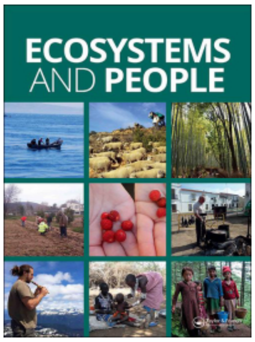

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RESEARCH: RELATIONAL TURN IN SUSTAINABILITY

From situated knowledges to situated modelling: a relational framework for simulation modelling

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ABSTRACT
In this paper we extend the use of a relational approach to simulation modelling, a widely used knowledge practice in sustainability science. Among modellers, there is awareness that model results can only be interpreted in view of the assumptions that inform model construction and analysis, but less systematic questioning of those assumptions. Moreover, current methodological discussions tend to focus on integrating social and ecological dynamics or diverse knowledges and data within a model. Yet choices regarding types of modelling, model structure, data handling, interpretation of results and model validation are not purely epistemic. They are entangled with values, contexts of production and use, power relations, and pragmatic considerations. Situated Modelling extends a relational understanding of the world to scientific knowledge production and with that to modelling itself in order to enable a systematic interrogation of these choices and to research social-ecological transformations relationally. To make tangible the situatedness of simulation modelling, we build on existing practices and describe the situatedness of three distinct modelling approaches. We then suggest four guiding principles for Situated Modelling: 1. attending to the apparatus of knowledge production that is socially and materially embedded and produced by e.g. research infrastructures, power relations, and ways of thinking; 2. considering how agency is distributed between model, world, data, modeller in model construction; 3. creating heterogenous collectives which together occupy the formerly individualised subject position; and 4. using agonism as an epistemic virtue to retain and work with significant differentiations of social-ecological dynamics throughout the modelling process.

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Introduction

A better understanding of social-ecological dynamics is much needed to tackle current crises, such as biodiversity decline, to gain more realistic and accurate climate change projections and foster transformations onto more sustainable pathways (Folke et al. 2010; Beckage et al. 2020). Integrating knowledge across disciplines and co-producing it with non-academic actors is increasingly suggested as the way forward (Chambers et al. 2021). How to go about integrating and representing knowledges from diverse actors in analysis and governance of social and ecological relations at multiple scales has become one of the foci in sustainability science (Tengö et al. 2017; Norström et al. 2020; Caniglia et al. 2021, 2023). This includes reflections on collaboration between researchers and non-academic actors in processes of knowledge co-production (Chambers et al. 2021), analysis of the ontological and epistemological commitments underlining interdisciplinary water research (Krueger and Alba 2022), efforts to incorporate human behaviour in climate models (Beckage et al. 2022) and development of novel ways of theorising on social-ecological systems (Schlüter et al. 2022).

Seeking to further grasp the ever-changing interrelations between social and ecological dynamics, scholars have begun to engage with relational process-based philosophies and approaches (West et al. 2020; Mancilla García et al. 2020; Walsh et al. 2021; Artmann 2023). Rather than specifying as the basic unit of analysis 'the social' and 'the ecological' as separate and stable entities that may interact, relational approaches start from social-material processes

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or ways of becoming from which entities emerge and manifest as stable. Relational perspectives are particularly aware of the role research and researchers play in constructing entities (Wamsler et al. 2021; Bentz et al. 2022). However, as Walsh et al. (2021) suggest, relational approaches in sustainability research remain marginalised with few studies explicitly taking such a perspective. In this article, we set out to develop a relational perspective in thinking about and doing simulation modelling.

Simulation modelling as a research method helps to generate knowledge about social-ecological dynamics because it can simulate the development of a complex system over time given assumptions about its structure and rules of change. Models have proven useful tools to better appreciate, simulate, and predict the complex interplay between social and ecological dynamics in diverse fields such as Earth system science and research on social-ecologcal systems (Steffen et al. 2020). They cut through the complexity of the world and thus are helpful to account for multiple temporal and spatial scales (Lippe et al. 2019). Models can also be important tools in processes of transdisciplinary knowledge production (Schlüter et al. 2019) and in shaping public discourses and policy interventions (Budds 2009). Participatory and collaborative modelling has been put forward to collectively reason about environmental problems and to use the model design and analysis process for reflecting both on the problem at stake and the process to deliberate about it (Étienne 2014; Gray et al. 2018; Schlüter et al. 2019, 2019c). Despite these potentials and advances, models often remain biased towards either a social or an ecological perspective and the integration of social-ecological interdependencies and feedbacks in simulation modelling has remained a major challenge (e.g. Elsawah et al. 2019; Drechsler 2020; Beckage et al. 2020).

Significant methodological and theoretical efforts have been dedicated to developing methods to represent and analyse interconnected social-ecological dynamics and to deal with uncertainty. Examples include procedures to enhance transparency about modelling choices (Schlüter et al. 2014; Grimm et al. 2020, Gotts et al. 2018) or the modelling process (Schmolke et al. 2010) and considerations about the role of uncertainty (Moallemi et al. 2020). However, they often remain on a rather technical level with the aim to assess the consequences of uncertainties in data or model structure for making inferences from models, and to increase credibility of the model. There is awareness that model results should be interpreted in view of the assumptions that inform model construction and analysis, but there is less questioning of – and reporting about – where these assumptions come from and what is left out (Horst et al. 2023). Moreover, modelling study discussions tend to focus on integrating dynamics within the model itself and consider less the context in which modelling processes are developed or how to maintain relevant, maybe even conflicting, differentiations in- or outside of the model.

Context, choices and assumptions underpinning modelling practices, however, matter (Banitz et al. 2022). They matter because they influence the knowledge generated through the modelling process and the actions and solutions proposed if the model aims at supporting action. Choices regarding modelling approaches, model structures, data handling, interpretation of results and model validation are not of a purely epistemic nature. They are entangled with (subjective) values, discourses, gendered relations, pragmatic considerations and institutional contexts (Addor and Melsen 2019; Melsen et al. 2019; Babel et al. 2019; Ellenbeck and Lilliestam 2019; Undorf et al. 2022). Models also reflect specific ways of understanding the world and by doing so they contribute to legitimising some worldviews and knowledges while concealing others (Cornejo and Niewöhner 2021).

In this paper, we introduce Situated Modelling as an interdisciplinary framework to interrogate how modelling as a process is contextualised and shaped by modelers' more-than-epistemic choices. Situated Modelling extends a relational understanding of the world to scientific knowledge production and with that to modelling itself. More specifically, Situated Modelling draws from feminist Science and Technology Studies (STS) to introduce a way of understanding and doing simulation modelling that pays particular attention to the process and practices of modelling. We operationalised these insights for modellers and non-modellers alike in the shape of four guiding principles. First, Situated Modelling entails an ongoing reflection and analysis of the context in which models are developed and used (socio-material embeddedness). Second, it calls for interrogating how model(s), 'real' world, data, modeller(s) interact and shape the modelling process. We understand agency as distributed in decision-making practices and decisions taken by modelers as an outcome of such practices (distributed agency). Third, Situated Modelling fosters the development of subject positions occupied by diverse collectives from whence to practise Situated Modelling (heterogenous collectives). Lastly, it involves balancing, integrating and differentiating knowledges throughout the modelling process (epistemic agonism).

To develop the idea of Situated Modelling and its key principles we collectively engaged in a process of examining modelling practices in light of Haraway's concept of situated knowledges and process-relational philosophies (Barad 1999, 2007). We focus on modelling practices in the three different working groups where the authors are based: the Stockholm Resilience Centre's SES-LINK group at Stockholm University, the Whole Earth System Analysis Group (WhESA) at the Potsdam Institute for Climate Impact Research (PIK) and the Hydrology & Society (H&S) group at the Integrative Research Institute on Transformations of Human-Environment Systems (IRI THESys), at Humboldt University in Berlin. We chose these three groups because they represent a diversity of modelling approaches regarding the purpose of modelling, the scale, the degree of incorporation of empirical data and the emphasis given to model development vs. model output. Despite differences in approaches, these groups share a keen interest in accounting for and understanding the interactions (bidirectional feedback) between ecological and social processes and to reflect about modelling as a knowledge-making practice.

We begin by introducing the concept of situated knowledges (Haraway 1988) and expand it to analyse modelling practices. Building on this, we provide a reflection on the practices of modelling in the three working groups of SES-LINK, WhESA and H&S paying particular attention to integration challenges and decision-making processes. We then build on these discussions, to elaborate the four guiding principles for Situated Modelling as a framework for designing interdisciplinary projects as well as a personal stance. We conclude with the opportunities that Situated Modelling offers for understanding social-ecological dynamics and their transformation towards sustainability, e.g. in ecosystem management and biodiversity restoration, and for reflecting on assumptions embedded in the models we use to gain such understandings.

Situated knowledges: a relational perspective on knowledge production and objectivity

The interdisciplinary field of Science and Technology Studies (STS) has opened up scientific knowledge production as an object of social scientific inquiry (e.g. Latour and Woolgar 1986; Traweek 1992; Cetina and Karin 2009). One foundation of STS is the feminist claim that all knowledge practices are situated as well as performative. The concept of 'performativity' suggests that knowing the world is not a purely representational act but always also a practice of world-making: the world is produced with what we call knowledge 'on' the world (Barad 2007; Mol 2002, applied to sustainability science, see; Hertz et al. 2021; Hertz et al. this issue). The notion of 'situatedness' adds that reflecting on where knowledge is created is therefore crucial for understanding world-making practice. Ultimately, this has consequences for how we think about 'objectivity' and gain understanding about the world. This, in turn, influences how we engage it, e.g. in sustainability transformations. In the following paragraphs we will elaborate on these two concepts (see also Table 1 for background information on feminist STS).

In her programmatic essay on 'situated knowledges' Haraway (1988) uses the metaphor of vision and likens objectivity to a 'gaze from nowhere' (ibid: 581). She argues that a kind of science that separates both knowledge from contexts of production and researching subject from researched object perpetuates the illusion of 'omniscience'. She, moreover, asserts that relativism, often presented as an alternative to objectivity, mobilises the same 'god trick'. It likewise eschews responsibility in knowledge production: 'Relativism is a way of being nowhere while claiming to be everywhere equally. […] Relativism is the perfect mirror twin of totalisation in the ideologies of objectivity; both deny the stakes in location, embodiment, and partial perspective; both make it impossible to see well' (ibid: 584).

Haraway contrasts both conventional notions of objectivity and relativism with an alternative account of 'feminist objectivity', of 'views from somewhere' (ibid: 590). She insists on the embodiment – and thus situatedness – of all 'vision' (including 'objective' accounts). This extends to technologically mediated visions produced in interaction with, for example, microscopes, telescopes, GIS mapping or simulation models. According to this account, knowledge is intimately tied to its origin, and locatable in specific social, epistemic, material, political, historical and ethical contexts (see Principle 1). Rather than asking for a novel way of cutting these ties in an attempt to gain 'objective' knowledge, Haraway calls for the conscious production of situated knowledges. The formerly passive objects of knowledge, she continues, are not passive at all. The world does not consist of fixed entities to be discovered, but of active participants in the process of knowledge production (see Principle 2).

To better capture simulation modelling as a situated practice, we think of it as a particular constellation or 'apparatus' (Barad 2007), which performs particular worlds and not others (see also Rickhard and Ludwig, this issue, on the role of models in enacting river ontologies; see also below and Figure 1 and Table 2 for background on what we consider modelling practices.). A modelling apparatus cuts through the complexity of the world in a way that is contingent on a particular, situated arrangement of world, data, model and modeller including, for example, the ability of models to simulate interventions. In her analysis of scientific models of algae growth in the English Lake District, Tsouvalis (2023) describes this cutting as a 'crafting of realities' that depends on a 'vast hinterland' of models. This hinterland, in turn, consists of other methods, crafted data, previously crafted realities and disciplinary trials. It may either limit or further the performative effects

Table 1. Background Box on Feminist STS (for modellers).

Feminist scholars have been key to the interdisciplinary field of Science and Technology Studies. They not only challenged biases in established methodologies in the field (see e.g. Star 1990 for Actor-Network Theory), but de- and reconstructed what it means to produce scientific knowledge in a fundamental way. Feminist researchers have addressed equity issues, such as the underrepresentation of women in academia and the lack of research on female concerns (e.g. Harding 1986, Sent and van Staveren 2019; Barker 1995; Tuana 2006). Their analyses illuminated how scientific knowledge production is enmeshed in the construction of sex and gender, how imaginaries of 'male' and 'female' traits run through scientific knowledge production and representations, and the systematic construction of science and technology as a male domain (e.g. Harding 1986; Longino 1990; Martin 1991; Wajcman 1991, 2007; Fausto-Sterling 1992; Keller 2007; Haraway 2010).

Feminist STS scholars have deconstructed dominant narratives, e.g. of 'progress' or 'technological determinism', but above all of 'objectivity' as detached representation of the world (Harding 1986; Haraway 1988, 1991; Longino 1990; Barad 1999, 2007). The inquiry into 'objectivity' has resulted in different lines of argument. Some argue that knowledge is objective once produced from the standpoints of collectives affected by and concerned with the problem at stake, whose voices have been silenced in mainstream science. This has been coined as the notion of 'strong objectivity' (Harding 1992; Crasnow 2014; see also Longino and Lennon 1997 on feminist epistemology). Another line of argument challenged the conventional understanding of the knowing self. In her 1988 essay Situated Knowledges Donna Haraway passionately engages social constructionist and Marxist critiques of objectivity alongside of a critique of 'strong objectivity'. She denies the absolute superiority of any subjective standpoint (see also our Principle 3) and calls for the creation of partial and situated knowledges.

More recently, the 'new materialist' feminists have built on this proposal to develop more processual and performative accounts of scientific objects and their agency (Barad 2007; Coole and Frost 2010; Dolphijn and van der Tuin 2012; Hinton 2014; see also our Principle 2). They emphasise scientists' responsibility vis-à-vis the world via the effects of one's choices in scientific knowledge production: 'Scientists are involved with their objects of study rather than aspiring to detachment; scientific understanding is situated and intra-active rather than totalizing and explanatory; the telos of scientific work is transformative and futural rather than representational and retrospectively reconstructionist. The commitment to objectivity requires justice to both the objects of inquiry and the diverse actors who participate in or otherwise encounter science; and this commitment can only be fulfilled in a reflexively critical reflection upon one's entire practice, not merely the results abstractable from it' (Rouse 2002, p. 160).

of a model (irrespective of the effects we might wish it would have), e.g. depending on whether it counters or reinforces already dominant narratives. Economic models have been driving interventions and management grounded in particular assumptions, which have proven difficult to challenge, whereas numerous papers question the rational actor model, it is nevertheless still widely used (e.g. Groeneveld et al. 2017; Burgess et al. 2020). Lade et al. (2017) use different models to assess the consequences that emerge from different poverty narratives and what these imply for poverty alleviation, thereby challenging oversimplified economic models (see also Principle 4). In the words of Karen Barad (2007), 'practices of knowing are specific material engagements that participate in (re)configuring the world' (ibid: 91).

Like Haraway, Barad maintains that 'objectivity cannot be about producing undistorted representations from afar; rather, objectivity is about being accountable to the specific materializations of which we are a part' (ibid.). Modellers are part of modelling as a material practice, through their investment in the worlds that are being modelled and the many choices they make during model construction, validation and use.

Creating situated scientific knowledge becomes a productive practice of building webs of knowledges from heterogeneous collectives occupying subject positions that affect one another (Hoppe 2021, pp. 80, 87, see Principle 3). As these knowledges and positions involve different people and research traditions, the hope is for the agonistic clash of knowledges and positions to be productive (see Principle 4) and at times surprising. This, in turn, might strengthen awareness of the situatedness of particular knowledge claims and ultimately allow researchers to assume responsibility for the knowledges they co-create.

From situated knowledges to situated modelling: discussing a relational perspective with modelling communities

Starting from the more theoretical considerations outlined above, three interdisciplinary research groups working with or on simulation models set out to discuss how a relational perspective could inform modelling practice: SES-LINK, WhESA and H&S. We developed the four principles outlined below as a joint operationalisation of Situated Modelling. Interdisciplinary collaborations and discussions at the IRI THESys informed by Science and Technology Studies (STS) had already contributed to developing a first concept of Situated Modelling. A series of workshops organised by Anja Klein, Krystin Unverzagt and Rossella Alba then brought together participants from all groups (December 2021, May 2022, October 2022). Some of us had also already ventured into exploring possible implementations (e.g. Klein 2018; Niewöhner 2021; Krueger and Alba 2022).

For this paper, we chose to stay with examples from our own working groups because they already represent a range of modelling approaches across scales. Each of these approaches include practices that inspired the concrete shape Situated Modelling takes in this paper: participatory hydrological modelling, agent-based and dynamical systems modelling of smaller-scale social-ecological systems, and Whole Earth System Analysis with large-scale social-ecological dynamical systems modelling. A shared interest between all three communities and the non-modelling social scientists in the team of co-authors is how (and if) models can account for coupled/intertwined socio-cultural /human and biophysical/ecological dynamics. Each community problematises and tackles the complexity of this fundamental interconnectedness differently (see Table 3 for a more detailed comparison). And each community has situated practices of decision-making in the face of uncertainty. This, in turn, leads to particular methodological questions and innovations.

During our joint workshops, we mutually interrogated the ontological and epistemological foundations of the three modelling approaches. In order to focus our discussion, we chose to compare the understandings and practical handlings of 'uncertainty' and 'complexity' (see Table 4), concepts that have been prevalent and mobilised for methodological innovations in all three modelling communities. These structuring notions helped us interrogate the situatedness of our respective practices. We also unpacked decision-making in the model construction process with concrete examples from each of the modelling communities (see Table 5 below on 'junctures in modelling'). These joint activities allowed for developing a first, grounded understanding of the situatedness of our own modelling practices.

A modelling process can be described as consisting of a number of steps (see e.g. Schmolke et al. 2010 for participatory ecological modelling with ABMs or Jakeman et al. 2006 for environmental modelling). For non-modellers, we provide a more systematic, introductory overview of the modelling process and some technical terms in Figure 1 and Table 2. Throughout the paper, we discuss the 'steps' as *modelling practices*. These practices follow a temporal order to some extent, but how they play out in practice is iterative and situated. The process strongly varies between modelling community, model purpose and modelling methods, e.g. with regard to the time and effort allocated to a particular step. As we are laying out a relational and practice-oriented approach, we focus less on establishing a distinct sequence of steps, and more on the differences in how certain steps play out in practice. The four principles following in part 4 are applicable throughout the whole modelling process. Which practices we refer to more specifically throughout the paper is relative to specific parts of our overarching argument, and sometimes to terms used in the cited literature. In Principle 2, we go into what Situated Modelling entails for model validation, and in Principle 4 we address model documentation.

SES-LINK

The SES-LINK research group is composed of modellers and empirical researchers from the natural and social sciences (in this paper: Tilman Hertz, philosopher; Emilie Lindkvist, sustainability scientist;

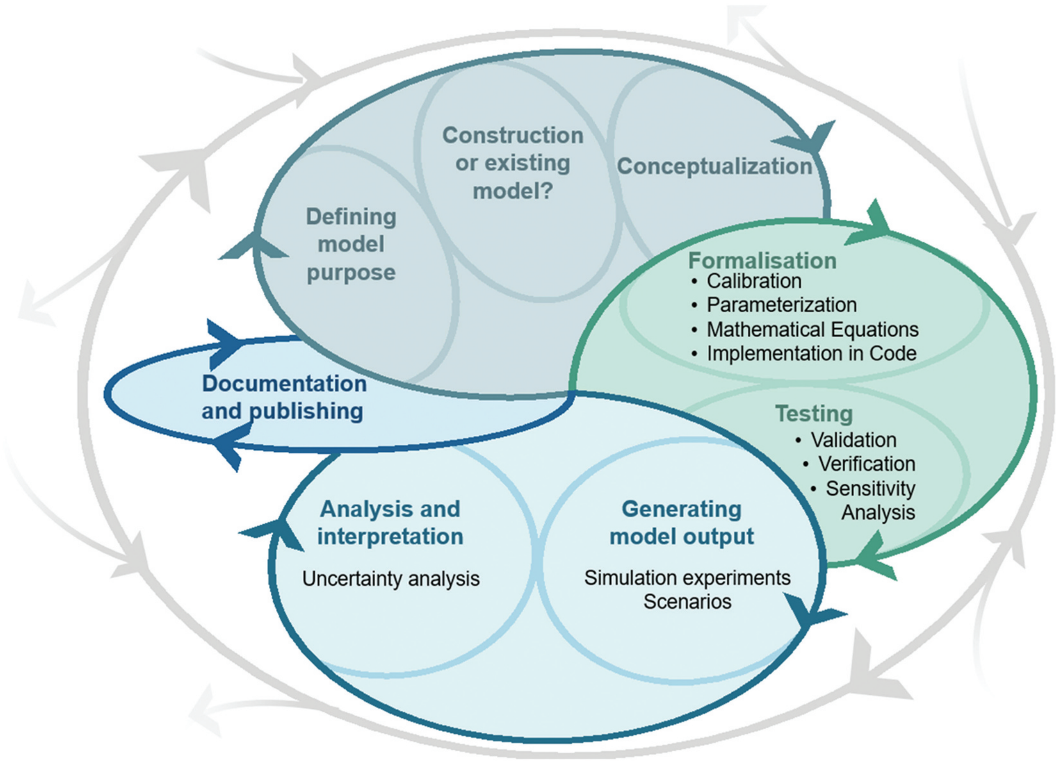

Figure 1. Iterative steps in a modelling process.

Table 2. Background on modelling steps (for non-modellers).

For the modelling process it is important to establish the model purpose and its context, and to decide whether one will construct a new model or re-use an existing model, e.g. adapting it to a particular case, extending or coupling it. In conceptualising the model further, modellers may take initial decisions on the model boundaries, relevant processes and entities, rules, relationships, model complexity and spatio-temporal scales. This conceptual model is then formalised, e.g. through the definition of mathematical equations and implementation of the model in computer code (see also Principle 4 on recoding a model in a different programming language).

Model formalisation and model testing go hand in hand and may impact, again, on the initial conceptualisation of the model. This involves calibration, parameterization, verification and validation. Verification means testing whether the computer code is correct and doing what it should. Parameterization refers to the inclusion of relevant smaller-scale processes into a model via fixed or stochastic values. The influence of the settings of parameters on model behaviour then may be systematically tested. Calibration and validation ensure that the model behaviour aligns with the expectation of how a certain phenomenon would unfold in the 'real world'. Calibration commonly refers to iterating over the model several times until it is validated. Sensitivity Analysis (SA) tackles the relationship between model settings and model output, e.g. by exploring the space of potential model behaviours and results given particular initial settings of parameters. Uncertainty Analysis (UA) is a way to evaluate the uncertainty of the model output. This uncertainty may be quantified with statistical methods (see also Table 3, Table 4).

Model results may be quantitative output data, or qualitative insights into the behaviour of the model. This output is generated by running the simulation model many times, with different settings of model variables, representing e.g. different what-if scenarios. SA and UA can be part of the model development process, but depending on the context and purpose of the model these may also be results in their own right (see also Principle 2, p. 14), as well as other insights won during the process of model construction and use.

The data as well as the behaviour of the model are analysed and published. The model may also be published in a fitting database, alongside a documentation of the model and sometimes also the modelling process (see also our Principle 4).

The grey circle and the incoming and outcoming arrows indicate that modelling is always happening in a specific context. Different output can be generated throughout the process, and that input, e.g. in terms of empirical data, context, or participatory processes, may also come in at different moments.

Romina Martin, ecologist; Maja Schlüter, system scientist; Nanda Wijermans, cognitive and computer scientist). The group jointly constructs models to explore the non-deterministic, path-dependent, dynamical unfolding of social-ecological systems, such as small-scale fisheries (e.g. Wijermans et al. 2020) or agricultural systems (e.g. González-Mon et al. 2021, 2023).

The Stockholm Resilience Centre (SRC), large grants from the European Research Council (ERC), and grants funding interdisciplinary/multi-method research, e.g. by the Swedish Research Council (Interdisciplinary Research Environment Grant) provide the institutional setting and enable long-term teamwork. From its inception, the SRC sought to provide a shared conceptual frame for empirical and transdisciplinary SES research within its bounds with an explicit interest in resilience, intertwinedness and Complex Adaptive Systems (Berkes and Folke 2000). The group contributes the conceptual and methodological basis of SRC's research, however, especially encountering perceptions of models strongly influenced by e.g. economical or biophysical models, the group works towards broadening the understanding of what models can be or do within the Centre.

The SES-LINK approach to modelling draws on several modelling traditions, such as agent-based modelling (ABM) as developed within complexity science, within the social simulation and the ecological modelling communities, and participatory modelling as developed by the Companion Modelling Initiative (Étienne 2014). In addition, the group further develops the use of stylized dynamical systems models as thinking tools.

Modelling happens in close collaboration with empirical researchers from within and outside the group conducting place-based fieldwork. The empirical groundedness of the models distinguishes the SES-LINK approach from purely theoretical modelling that relies on abstract concepts. At the same time, the approach differs from empirical models that are calibrated against quantitative data or represent one particular case in great detail. SES-LINK does not aim to generate case specific, quantitative model-based outputs. Instead, it seeks to develop generalised, but context sensitive understandings of complex dynamics and middle-range theories. The understanding or explanations generated are always considered as one explanation among several possible ones. Assumptions about model-world relations remained implicit during our discussions.

To address the fundamental intertwinedness of social-ecological systems, models generally include interacting social and ecological entities within one model. Conceptually, the group developed the notion of 'Social-Ecological Action Situations' (Schlüter et al. 2019) and works with process relational perspectives (e.g. Mancilla García et al. 2020, Schlüter et al in prep, see Table 3 for more detail).

With regard to choices in the modelling process and in terms of concrete practice, the SES-LINK models are often co-constructed by modellers and non-modellers, i.e. researchers who have in-depth fieldwork experiences. The researchers negotiate decisions about what to include, e.g. in the model structure through iteration between model conceptualisation and formalisation, the analysis of empirical data and/or stakeholder participation, narratives from other cases, theory, and existing models (e.g. for fish regeneration). Decisions are strongly contingent on a model's purpose. Equally important are the choices about what to leave out, not only in terms of excluded entities but also removed ambiguities in order for the model to

Table 3. Relevant differences in modelling SES in the three modelling communities.

	SES - LINK	WhESA	H&S
Approach	Inclusion of social and ecological entities and dynamics within one model to represent their intertwinedness within one SES. These entities interact within institutional and biophysical environments.	Creation of World-Earth Models with feedback loops between social and biophysical spheres up to a planetary scale, often via the coupling of global models of biophysical, economic/ metabolic and/or socio-cultural dynamics.	Hydrological modelling as a social process, participatory hydrological modelling
Methodological innovation	Social-Ecological Action Situations (SEAS); Combining process-relational philosophy and modelling, i.e. 'relation-based modelling' (RBM)	Copan: Core modelling framework, Using qualitative and participatory methods for global models, Complex systems analysis of planetary-scale SES dynamics	Combination of insights from STS with (participatory) water modelling and uncertainty analysis
Example models	PoliSEA (Orach et al. 2020): an ABM that contains social and ecological elements – interest groups, coalitions, policy makers and fish populations; Poverty Traps (Lade et al. 2017): A dynamical systems model which includes asset dynamics, phosphorus and soil or water quality; BeeCome/RBM (Schlüter et al in prep): An ABM of the emergence of a fishery assemblage; see also: https://www.seslink.org/models/	EXPLOIT (Barfuss et al. 2017): coupling of agent- and equation-based model components, representing a stylized 'ecosphere' and 'anthroposphere', within one modelling framework. InSEEDs (Schwarz et al. 0000): coupling of the pre-existing global biophysical biosphere model LPJmL with an ABM that represents human behaviour/ agents regarding land-use decision making (see also Principle 1) See also: https://www.pik-potsdam.de/en/institute/departments/activities/copan/models	Various tailor-made (Bayesian) statistical or machine learning models; rainfall-runoff models (e.g. bucket model, Dynamic Topmodel); water quality models (e.g. Extended Export Coefficient Model (ECM+), sediment mixing models); erosion models (e.g. EUROSEM); See also Table 4
Details of the approach	The group has developed a framework based on Ostrom's concept of action situations that proposes social-ecological action situations as key processes generating SES dynamics (Schlüter et al. 2019). SE-AS enables a representation of key social-ecological interactions when developing ideas and models about SES dynamics. By exploring possibilities of constructing SES models from process-relational perspectives (e.g. Landa 2006; Barad 2007) they aim to go beyond the notion of interacting entities which produce system-level outcomes. Instead, the group wants to model how phenomena and SES emerge from *assemblages* of human and non-human elements and their *relations* within the model; and to better understand the material and discursive processes that shape the model (Schlüter et al. 0000, see also Principle 2).	The group has developed a taxonomic framework to classify and disentangle conceptualisations and model descriptions of planetary SES based on three categories describing (i) biophysical, (ii) socio-metabolic (including socio-economic) and (iii) socio-cultural entities and processes (Donges et al. 2021). Interactions and feedbacks connecting these processes and entities can be categorised and described using derived taxonomies based on these three taxa. Copan: CORE: This modular software framework builds on this taxonomy and makes it possible to easily combine different modelling approaches (e.g. ABMs with dynamical system models) and thus adequately connect biophysical with socio-metabolic and socio-cultural spheres. WhESA modelling with copan: CORE is based on a set of guiding principles for World-Earth Models (Donges et al. 2020): (i) Models should represent complex social and Earth system processes in both an explicit and dynamic fashion to incorporate co-evolutionary processes and feedback-loops between spheres. (ii) Models should capture possible nonlinear dynamics and tipping points (both social and biophysical) as well as their interactions. (iii) Models should capture interactions across scales, up to the planetary scale. (iv) As this approach comes with many uncertainties, modellers should always conduct a comprehensive evaluation of state and parameter spaces of the model, such as an extensive sensitivity analysis and exploration of possible resulting trajectories.	This group does not aim to explicitly integrate social processes or entities in the model, but uses participatory approaches with stakeholders to, among other reasons, account for 'the social' in social-ecological processes. Beyond this group, the field of socio-hydrology has since also promoted other modes of bringing 'the social' into hydrological models (e.g. Yu et al. 2022). These include the use of systems dynamics approaches and, increasingly, agent-based modelling. In earlier hydrological models, the social used to be included in the model only through water abstraction volumes and other boundary conditions.

run. On the one hand the need to be explicit for model formalisation can enhance transparency and mutual understanding, on the other, important nuances are lost. This interdisciplinary negotiation makes the

Table 4. Background box on uncertainty and complexity in modelling (for non-modellers).

Uncertainty in (quantitative) environmental modelling is considered to stem from a variety of sources. Researchers in the field correspondingly use different methods to tackle uncertainty, such as various quantification methods. What is considered a relevant source of uncertainties is contingent on model purpose, method, scale, or integration of social processes In the broader literature on uncertainty, a number of non-complementary subcategories circulate. These include measurement uncertainty, data uncertainty, model structural uncertainty, technical uncertainty, and related concepts such as ignorance, risk, indeterminacy, and ambiguity. These already hold some insight as to the socio-technical embeddedness of modelling (see e.g. Claeys et al. 2010 and our Principle 1).
Complexity in modelling may on the one hand refer methodologically to a spectrum of simple to complex models, where complex models contain more detailed processes and parameters. The principle of model parsimony – keeping the model as simple as possible but as complex as necessary – is a concept that suggests a balance between the two. It remains open what 'necessary' means in a particular case. Model parsimony can have epistemological reasons, but it can also relate to limitations of computability and technical infrastructures (WhESA, H&S, see also Principle 1). On the other hand, in parts of the SES community (in our case, in the SES-LINK group and WhESA), social-ecological systems are ontologically captured as 'complex adaptive systems' (CAS, Preiser et al. 2018). This means that these communities assume that the systems that they model display emergent phenomena and non-linear dynamics, which arise from many social-ecological interactions across scales.
Interestingly, conceptualising and modelling SES as CAS appears to de-centre the concern with quantifying modelling uncertainties from a number of distinct sources that prevails in, for instance, hydrological modelling. The CAS concept suggests that some uncertainty is irreducible (see e.g. Schlüter et al. 2012). Moreover, seen from this ontological perspective, modelling serves as a means to explore possible system-level consequences of this uncertainty. This occurs, for instance, when the simulation generates unexpected outcomes. More data, in this sense, then does not necessarily lead to less uncertainty but may enhance understanding (Lindkvist et al. 2020).

model building process itself an important contribution to enhance system understanding that is at least as important as model results. A paper spelling out their particular approach is in preparation. The potential contingency of model structural decisions based on more subjective factors, e.g. a modeller's habits, is recognised, but not handled systematically.

Whole Earth System Analysis group (WhESA)

WhESA extends the understanding of 'Earth systems' in the Anthropocene to better represent social-ecological co-evolution in traditional Earth system models as well as to create novel approaches to model planetary SES, so called World-Earth models (see for example Steffen et al. 2020; Donges et al. 2021). The approach is rooted in insights, frameworks and methods from Earth system science, complexity science, the science of social-ecological systems and resilience theory, together with further disciplinary influences.

The WhESA research group is a part of the broader COPAN collaboration located at the Potsdam Institute for Climate Impact Research (PIK). It includes researchers from the natural and social sciences (in this paper: Jonathan Donges, climate physics, Earth system and complex systems science; Hannah Prawitz, ecology and social sciences; Luana Schwarz, social-ecological systems and cognitive sciences). During the past three decades, PIK has been a crucial site for developing interdisciplinary and transdisciplinary Earth system science and analysis. Since the early 1990s, studying the dynamic co-evolution of human societies and the biophysical Earth system has been a foundational aspiration for PIK (Schellnhuber 1998, 1999). The approach to investigating the impacts of climate change on human societies and human-Earth system interactions, however, has been dominated by a neoclassical economics paradigm.

To tackle the interconnectedness of SES, WhESA goes beyond scenario approaches in Earth system modelling, such as used by most Integrated Assessment Models (IAMs), in which prevailing social narratives are driven by macroeconomic optimisation paradigms. Additionally, it includes socio-cultural dynamics (Donges et al. 2021, see Table 3 for more detail). WhESA does not aim to project the future co-evolution of social-ecological systems with a high certainty. Instead, WhESA modelling explores qualitative trends and seeks to generate a better understanding of the complex and intertwined planetary SES in the Anthropocene. This exploration focuses on critical interactions and feedback loops and resulting tipping points, cascading regime shifts and resilience capacities (for more detail see Table 3). In this regard, WhESA resonates with the SES-LINK group's approach to modelling and with recent global models published (e.g. Beckage et al. 2018; Moore et al. 2022).

Similar to the SES-LINK group, WhESA members are currently starting to explore the possibilities of using qualitative methods. This includes stakeholder involvement throughout the modelling process. This requires the development of novel methodological approaches, especially due to the large scales the group operates on, as compared to local and regional settings, in which participatory methods are more established already. Following the principles formulated for the Copan: CORE-framework (Donges et al. 2020; see Table 3), the group engages in active discussions regarding modelling choices, both within the WhESA/COPAN group, and with experts from other fields. As a relatively young research community operating at the intersection of Earth system science with diverse disciplines (for instance sociology and cognitive science), it is central to make the work connectable and adaptable to other research fields. For the same reason the development of novel methods and approaches will be central in the years to come. The researchers are convinced that this endeavour should be accompanied by a diversification of the research community in terms of inter- and transdisciplinarity as well as the inclusion of a broad range of qualitative and quantitative research approaches.

IRI THESys Hydrology & Society Group (H&S)

H&S conducts water research from an interdisciplinary perspective using mixed methods including, and often combining, qualitative and quantitative approaches. Co-author and hydrologist Tobias Krueger is leading the group and working with co-authors Rossella Alba (human geography), Anja Klein and Jörg Niewöhner (both cultural anthropology) and Krystin Unverzagt (STS). The IRI THESys provides an inter- and transdisciplinary research environment and hosts teaching and research in STS, as well.

Other than at the WhESA and SES-link groups, the H&S group does not focus explicitly on integrating social processes or entities into hydrological models. The group has a keen interest in researching how hydrological knowledge and modelling practices are mobilised in water research and policy (see Krueger and Alba 2022). In particular, Krueger has a longstanding interest in the philosophical foundations and social nature of hydrology as a practice, and modelling and uncertainty analysis in particular (Krueger et al. 2012, 2016; Beck and Krueger 2016; McMillan et al. 2018). Another key interest of the group is towards understanding how social dynamics shape the development of hydrological models, for instance in participatory settings (review by Krueger et al. 2016 for hydrology, not just models). The participatory setting may add an agonistic element to the hydrological modelling case (see Principle 4 and Table 4).

Generally, hydrological modelling is underpinned by a positivist research tradition. It usually aims to accurately represent real phenomena, even if philosophical and practical limitations as reflected in the debate around uncertainty (Krueger and Alba 2022) have eroded this basis in the recent past. The connection to 'reality' also means that measurements of hydrological processes (data) play an important role in hydrological model development. Hydrological modelling has a long tradition of quantifying uncertainties and reflecting on this (e.g. Beven 2009). Methodologically, this interest in quantification results in categorizations of types of uncertainty, e.g. data uncertainty, calibration uncertainty (sometimes called parameter uncertainty) and model structural uncertainty. Data uncertainty is particularly attended to as quantitative data is important for model calibration and validation. There are ongoing discussions on the subjectivity of the choices needed in the face of uncertainty (e.g. Melsen et al. 2019), which Krueger and Alba (2022) extended from being a mainly epistemological concern to the need to attend to the performativity of models and decisions in model construction (see also beginning of Principle 3).

Situated modelling: four guiding principles

Starting from our interdisciplinary discussions of modelling practices and our reading of feminist STS scholarship above, we identify four guiding principles that serve to render the notion of situated knowledges productive for modelling. These principles pertain to understanding and reflecting on modelling practices and decision-making in model construction and use as situated (Principles 1 and 2). They also aim to actively situate one's modelling practices differently and move beyond 'integration' as the ultimate way to handle diverse knowledges about social-ecological systems (Principles 3 and 4).

In elaborating these principles, we seek to strike a balance between remaining attentive to the individual logics of practice of different modelling communities and suggesting a more general framework. This in turn could inform interdisciplinary research projects emphasising epistemic agonism (see Principle 4) or a more personal stance and reflection when constructing a model. The local or global, more empirical or more theoretical, systemic or processual models we work with in the respective research groups can have different pitfalls and may lend themselves to the different suggestions to a greater or lesser degree.

Principle 1: socio-material embeddedness

> Situated knowledges are about communities, not about isolated individuals. The only way to find a larger vision is to be somewhere in particular. (Haraway 1988, p. 590)

Situated Modelling entails attending to the apparatus of knowledge production as it is socially and materially embedded in and produced by e.g. research infrastructures, power relations, and ways of thinking.

Beyond Haraway's broad statement on the situatedness of scientific knowledge, Science and Technology Studies, anthropology, and the history and philosophy of science have contributed to a clearer understanding of knowledge-production practices. These works, and ethnographies of the everyday work of scientists in particular, help us understand *where* simulation modelling as a knowledge-production practice is situated socially, epistemically, and in institutional and technological infrastructures and developments (see e.g. Galison and Galison 1996). We argue that it is crucial to reflect on the diverse ‘origins’ of a model to better understand and make explicit assumptions and path dependencies that affect modelling practices, and to work towards removing barriers to accessibility and participation (see also Principle 3). In order to do so, we understand modellers and modelling practices as embedded in ‘thought collectives’, which can be research groups or disciplines, that share a particular ‘thought style’ (Fleck 1935). Modelling collectives are also embedded materially and discursively in institutions, infrastructures, technologies, disciplines, worldviews, habits and methodologies, which they in turn stabilise (Babel et al. 2019). They may share particular ontological and epistemological commitments or be part of broader research paradigms (see e.g. Morita/Suzuki 2019 for resilience and SES research, Li Vigni 2020b, 2020a, 2021, on complexity science). Such collectives do not only shape model construction but, vice-versa, are also shaped by especially larger-scale models that engage several generations of researchers. Babel describes a case as ‘far from unique’ where constructing a global hydrological model played a stabilising and integrative role in assembling researchers, investments in high performance computers, and other equipment into a new research group (Babel et al. 2019: 6f).

The large models at PIK such as the LPJ (Lund-Potsdam-Jena) dynamic global vegetation model (see e.g. Sitch et al. 2003; Drüke et al. 2023) are another example for how the same models are used over decades to train generations of young researchers. They are also (re-)used in research on novel ways to model coupled social-ecological systems, such as the aforementioned InSEEDs model (see Table 3). One component is a newer version of the LPJ-model of biophysical processes; the other an Agent-Based Model of human processes. The group worked with certain properties of the pre-existing models, like an established set of plant-functional types, as well as land management options of the biophysical model. This created certain path dependencies for the integrated, social-ecological model, for example with regard to the information feedbacks between the biophysical and the human model. In a similar vein, Jensen argues that models are also situated within already existing ‘model ecologies’: New models are not just developed in a particular community, but also in relation to existing models, partly using similar data (Jensen 2019). These could be relations of extension, comparison, and modification, but also of disagreement and dissociation.

On a more practical note, modelling cultures have been distinguished by how they approach model implementation into computer code and the role of simulation. In her ethnographic work on meteorologists and astrophysicists, Sundberg (2010a, 2010b) contrasts ‘cultures of calculation’ and ‘cultures of simulation’ as collective ways of relating to computer simulation in modelling practices. Cultures of calculation are characterised by an in-depth focus on mathematical models, write the model code themselves and focus on the simulation of reasonable scenarios. Cultures of simulations tend to use existing computer programs, show a more playful attitude in exploring model simulations and focus on extreme, yet interesting model scenarios. She shows how these cultures manifest side by side and relative to specific situations rather than as clear-cut collectives.

Modelling collectives and their shared thought styles are again more widely situated within societal, political, technological and historical developments. Bloomfield (1986) for instance shows how the System Dynamics Group at MIT and its WORLD models reflect Forrester’s middle-class conservative situation and a concern with the maintenance rather than change of social order. Ample work explores the emergence of Climate and later Earth system models in relation to geopolitical concerns like the Cold War, (military) technological developments, and philosophical stances of the time (Doel 2003; Edwards 2013; Hamblin 2013; Chakrabarty 2019; Heymann et al. 2019; Furuhata 2022).[1]

Approaching thought collectives as social collectives also brings questions of social difference, power, privilege, accessibility, diversity and inclusion (see e.g. Packett et al. 2020 on gender bias in water modelling). How thought collectives are institutionalised and infrastructured contributes to unequal access to resources, e.g. computing power, data, funding, networks, visa and travel restrictions. Rethinking how academic conventions are exclusive, e.g. participating in in-person conferences involving aeroplane travel, goes hand in hand with sustainability concerns (see e.g. the recent commentary by Wassénius et al. 2023). Unequal infrastructuring is perhaps most succinctly illustrated by the global distribution of Climate Models and large IAMs and the computers able to run them which are with few exceptions located in the global North. Barnes (2016) analyses how Egyptian scientists with less access to computing power have to go to great lengths in order to get Global Circulation Model data to drive their local hydrological models.[2]

While not every model needs a super computer, doing Situated Modelling might mean considering how models can be built and documented such that they work in diverse research infrastructures, e.g. are not computationally intensive, or are more widely accessible for diverse audiences and participants. This might diversify modelling as a worldmaking practice (see also Principle 4). Attending to the socio-material embeddedness of one's modelling practice does not amount to pinpointing an individual subject's stable position (see also Principle 3). Embeddedness needs to be thought processually. These are some questions that can help reflect on where one's practice is situated: Who is my thought collective? Which ways of constructing and reasoning with models appear self-evident to me? Which disciplines, schools, paradigms have influenced me how and why? Which societal, historical and technological developments make my work possible? Which other model(s) or model parts does the model build on or deviate from and why?

Principle 2: distributed agency

> A corollary of the insistence that ethics and politics covertly or overtly provide the bases for objectivity in the sciences as a heterogeneous whole [...], is granting the status of agent/actor to the 'objects' of the world. [...] Accounts of a 'real' world do not, then, depend on a logic of "discovery" but on a power-charged social relation of "conversation. (Haraway 1988, p. 593)

Situated Modelling involves considering how agency is distributed between model, world, data, modeller throughout model construction and use. This also has consequences for model validation.

Donna Haraway and others (see Table 1) acknowledge the agency of objects in processes of knowledge production. She understands knowledge production not as 'discovery' but as multi-vocal 'conversation' (ibid: 593) with occasionally surprising outcomes. The first principle accounted for the larger contexts of everyday situations. Now, we draw attention to *what* is happening in such concrete situations of model construction, its consequences for model validation and when a model is considered 'good enough'. Attention to distributed agency entails interrogating who has the 'voice' to influence e.g. decision-making processes and with which consequences.[3]

From our view, the specificity of modelling as a scientific knowledge practice is the performative interaction of model, world, data and modeller. This differs from an understanding of models only as direct representations of some phenomenon in the world or as neutral tools that researchers use (Morgan and Morrison 1999; Edmonds et al. 2019). This processual view accounts for heterogeneous actors and distributed agencies that partake in modelling. Concretely, Members of the SES-LINK group developed a process-relational approach to understand how the apparatus shapes the emergence of the model and vice versa (Schlüter et al in prep). It explicitly values the insights already generated during the process of model construction and seeks to strengthen the transparency and reflexivity of modelling.

Modelling may at first glance mainly be about aligning the model with data on the world and the modeller's intentions. With the inclusion of 'world' in the above list, we want to highlight that 'the world kicks back' (Barad 2007, p. 215) in other ways than data. On the one hand, the involvement of 'the world' is exemplified in the many contexts evoked in Principle 1. On the other hand, decision-making in model construction and use can be understood as 'more-than-rational' (Peters 2018). It also has embodied, emotional, aesthetic and experiential dimensions (Munk 2013; Myers 2015; Walford 2020; Kozlov 2023). Participatory hydrological modelling (Krueger et al. 2016) opens up the modelling processes to the scrutiny of stakeholders, thereby in a sense shifting agency to 'the world', strengthening transparency and reflexivity with a focus on model output.

In addition, the model in this interaction is rarely 'the one' model. Throughout the modelling process it materialises in different ways, involving different technologies, which could be called model formats (Klein 2018; Vorms 2012). Literature on model validation gives us some concrete hints as to how the specific affordances of models matter. In hydrology, for example, McMillan et al. (2018) distinguish between perceptual model (captured by graphs, drawings etc.), formal model (mathematical equations), and procedural model (computer code). The recognition is that models become less and less rich along this sequence, whereas more and more contingent choices and technical constraints come in. Each model format affords different engagements with the world and moments of participation by modellers and others (see Principles 3 and 4). In comparison to hydrological modelling, for ABMs mathematics presents less of a constraint – or can be considered to have less agency – in shaping the final ABM than the implementation in code and the simulation runs.[4]

This processual view has consequences for model validation and for when a model is considered 'good enough' or an 'adequate representation' for a specific purpose (see Edmonds et al. 2019, also; Parker 2020). Between the three modelling communities that collaborated on this paper, there is already a diversity in terms of model purposes and validation practices. We use models to quantify uncertainty and project alternative future developments of a system (H&S, WhESA), to better understand complex system properties and dynamics (WhESA, SES-LINK), and to explore qualitative trends and support middle-range theorising (SES-LINK). Hydrological models are calibrated using quantitative data, assuming a relation of adequate representation connecting model, data and world in order to get a certain target phenomenon 'right'. What is more implicit there is what 'right' means in which concrete case (see also vignette in Table 5). In our interdisciplinary discussions, it turned out that 'objectivity' is not necessarily the main criterion modellers use when evaluating models. The 'adequacy-for-purpose view' (Parker 2020) reduces overconfidence in modelling results and opens the space for additional validation criteria. Beyond valuing data-heavy, quantitative models or model parsimony it may be relevant to ask: 'Is the model good to think with? Is the model plausible given available knowledge and empirical data? Did the modelling process include different stakeholders and knowledges?' or 'Is it transparent enough for stakeholders to understand and relate to?'

Considering distributed agency hence brings into view that the decision on having reached adequacy is not unilaterally forced by the model-target relationship but involves the modeller's judgement and other, more-than rational aspects. Which other actors and agencies, then, participate in modelling decisions, extend the modelling apparatus, or disagree with its verdict on validity?

Principle 3: heterogenous collectives

> Subjectivity is multidimensional; so, therefore, is vision. The knowing self is partial in all its guises, never finished, whole, simply there and original; it is always constructed and stitched together imperfectly, and therefore able to join with another, to see together without claiming to be another. Here is the promise of objectivity: a scientific knower seeks the subject position, not of identity, but of objectivity, that is, partial connection. (Haraway 1988, p. 586)

Situated Modelling is done by heterogenous collectives which together occupy the formerly individualised subject position, creating partial connections. This includes carefully choosing who and what to relate to as well as to exclude in assembling these collectives to include plural values and worldviews.

Doing Situated Modelling means rethinking the epistemic privilege of an individual subject which constructs and uses models from a distinct, allegedly 'objective' position. Several studies explore the role of 'subjectivity' and "values" in environmental simulation models (e.g. Oreskes et al. 1994; Krueger et al. 2012; Pulkkinen et al. 2022; Undorf et al. 2022). They suggest that subjective modelling assumptions prescribe the space within which policy recommendations can be made (Keepin and Wynne 1984). Other studies reflect on the value-laden "assumptions" that modellers make in cases of incomplete knowledge (e.g. Petersen 2008; Kloprogge et al. 2011). Melsen et al. (2018), examining the impact of legacy on model choice, explore empirically how hydrological models are products of social context and how subjective choices made by the modeller impact results.

Krueger and colleagues have reviewed the subjectivity and ethical load of choices in environmental modelling (Krueger et al. 2012; Beck and Krueger 2016; Krueger and Alba 2022). With reference to Mol (2002) and Barad (2007), they argue that '[k]nowledge practices are not externally given but involve choices. These choices matter as they enact a world that could be different. Whether these choices are made explicitly or are inscribed in research traditions, researchers have an ethical responsibility towards the worlds they enact' (Krueger and Alba 2022, p. 11). So, they continue, unearthing which worlds are at stake in modelling choices requires close collaboration between interpretive social sciences and modellers – sometimes of an agonistic kind (see below).

However, such discussions of subjectivity in modelling choices may not go far enough. In order to further eliminate subjectivity, they continue to separate knowing subject and knowledge. As Barad notes, reflexive endeavours that maintain the divide between words and things, knower and known, ontology and epistemology, remain representationalist instead of recognising the performativity of scientific knowledge practices (Barad 2007: 88f). As it may be impossible to include all ontological, epistemological and ethical assumptions subjectivity cannot – and arguably should not – ever be fully eliminated from modelling choices. We argue that it matters to always remain open to various competing choices, to continually strive for a plural position.

For Haraway, the subject position is not a place of bounded, fixed identity, not even a certain positionality affecting knowledge production. It is a processual and partial (sensu Marilyn Strathern) position from which to create webs of connection. Concretely, this means inviting diverse perspectives and practices, which in turn affect and change the initial position. Examples are the practice of negotiating modelling choices as done in the SES-LINK group, facilitating stakeholder participation in different stages of the modelling process, as our three modelling communities do, or rethinking this participation for global scale models, as WhESA does). Producing robust, situated knowledges as heterogeneous collectives requires openness and curiosity but sometimes also 'passionate detachment' and clarity on what to exclude (see also Giraud 2019). *Who* else should be invited to 'sit at the modelling table' and why would their presence make a difference? And which connections should be severed? Thereby, a collectivised subject position made up of different kinds of agencies replaces that of the individual knower which prevails in many conventional research practices.

With this and the following principle we move from understanding modelling practices differently towards a practice of Situated Modelling, which in some ways may come down to inviting others to disagree with what is being done. We suggest a particular way of how to organise this disagreement and who these 'others' may be in Principle 4.

Principle 4: epistemic agonism

> I want to argue for a doctrine and practice of objectivity that privileges contestation, deconstruction, passionate construction, webbed connections, and hope for transformation of systems of knowledge and ways of seeing. (Haraway 1988, p. 584)

Situated Modelling emphasises epistemic agonism to retain and work with significant differentiations of social-ecological dynamics throughout the modelling process. The aim is not seamless integration of, e.g. different data or knowledges, but an interrogation of underlying logics and norms, as well as the preservation of alternatives, gaps and incommensurabilities.

Following Barry and Born (2013), we use 'agonism' as an epistemic virtue to guide the *'how?'* of a Situated Modelling practice. The notion of agonism in political and social theory marks the idea that certain forms of conflict within a society or group of people may generate a political good (e.g. Mouffe 2013). Agonism rests on the assumption that the world is constituted not only of a plurality of knowledges and values but, in fact, an irreducible plurality of legitimate ways of arriving at these. Therefore, no final arbiter exists to align or integrate this plurality. Hence, rather than conceptualising conflict as an obstacle to consensus, one might value conflict as constitutive of democratic process.

We suggest that modelling processes need to preserve significant differences to produce 'good' understandings of social-ecological dynamics. Two different social groups within a community might for example hold contradictory interpretations of a particular event. One group might suggest an environmental problem frame where another sees a problem of social inequality. Epistemic agonism suggests that both are valid interpretations. Each, however, holds possibly different consequences for social action. Similarly, a significant difference in model representations might stem from two different interpretations of what a particular actor does within a social-ecological system. Here fundamental epistemological differences in knowing material and social dynamics need to be addressed. Such differences often disappear in modelling processes as model resolutions change, data is aggregated, algorithms are fixed, or models are coupled. The plurality, ambiguity, and contradictoriness of social-ecological dynamics are levelled for the sake of a functioning model. Achieving a good enough fit between world, data and model for a particular model purpose has its own merit. Yet, we argue that there are political and ethical questions inherent in social-ecological dynamics such as 'Who benefits?', 'Who is accountable?', 'Who suffers?' and 'What are legitimate alternative worlds?'. These questions require a parallel multiplication of possible, contingent interpretations of the world.

Epistemic agonism addresses this tension between integration and differentiation. Starting from epistemic humility, i.e. the recognition that no way of knowing is and therefore should be essentially privileged, this tension regularly cannot be resolved within models as either/or decisions have to be made. Instead, Situated Modelling records significant differences if a decision in the modelling process erases them or makes them invisible. This record of 'lost differences' can be kept alongside the modelling process to (1) iteratively (re-) introduce some of these differences into the model and (2) consider whether other forms of representation, e.g. narrative or visual, should complement the model. Second, Situated Modelling strives for building significantly different models that encode divergent interpretations and epistemic and ethical virtues to see how these models might enact alternative worlds.

Crucially, epistemic agonism therefore involves engagement, conversation and mutual interrogation with other thought collectives. Inter- and transdisciplinary research with and around models of course has a long tradition. However, rather than simply including 'subjugating viewpoints' qua their perceived otherness and thereby reifying them (see also Haraway 1988, p. 584) we ask modellers to consciously reflect on which differences could make a difference for model construction and output. 'Others' may be stakeholders and members of the public with very different ontologies or worldviews than the Western/naturalist one. They may be human or even non-humans, e.g. when moving the computational model between programming languages, operating systems or computers (see also Principle 2). Disciplinary belonging may be a relevant difference, but fault lines can also run between methodologies. Quantitative and qualitative approaches within the same discipline may, in fact, have very little in common.

Hence agonism as an epistemic virtue helps to ground the modelling process not only in the mathematical but also in the political and ethical complexity of social-ecological dynamics. It encourages modellers to engage the plurality of efforts 'out there' to build common worlds. It builds a basis for interdisciplinary and participatory approaches in modelling. Epistemic agonism lowers the risk of having one's own position and way of being in the world reduced to a mere annexe in someone else's worldview, analytical frame or project. This is why recording significant differences and diversifying models benefits from disagreements and interventions of non-modellers, be they researchers, specialists from different disciplines or publics that eventually have to live with the model outputs. This can happen around a shared case study. But for global-scale or abstract models it may highlight the need for attention to scaling practices and conceptual foundations which may significantly impact the resulting model. These may include understandings of the global in terms of an Earth system (Schellnhuber 1999), global scapes and flows (Appadurai 1996), global assemblages (Ong and Collier 2005), the terrestrial (Latour 2018) or Gaia (Lovelock and Margulis 1974, Lenton and Latour 2018). Agonism is thus mainly about creating opportunities for disagreeing, about the model or the modelling process, from within and without the core modelling team.

Conclusion

Some of the four principles we laid out above may relate to existing modelling practices, e.g. participatory approaches. Our approach forces the researcher to query what exactly is being done under any methodological label and with what consequences. Situating research may be just as important as 'stakeholder engagement' to legitimise outputs, connect them to context, create more transparency, and enable those that use the model to judge what the new insights can be used for. Situated Modelling allows for plural world-making projects with and within models. Other contributions to this special issue initiate much needed methodological innovation by suggesting operationalisations of relational thinking (e.g. Perez-Hammerle et al. this issue; Muraca this issue). Yet, with regards to the relational turn in sustainability science we believe that a relational perspective is not only about a better understanding of social-ecological relations. Implementing one ontology at the expense of others is performative as Rickhard and Ludwig (this issue) suggest. Hence, relational thinking must in addition extend to the relationship between knowledge and world itself.

Situated Modelling can help modellers to reflect on implicit assumptions and their own socialisation more systematically and highlight previously unconsidered aspects. It further exemplifies how a relational approach to knowledge might facilitate collaboration in broader sustainability science. Understanding the situatedness of collaborating parties' knowledge practices in transdisciplinary and interdisciplinary research can help the 'consumers' of results – by pointing out that particular knowledge practices make visible specific kinds of transformations.

It has become increasingly clear that social-ecological systems are being shaped by multiple, complex, and dynamic world-making projects by humans

Table 5. Empirical example of an agonistic inquiry into junctures in modelling.

Along with our joint workshops, we also began to unpack decision-making in the construction process of a hydrological model of water quality in two watersheds in the UK developed by co-author Tobias Krueger (Smith et al. 2015). Modelling was originally meant to feed purely 'analytical' knowledge into deliberative processes but was soon opened up to stakeholder participation when Krueger joined the project. During his training as a PhD researcher, he had begun to consider stakeholder participation as a way of handling uncertainty. Krueger developed an export-coefficient type model of nitrogen and phosphorus transfers from land to water for the catchments. He parameterised the model with available data and calibrated export coefficients within ranges found in the literature. Everything was set to choose a subcatchment and vary the model variables for land use, livestock numbers and sewage treatment options to see how pollutant transfers would change against the background of the Water Framework Directive water quality status classes. Yet at the stakeholder workshops, members of the farming community rejected the model as a sensible basis for discussion. They questioned the model's focus on land use change (which was comparably straight forward to model). Eventually, they agreed on a model that instead explicitly included less intrusive *land management practices* (on which less data and knowledge existed for modelling). Krueger elicited from the farming community practices that they would consider taking up first, instead of implementing all possible ones in the model. An exchange among the co-author team on this and other modelling processes resulted in various reflections about the different ways in which the modelling process was situated. Here, we briefly point to some of them: alternative ways of slicing through reality, of designing model structure, and of engaging the social in the modelling process.
Firstly, the model constructed by Krueger cuts through reality in terms of a 'problem' rather than, for example, a research question or a system. For a model that maps a *problem*, some causes and effects need to be assumed as given. The choice to slice through the world in this way seemed situated in a desire to understand something general, and in a particular idea of generalisability of knowledge. Due to this situatedness, the researchers cut the world into pieces, first of all, according to the *similarity* between the two places (nitrogen and phosphorus exported from the watershed) rather than what may differ between the two places (e.g. specific land use activities), or according to other water quality conceptualisations.
Second, in the described model, a separation into input and output appeared situated in the desire to assess the effects of a given set of modifications of some elements on other elements. This assessment was furthermore bound to a particular time frame: the time frame needed for pollutants to transfer to a watershed, rather than, e.g. the time needed for pollutants to feed back into policymaking. This hints at a pragmatist perspective on knowledge where knowing is an ongoing process of dealing with problems. This shifts the criteria for good knowledge on the successful observation of hypothesised outcomes, an epistemological approach which is not without alternative.
Lastly, in terms of ethical situatedness the modelling approach seems situated in a particular perspective on (right) action, a particular view on people, and a political landscape in which there already exists a regulatory framework. Krueger included stakeholders in building the model and eventually responded to the farmers' wishes to include land management practices rather than using only pre-conceived land use as variable.
Some alternative choices would have been a model of the social according to, for instance, a theory of behaviour or in terms of a social mechanism, or a stakeholder engagement exercise that questions people on *how they decide* to adopt land management practices. The situated decision to engage stakeholders to gain insight on what people think about changing land use practices when confronted with the model enacts a view on people's decision-making as voluntary rather than pre-conditioned through set factors. Thus, it appears manageable. A particular implicit notion of people goes along with ethical implications. Krueger did not test action options against an outcome benchmark. He considered options among possible land use practices that concrete people said they *preferred* and thereby excluded other, potentially effective options. This implicitly enacts a notion of ethics and social order according to which the affected people, aware of a shared collective fate, seek to identify a good practice and are listened to. If Krueger had chosen to stay with preconceived types of land use, modelling would have enacted a world in which good action resides more in implementing *the best possible available option for action* given a *substantive, preconceived, universalist good*. Different notions of the good, of people and of how the social unfolds could have been enacted through other approaches to modelling, for instance by modelling aggregated individual preferences for action or including a relational element in the way those individual decisions are made.

and non-humans, operating on vastly different scales. They are entangled with complicated societal and ecological circumstances; circumstances that are full of social struggle, power inequalities, political conflict, and material uncertainty. In such circumstances, modelling itself inevitably needs to be understood as a plural practice of representation and world-making that is partial to specific political and ethical positions. Situated Modelling remains wedded to best scientific practice in the received sense of the term. In addition, however, it finds ways of addressing conflicting world-making projects within scientific practice rather than as an afterthought.

This has implications for SES management. If we take relational thinking seriously, the 'one ecosystem to manage' does not exist. Situated Modelling could help to mediate and moderate the plural social-ecological dynamics and visions that shape ecosystems by balancing, integrating and differentiating knowledges throughout the modelling process in order to build models that might enact alternative worlds. This implies that a diverse range of non-relational ways of describing the world may legitimately exist alongside relational ones.

Vis-à-vis policy and decision-making needs, Situated Modelling means that science ceases to be either a neutral arbiter or political activist. Instead, Situated Modelling fosters a debate about how far producing knowledge does and ought to put limits on what is politically thinkable. Situated Modelling acknowledges that any kind of 'management strategy' that appears plausible based on model output is always already politically and ethically positioned. It potentially opens up the terms of scientific knowledge production for public discussion. We believe that Situated Modelling thus helps to build capacities to aspire to shared futures.

Ultimately, understanding modelling as a practice of world-making provides a foundation for addressing the knowledge-action gap in sustainability transformations. Somewhat ironically, this often-lamented gap is sustained by a universalist understanding of scientific objectivity, i.e. the assumption that the best available representation of social-ecological dynamics ought to lead to the best possible world. The humbler concept of situated knowledges, instead, does not insist on a singular perspective but appreciates and works through the conflicted nature of plural world-making projects pursued in attempts to adapt to a rapidly changing planet. A relational perspective on knowledge such as applied in Situated Modelling thus challenges the conventional view that knowledge production can and ought to be separated from value judgements and politics. If knowing relates to world-making, and radical social-ecological transformation is the goal, we also have to consider radical changes in modes of knowledge production.

Notes

1. This kind of modelling co-produced 'the planet' or 'the Earth system' as a new scientific object in the 1960s/70s along with the emergence of novel theoretical concepts like Lovelock's Gaia hypothesis (see e.g. Schellnhuber 1999; Chakrabarty 2019). The very idea of a World system to be known in full and objectively is what Haraway (1988) later took as one point of departure to call for the production of partial, situated knowledges. To her, these models seemed to epitomise the god-trick
2. Of the 49 research groups that develop the about 100 models featured in the sixth and latest WCRP Coupled Model Intercomparison Project (CMIP), and the 2021 IPCC report, only 12 groups were not located in the global North. One group is located in India, the other eleven in China, Japan, South Korea and Taiwan. For a critical history of climate change research and colonialism see Mahony and Endfield (2018), Mercer and Simpson (2023).
3. Of course, in a purely Baradian view one could understand these broader contexts as integral parts of the modelling apparatus. In that sense, Principles 1 and 2 are not about micro- and macro-scale analysis, but it is a difference in emphasis. Principle 1 is about how apparatus' may be conditioned and the stable agential cuts it is predicated upon, whereas Principle 2 centres more around the question of agencies.
4. Hence, for ABMs, Anzola (2021) distinguishes between conceptual model, computational model (model structure and simulation runs), and the post-computational model of the phenomenon: 'The model of the phenomenon is the most elaborate form of representation in the simulation life cycle. It is used, initially, to make sense of emergent dynamics during the early stages of the simulation; later, it helps to test knowledge claims, following a comparison with the target phenomenon' (Anzola 2021, p. 398).

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