easy to organize the construction of a model with the involvement of experts and to select which decisions are to be documented. Discussions and decisions should in any case be documented if they have led to a change in the structure of the model. This mainly happens during the feedback processes between the social components as outlined in Fig. 1. The incentive to model is important, but rarely an aspect of prolonged discussion. It just needs to be described. On the other hand, the exact scientific question is constantly being reworked. Here it could be interesting to document exactly, for example, if a question cannot be modelled in this way due to a lack of data. During the processes “Operationalisation” and “SV Identification” of a model, there are extensive discussions that can never be fully documented. In this case, one should limit oneself to the versioning of the models. Thus, only executable versions are included in the documentation. The remaining decisions can possibly be viewed using versioning tools such as GitHub. A final aspect of the documentation are the “Assessment rules”. These usually evolve during the modelling process, especially when important system components are changed. Therefore, their development should also be documented.

In contrast to other formulations of GMPs for describing and replicating modelling efforts, we would like to emphasise the critical importance of the modeller’s decisions during the modelling process. These decisions may have been discussed with experts and perhaps also with stakeholders and laypersons in a participatory process. The modeller ultimately decides what is integrated into a model and how. We assume, similar to the findings of Hämäläinen and Lahtinen (2016), that these decisions and, according to our considerations of the modelling process (Fig. 1), the selection of experts involved in the process, as well as the currently prevailing idea about the system to be modelled, have a profound influence on the resulting model structure. Not all social aspects can be represented in a model documentation, but the processes outlined above that lead to the development of a model and the feedback loops can be used to document what is relevant for the interpretation of model results and the measures derived. When modellers publish their results, the guiding principle must also be that the social aspects are presented as transparent and comprehensible as possible.

Finally, we presume treating social aspects in applied models such as SES models as processes themselves and not only as agents or entities with fixed behavioural modes will lead to a new structure of such models. Processes are the components which drive the dynamics of a model. Including social processes would lead to a completely new class of models. In our structural perspective we present a way to select the appropriate social levels and processes depending on the research question (“Impact parameter” in Fig. 2). The demand to embed humans and ecological aspects in SES models was formulated already (e.g. Schlüter et al. 2019b), which lead to add human individuals as a new agent into the ecological model. For the inclusion of institutions, Rounsevell et al. (2012) discussed the possibility of also modelling them as agents with their own incentives and behaviour. However, this approach does not take into account the dynamics of the social system. New institutions cannot simply emerge. They first have to be created by a group of people, established as a habit and then spread. Our proposed approach should at least be able to identify at which levels dynamical treatment of such agents or institutions is necessary.

### 5.1. How our expanded concept of GMP relates to the established view

Our analyses of the modelling process through a sociological lens led to a structurally different outline of the modelling process, which others describe as the modelling cycle. Although we can relate steps from the scheme by Jakeman et al. (2024) to our structure, some differences need to be highlighted.

The phases outlined in their scheme are a collection of several aspects of our proposed framework. We describe these aspects in our scheme as distinct processes and feedback loops, always from a sociological point of view. Explaining the modelling process in terms of social components, linked by generative processes and feedback loops, allows for a clearer definition of one’s own position within the ongoing process of the modelling project. But we have to admit that our scheme does not take into account some of the more technical aspects of modelling, which are mostly subsumed under the “Model sensu strico”.

According to our scheme in Fig. 1, there are several circular structures active during the modelling project, which are formed by generating processes and corresponding feedback loops. The processes “Operationalisation”, “SV Identification” and “Application” together with the “Refinement” feedback loop in our scheme represent almost the modelling cycle as in Jakeman et al. (2024). Not all the ongoing feedback loops shown in our Fig. 1. There are feedback loops that directly connect adjacent social components (blue circles). These, together with their generating process, lead to a circular structure of improvement of that particular social component.

Both approaches also differ with regard to the question of how the end of a modelling process is defined. Whereas a ‘modelling cycle’ by definition has no clear endpoint, our modelling scheme determines the endpoint through the negotiated “Assessment rules”. These describe the conditions under which the model is good enough to fulfil its purpose and satisfy all the people involved. This is when the model is finished and modelling stops. In the case of our example regarding a model to assess the impact of rewetting agricultural peat soils on biological diversity (Fig. 3), “Assessment rules” level out conflicting interests and describe the degree of acceptance of certain effects under given conditions as social aspects. They have a balancing character in the form of cost-benefit equations (trade-offs).

The identified nested structure of modelling shows an increase in satisfied “Assessment rules” and modelling participants up to the point where the whole society can benefit from and accept the model. This social component, "Societal narratives & beliefs”, has never been explicitly recognised as part of the modelling processes published to date. Although policies are often derived as an essential outcome of these models, the feedback to change existing ”Societal narratives & beliefs” has not been considered in such policies. Particularly in the case of climate and COVID models, we have seen that ignoring this level of society pushes modellers back into the ivory tower.

Finally, we do not claim that this is the only possible structure of a modelling process from a sociological point of view. However, we think that it is a clear starting point to change positions and to encounter new aspects of the modelling process that modellers were not aware of before. The scheme is rather simplistic and there are probably many more social aspects to consider. It is conceivable, for example, that modellers will choose a particular preferred model type based on their specific world view and that this is reflected in their modelling practice and in their perceptions of GMP. Extensive empirical research on this and related questions could be conducted in the future. According to Scholten (2008), any decomposition should not be too detailed to be of practical use. Thus, our scheme does not decompose the technical levels of GMP in more detail, as these aspects have been thoroughly discussed in other papers on the topic (see Jakeman et al. 2024) for an overview of the most important articles.

We have focused on the social aspects that define the modelling and problem-solving process as a whole. We keep the amount of social level to a minimum, aware of the problem that the audience of this journal is not primarily trained in dealing with sociological concepts. The ontological structure of our model concept should act as the backbone of a system to help modellers and laypersons identify these aspects throughout their projects. They should also recognise that social aspects, decision making and path dependencies are important aspects in modelling projects and should be treated and documented accordingly.

## 6. Conclusion

In order to understand and solve societal challenges, it is not enough to model only the mechanisms outside of society, such as those of nature or climate change, but also all the side effects and feedback loops to and within society. This is the basic idea behind the SES approach. Since the diversity of perspectives seems to be ineluctable in every society, one should abandon the endeavour a universal concept for integrating social aspects into ecological models and vice versa. In our view, however, this does not mean abandoning all endeavours to establish standards by which good models can be distinguished from less good ones. This is because the combination of the two perspectives on the social in applied models that we have identified provides us with the first fundamental considerations that will help us here. If we now ask how modellers proceed in practice when constructing a meaningful model that is appropriate to the research problem, we assume that rules for GMP could be explicated in the discussion within the scientific community and summarised in a working guideline.

In particular, we see our reflections on the procedural perspective as our own contribution. These enable modellers as well as other experts and laypersons to understand the social dynamics associated with the modelling process. This can lead to a more conscious selection of experts to include in the process and hence to formulate a more appropriate research question. Following that, the model structure will change and thus the results presented and conclusion drawn from this modelling effort. In particular, the “Assessment rules” introduced as a component of the social system, which have never been explicitly stated in the model description, expand the understanding of the model and define the limits of the model’s validity. Here, too, the decisions of the experts involved are particularly important with regard to the areas of application for which the model should be used. Eventually, modellers who are aware of all these social impacts on the resulting model structure and dynamics will create better models and better model documentation. As a result we expect not only a better understanding of the performance of applied models in societal discourses, but also support to identify tipping points in such models and thus find levers and leverage points to intervene in social-ecological systems (Meadows, 1997).

## CRediT authorship contribution statement

**Ronald B. Bialozyt:** Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Martina Roß-Nickoll:** Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Richard Ottermanns:** Writing – review & editing, Writing – original draft, Visualization. **Jens Jetzkowitz:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Funding acquisition, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Data availability

No data was used for the research described in the article.

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