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Navigating the space between empirics and theory – Empirically stylized modelling for theorising social-ecological phenomena

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ABSTRACT

The potential of agent-based modelling (ABM) for developing theory has been recognized, yet methodologies are lacking. Building theories of social-ecological systems is challenging because of complex causality, context-dependence, and social-ecological interdependencies. We propose an approach that addresses these challenges through combining case-based empirical research with ABM in a collaborative modelling process. In-depth empirical research is essential for identifying a puzzle and potential explanations thereof, and for recognizing context and social-ecological interdependencies. Collaborative model building and analysis enables careful abstraction and reflection, and allows further exploring and testing the emerging theory in dynamic contexts, leading to better-grounded and transparent assumptions and theories. We call this approach BIM (Being In the Middle) and articulate it through three features: contextually embedded, collaboratively abductive and empirically stylized. We highlight how BIM facilitates new interdisciplinary avenues for discovering social-ecological interdependencies, discuss how it can be applied and what challenges and frontiers lie ahead.

1. Introduction

The need for theories and theorising to address complex sustainability problems is becoming increasingly recognized (Bodin et al., 2019; Magliocca et al., 2018; Meyfroidt et al., 2018; Sahle et al., 2024; Schlüter et al., 2022). Yet, theorising social-ecological phenomena in ways that account for their situated, complex and social-ecological nature is challenging (Preiser et al., 2018; Schlüter et al., 2022). Researchers have proposed different empirical and model-based approaches to address this challenge. Some, for instance, have begun to synthesise insights from place-based research (Norström et al., 2022) to develop more generalized knowledge in support of policy making (Alexander et al., 2019; Magliocca et al., 2018). Others have proposed archetype analysis to synthesise results from case studies in context sensitive ways (Oberlack et al., 2019). On the modelling side, researchers in the social sciences and ecology have long argued for the potential of agent-based modelling (ABM) to support theory development in complex systems (Antosz et al., 2023; Conte and Paolucci, 2014; Dilaver and Gilbert, 2023; Grimm et al., 2024; Lorscheid et al., 2019; O'Sullivan et al., 2015; Smaldino et al., 2015). However, there are few examples of model-based approaches to theorising complex social-ecological systems (SES) that have been formally characterised.

We address this gap and support theorising social-ecological phenomena by proposing an approach that combines agent-based modelling with in-depth empirical research. The approach supports theorising through a collaborative process of model building and analysis that iterates between empirical knowledge and theory, as well as contextual detail and abstraction; with the aim to explore or explain a social-ecological phenomenon. We call this approach "being in the middle" (BIM) because it sits in between highly detailed, case-specific and highly abstract, theoretical models and between empirical research and modelling. The aim of this paper is to articulate the approach and discuss

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how it facilitates building interdisciplinary theory of complex SES.

The kind of theory that we aim to build is about complex and social-ecologically intertwined phenomena. This entails that the emerging theories are not deterministic, they are context sensitive or referred to as middle range, they focus on how intertwined social-ecological processes unfold, and how phenomena emerge resulting from complex causation (Schlüter et al., 2019a). More specifically, theorising aims at providing plausible answers to specific questions or puzzles arising from empirical observations. The theories that result from a BIM process specify mechanisms and contextual conditions that bring about the phenomenon of interest. They specify how human and non-human actors interact when organised in a certain way and through this interaction may produce a particular phenomenon. Answering empirical puzzles contributes to theorising in various ways, such as discovering social-ecological mechanisms and building new social-ecological theories, expanding knowledge of existing theory to social-ecological phenomena, or challenging disciplinary assumptions, etc. Following Swedberg (2012), we speak of a theory already early on in the process of discovery, i.e. when making sense and trying to explain an empirical observation. What is more, we conceive of theorising, i.e. the process of building a theory, as a process which never ends.

The combined strengths of in-depth, qualitative, case-based research and agent-based modelling have been recognized before, yet they have so far rarely been leveraged (Alonso-Adame et al., 2024; Castellani et al., 2019). By embedding the modelling activities in the complex realities of SES in a particular location, we ensure that the model addresses an empirically relevant question, builds on different types of knowledge and is sensitive to contextual details that are deemed important for explaining a phenomenon across a class of similar cases. Yet, by focusing only on the essential details needed to explain a phenomenon across a class of similar cases, we develop theories that abstract from the specifics of any one location. This approach ensures that our models remain simple enough to be analysed effectively. By using ABM, which allows us to specify agents and interactions and trace the causal processes and mechanisms that produce emerging outcomes, we are able to develop generative explanations of a phenomenon of interest (Smith and Conrey, 2007).

We describe the BIM approach through articulating three key features and situating it in debates about the (fit-for-purpose) relation between data and model (e.g. Boero and Squazzoni, 2005), the appropriate level of abstraction (e.g. Gilbert et al., 2018) and relations between empirical evidence and theories in modelling (e.g. mid-level models (O'Sullivan et al., 2015)) or typifications (Boero and Squazzoni, 2005)). In so doing, we are specific about where and how empirical research links to modelling, where existing theories are used and how novel theories emerge. In particular, we focus on how the approach deals with the challenges of i) developing and testing possible explanations and social-ecological consequences of proposed causal mechanisms in ways that attend to complex dynamics and social-ecological intertwinedness, ii) abstracting general mechanisms while acknowledging contextual dependence, iii) working through tensions created by ontological and epistemological differences across participating disciplines (Elsawah et al., 2020), and iv) the situatedness of knowledge and its consequences for the generated understanding (Klein et al., 2024).

We have identified the key features of the BIM approach through synthesis of our experiences, as a group of interdisciplinary empirical researchers and modellers, in building ABMs of SES in the context of water governance, small-scale fisheries and agriculture for more than 15 years (see Table 1 for selected examples). In particular, we reflected on how our modelling activities addressed the challenges of theorising complex SES outlined above. Through articulating the BIM approach, we aim to encourage discussions and contribute to the debate about utilising agent-based and other simulation modelling for theory building. We conclude by discussing advantages and challenges of the BIM approach, and its use as an approach for theorising. With this paper we want to address empirical SES researchers and SES modellers alike. Bridging these communities is both valuable and necessary for SES theorising, given the lack of complexity-based social-ecological theories (Schlüter et al., 2023). We also hope that this approach of theorising through combining qualitative, case-based research with agent-based modelling can be useful for developing theories in the social sciences. While theorising from empirical evidence is nothing new in the social sciences, combining it with agent-based modelling in a collaborative approach opens up novel possibilities for discovering and scrutinizing evolving theories, as we will elaborate below.

2. Modelling social-ecological systems

Social-ecological systems have been modelled for different purposes, using different types of models with different degrees of empirical realism, ranging from empirical models of SES to support policy assessment in specific locations to fully theoretical models to describe SES phenomena (Schlüter et al., 2019b).

Empirical ABMs have a long tradition in natural resource management and SES research (e.g. Smajgl and Barreteau, 2014). They are developed using data from a SES in a specific geographic location, often with the aim to assess the response of the SES to external disturbances such as the impact of climate change or a new policy (Brinkmann et al., 2021; Zhang et al., 2023), or to explore the behaviour of the SES given certain initial conditions or structural settings. Empirical knowledge enters the modelling processes through qualitative data, e.g. from interviews, that is used to inform the choice of agent types and model rules and quantitative data, e.g. from surveys, remote sensing, hydrological or ecological data collection, to quantify agent attributes or biophysical processes and to parameterize, calibrate and validate the model. When there is no or little data, for example about human behaviour, assumptions are made based on observations, common sense, educated guesses or theory (e.g. Sanga et al., 2021a; Schlüter et al., 2017; Wijermans et al., 2023). These models incorporate many elements and processes, often at high resolution, which makes them effectively black boxes which are too complicated to meaningfully analyse their operational behaviour and identify causal mechanisms (Sun et al., 2016). These models are rarely analysed to understand how they work, i.e. what mechanisms brought about a particular outcome (Grimm et al., 2024).

On the other end of the spectrum are theoretical models of SES or social systems that are developed to study generic processes such as regime shifts (e.g. Lade et al., 2013), opinion dynamics (Flache et al., 2017) or diffusion of innovations (Kiesling et al., 2012). Theoretical models describe the SES with the help of a few fundamental processes which are represented using well-established theoretical functions such as Holling-type functions or replicator dynamics (e.g. Schlüter et al., 2016). They make no use of empirical data to model functional relationships or parameterize agent attributes or environmental dynamics. They are often simple enough to be analysed using mathematical tools as well as qualitative analysis of system trajectories. Their usefulness for understanding and addressing SES problems, however, depends strongly on how and by whom decisions are taken about which functions or rules to include and how to model them. This is particularly critical in cases when these decisions are made by modellers who have no experience or data of the corresponding real world phenomenon (Agar, 2003). In addition, the de-contextualised, highly abstract nature of these models risks missing important contextual conditions for the functioning of a mechanism, e.g. social networks may enable policy change or prevent it depending on the institutional and historical context in which they operate (Herrfahrdt-Pähle et al., 2020).

Somewhat less abstract are stylized or toy models that operate at an intermediate level of empirical realism (Schlüter et al., 2019b). They have also been described as 'specific but stylized' (Schulze et al., 2017). Stylized models use stylized facts, theoretical functions or simplified representations of actor behaviour motivated by empirical literature. They represent selected aspects of a phenomenon in order to explore the dynamics of the SES under changing conditions, such as changes in

Table 1
Models that contributed to the development of the BIM (Being In the Middle) approach.

Model (Key reference)	Exploratory question or explanatory hypothesis	Associated case study and empirical research	People involved in model development and analysis	Phenomenon of interest	Theoretical contribution
SMILI (Lindkvist et al., 2017)	What social-ecological mechanisms explain the emergence and persistence of different forms of self-governance arrangements in small-scale fisheries in Mexico?	Kino Bay Fishing village, Cooperatives in Northwest Mexico (Basurto et al., 2020)	Modeller, empirical social-ecological researcher of Mexican fisheries, SES researcher and modeller	Prevalence of cooperative self-governance in small-scale fisheries (system-level outcome)	Cooperatives can only thrive if the initial loyalty among their members is high, and they have similar reliability. Cooperatives can build up more loyalty than fisher-trader relationships which is an advantage under variable environmental conditions. Feedbacks between loyalty and cheating, and alignment between the state of a cooperative and the state of the fish population determine cooperatives' chance at survival.
PoliSEA (Orach et al., 2020)	Under which conditions can coalition formation among interest groups in fishery policy bring about sustainable outcomes for the managed fishery?	EU Common Fisheries Policy reform (Orach et al., 2017)	Empirical researcher with in-depth case knowledge and modeller; political scientist; SES researcher and modeller	Successful influence of environmental interest groups on policy making despite resource and influence disadvantage (system-level outcome)	Interest group participation in policy making can lead to qualitatively different outcomes under similar conditions. Coincidence and the right timing of coalition formation of environmental interest groups can generate a tug-of-war dynamic as a response to declining fish population and/or fishery income, which ultimately stabilises the fish population. Depending on the timing of its onset, the tug-of-war between competing interest coalitions can stabilise the fishery or reinforce the collapse.
SmallTrade (González-Mon et al., 2021)	How does the structure of socially embedded trade networks affect fish provision in the presence of catch fluctuations?	Small-scale fisheries in Baja California Sur, Mexico and the fish market in La Paz (González-Mon et al., 2019)	Empirical researcher of Mexican fisheries, SES researcher and modeller	Structure of the trade network that defines two types of traders with different network positions, and its social embeddedness in economic and social relations (system structure)	The structure of trade networks (proportion of trader types) influence fish provision at micro- (traders) and macro-levels while facing catch fluctuations. When facing spatially heterogeneous dynamics in fish availability, the connectivity of trade networks across regions leads to cascading effects between fish species and regions.
Ag-Innovation Model (Sanga et al., 2023)	How do different mechanisms of agricultural innovation influence food security and income inequality?	Food security and climate change adaptation of agriculture in Mali (Sanga et al., 2021b)	Empirical researcher and modeller, SES researchers, Malian agricultural scientists and researchers	Exogenous, foreign aid driven and endogenous, collective driven innovation mechanisms (mechanism)	i) Incorporation of social-ecological interactions in innovation dynamics influences model outcomes as opposed to only social interactions ii) Endogenous mechanism leads to higher food security and income inequality than the exogenous mechanism. iii) Bidirectional outreach is more effective than unidirectional outreach in improving food security.
AgentEx-I (Schill et al., 2016)	Can knowledge and confidence of resource users explain patterns of cooperative overexploitation?	Observations from a behavioural experiment (Lindahl et al., 2016; Schill et al., 2015)	Two SES researchers using behavioural experiments and two agent-based modellers	Sustainable use of common pool resources (system-level outcome)	Extending CPR theory beyond cooperation – able to explain patterns of cooperation and overexploitation.
FIBE (Wijermans et al., 2020)	How do differences in human behaviour/fishing styles affect a fishery?	Semi-generalisation of fishing styles based on a qualitative study of fisher motivations and practice. Fishing styles in the Baltic Sea (Boonstra and Hentati-Sundberg, 2014)	SES researchers skilled in social theory, sociological empirical case studies and SES modellers	behavioural diversity in fishing decision-making (micro-level behaviour)	Formalising available social fishery insights/theory concretely in a model. Exploring the consequences of diversity of fisher decision making and behaviour in relation to the same policy.

behavioural strategies (Dressler et al., 2018). Deliberately reducing resolution of parts of the modelled system enables researchers to focus on those structures and dynamics that are of concern for answering the research question. While many stylized models in SES research are inspired by empirical questions and challenges such as common pool resource management (Dressler et al., 2018) or poverty traps (Radosavljevic et al., 2020) and they often focus on particular types of SES such as pastoral or agricultural systems, they are not based on data from empirical research in a particular location. Instead, they are informed by the empirical literature about the type of system and phenomenon in focus.

The level of abstraction in a model is closely linked to its purpose. While highly abstract models can be used to test general theoretical principles or as an illustration or a 'proof of concept', highly detailed empirical models are typically used for prediction and policy support (Sun et al., 2016). For theorising, a degree of empirical realism is required to ensure that contextual details which are important for the functioning of the mechanism(s) are incorporated, while at the same time the model is abstract enough that its causal assumptions are relevant beyond the particular case (context-sensitive but not context-specific) and that the model remains simple enough to be able to scrutinize the functioning of the mechanism (O'Sullivan et al., 2015).

3. The social-ecological modelling that shaped the development of the BIM approach

Most of the models that informed the BIM approach have been developed in the context of governance of water, small-scale fisheries and agriculture, with the aim to understand their social-ecological dynamics and outcomes (see www.seslink.org/models/). These contexts are characterised by limited data availability, high social and ecological complexity (e.g. multi-species fisheries, diversity of actors involved in resource extraction and related activities, and innovation dynamics), and the embeddedness of resource use practices in social-ecological relations and institutions (Lindkvist et al., 2020; Sanga et al., 2023). The models were developed for the purpose of exploring how social-ecological interactions influence the adaptive capacity of a SES (e.g. SmallTrade, AgInnovation, FiBe) or for developing and testing possible explanations of observed phenomena, such as the dominance of fisher-trader relations in small-scale fisheries (e.g. Smili, PoliSEA,

Box 1
The PoliSEA Model (Orach et al., 2020)

The key empirical puzzle behind the combination of an empirical study with agent-based simulation modelling was the major fishery's policy change as a result of the EU Common Fisheries Policy (CFP) reform and the important role environmental interest groups played in its adoption. The research questions targeted by this BIM process were: *1) Does coalition formation enable disadvantaged environmental interest groups to influence policy, and if so, under which conditions?, 2) When and how can policy adapt to social-ecological change to maintain sustainable fisheries in a policy system that is dominated by industry interests?*

The BIM approach was useful and needed because existing theory offered little understanding of the causal mechanisms through which interest groups and interest group coalitions can influence policy change. Mechanisms of policy adaptation to social or ecological change are often black-boxed. Previous empirical studies of interest group influence focused mostly on the role of specific variables (such as the amount of funding or the adoption of a particular lobbying strategy) to explain interest group success, rather than tracing mechanisms through which interest groups through their interactions with each other and policy makers could attain influence. Combining a process tracing (PT) case study of the EU CFP reform process conducted by one of the team members with an agent-based model allowed us to 1) elucidate the causal mechanism that linked micro-, meso-, and macro-dynamics, such as change in interest group perceptions, lobbying strategies, and policy output; 2) identify the parts of the empirical context, important for explaining the phenomenon of interest group influence; 3) fill in the theoretical gaps in modelling the policy process and interest group responses to social-ecological change in the fishery.

The model formalised the EU CFP empirical mechanism, linking interest group responses to a perceived crisis, their resources, and lobbying strategy to their lobbying activity and success in influencing policy output (change in fishing quota). In formalising the mechanism, some assumptions could not be inferred from the EU CFP case. Instead we relied on insights from other empirical studies, for example, for setting a failure rate for coalition-building to capture that such alliances need to overcome organisational obstacles. Other aspects were stylized, relying on established theories – such as the assumption that interest groups always engage in lobbying when resources allow them to do so, or that coalitions are only formed between like-minded interest groups. Our implementation of social-ecological processes, such as catch and stock dynamics, also relied on theory and previously developed formal models. We identified these gaps and possibilities to back up our assumptions through a collaborative process, involving two sustainability scientists with varying expertise in social-ecological and policy processes, and a political scientist. Regular group meetings, where we sketched the conceptual model and discussed relevant theories and real-life cases helped us to decide which contextual elements identified in the empirical study needed to be represented in the model, and which elements could be made abstract. Both case expertise and familiarity with theory and the social-ecological phenomenon in question were instrumental to maintaining the "middle-ground" between stylized and context-bound.

We first used the PoliSEA model to test the assumption that coalition-building among interest groups influences the success of environmental interest groups and consequently, the emergence of sustainable outcomes for the managed fishery. Apart from shaping the model design, the BIM approach also influenced how we collaboratively explored the model results. We identified different outcomes produced by the model (fast decline and collapse of the fishery, slow decline and balancing) under the same set of initial conditions. We then zoomed in on individual model runs in each of the three outcome types to identify emergent mechanisms and their 'triggers' responsible for differences in dynamics. For example, the 'tug of war' between opposing interest coalitions stabilising the quota, which could either ensure collapse or slow it down, depending on its timing. The broad expertise in the PoliSEA team allowed us to reflect on the EU CFP case, other studies of interest group influence, and real-life scenarios of policy change to better understand the implications of the 'tug of war' dynamic, validate and assess the generalizability of our findings. A stylized representation of an empirical causal mechanism in combination with a collaborative exploration of model dynamics has allowed us to better understand the importance of timing for the effect of the coalition-building mechanism as well as identify the emergent 'tug of war' mechanism, playing a supporting role in ensuring or preventing sustainable outcomes. In this way, the PoliSEA model contributed to theorising about the mechanisms through which social and ecological change can influence change in policy through adaptive responses of interest groups. The empirical study identified a mechanism linking interest group participation and policy change, as well as conditions under which it activated. The model tested and developed it further by introducing a social-ecological feedback and exploring the role path dependence, stochasticity, and dynamics like the 'tug of war' for its effect.

AgentEx1). Table 1 provides an overview of all models that informed the approach. Three of them (PoliSEA, Smili, and SmallTrade) are described in more detail in Boxes 1-3 and are used to illustrate the key features of the BIM approach in section 4. For more detailed information on all models we refer the reader to the key references listed in Table 1.

While each model building process and resulting model is unique, they share some common features. First, all models address research questions that were motivated by an empirical puzzle or observed phenomenon in a particular place (e.g. Northwest Mexico), or case (e.g. the EU Common Fisheries Policy reform or the management of common pool resources). At least one person in the team conducted in-depth empirical research in the case, collecting and analysing data to answer a case-focused research question that was closely related to the modelling question. Second, the models were developed collaboratively by teams that were composed of empirical researchers and modelers from different backgrounds. The teams included researchers with experience in agent-based modelling, with knowledge of SES research and often somebody with disciplinary knowledge, such as political science or institutional economics, relevant to the particular question. In one case, the team was complemented by local researchers and practitioners from the case study region (Mali) (Sanga and Schlüter, 2025). Often, multiple team members had both modelling and theoretical/disciplinary expertise which made communication easier. Third, the models all aimed to abstract from the particular case to make a theoretical contribution.

4. BIM – being in the middle

The BIM approach is a collaborative process of model building and analysis that iterates between empirical and theoretical knowledge and between contextual detail and abstraction (Fig. 1, empirical knowledge in blue and theoretical knowledge in red). The process begins with an empirical puzzle that is posed by a case study, and a model purpose (top

Box 2
The SmallTrade Model (González-Mon et al., 2021)

The SmallTrade model aimed to explore the role of trade networks for dealing with catch fluctuations in a multi-species small-scale fishery context. It is based on the case study of a multi-species small-scale finfish fishery in Baja California Sur, Mexico where previous empirical research (using qualitative and network analyses) had revealed that trade networks are based on stable social relationships. The stability and social "embeddedness" of these trade networks represented the empirical puzzle that led the modelling process, contrasting with common assumptions that trade is based on supply and demand dynamics shaped by price mechanisms. Here, traders face variability in fish catches and struggle to meet the demands of their buyers, but also risk flooding the market with certain species at times. This empirical observation led the researchers to hypothesise that stable trade relationships help traders to deal with fluctuations in fish supply and demand (González-Mon et al., 2019), which was further explored with an Agent-Based Model. Therefore, we built the SmallTrade model with the purpose to: 1) understand trade-related processes that take place in regional trade networks embedded in social relationships; and 2) investigate how such embedded regional trade networks influence fish provision in situations of catch fluctuations, as found in spatially heterogeneous, multi-species fisheries. We focused on investigating how certain characteristics found in the empirical trade network could influence traders' capacity to deal with catch fluctuations at the individual level and for two different markets that receive non-substitutable fish species (i.e., avoiding fish scarcity at the markets when fish catches fluctuate).

The model benefited from a BIM approach that combined: a) an empirical-informed representation of trade network structures based on an empirical network collected in González-Mon et al. (2019); 2) trade processes (rules) abstracted (i.e., stylized) from the qualitative analysis of interview data; and 3) a semi-abstract representation of a multi-species fishery where actors can fish two species in two different regions. The empirically informed networks balance the level of abstraction between context-specific and abstract. Through this combination, the model is able to test the role of network structures that go beyond archetypical or theoretical networks (e.g., small world or scale-free networks). The empirically informed networks resemble the empirical network in certain characteristics such as the proportion of trader types and the number of links and its centralization, yet they can be manipulated in ways that are not possible with a model that represents the empirical network directly. For instance, it allows testing the role of different network characteristics while controlling how different networks resemble or differ with respect to the empirical network. In addition, the model remains applicable to several fishery contexts characterised by a multi-species and multi-region setting. This level of abstraction that is "in-between" a theoretical and an empirical model provides an understanding that is relevant for the case study under investigation, while allowing us to identify the role of certain trade network characteristics that we could encounter across diverse case studies of multi-species and spatially heterogeneous small-scale fisheries.

The BIM process consisted of continuous interactions between the qualitative data analysis and the model building process, facilitated by a collaborative process where the lead researcher (empirical expertise) worked closely with a modeller over the course of more than a year to co-develop the model. In addition, the model built on previous modelling and empirical experience in the case study (see Box 3), and other experts with experience in network analysis, ABM, or the local case study context, provided feedback at different stages of the modelling process. In this way, the SmallTrade model is based on empirical knowledge of the trade processes of an embedded trade network as found in the case study. The first empirical investigation informed the design of the model structure and processes, together with network and embeddedness theories. When designing the model, the need for further information about the network and trade processes became apparent, which motivated a second fieldwork campaign focussed on interviews with traders. This data collection was guided by questions that emerged during the model building process. The qualitative analysis of the interview data was done in interaction with the model building process, as new questions emerged from the model that motivated further analysis to the interview data, for example to elicit the trade mechanisms to implement on the model. Through this BIM process, the SmallTrade model helped to understand the trade mechanisms operating in the regional trade network.

In a small-scale fishery context, where data on trade networks are scarce and difficult to obtain, the SmallTrade model provided insights on how different types of empirically realistic, embedded trade networks influence the capacity of small-scale fisheries to deal with socio-environmental changes. Results highlight trade network characteristics that help deal with changing fishery contexts. This demonstrated the importance of investigating the embeddedness of regional trade networks while accounting for their spatial (i.e. geographical) connectivity and heterogeneous fishery dynamics, and helped start a process of theorising about the role of trade networks for dealing with changes in small-scale food production systems. It, for example, informed the comparative work in González-Mon et al. (2022) which further explored the role of social relations in empirical cases. More generally, this model contributes to developing theory about how social-ecological interdependencies (i.e., trade networks linked to dynamic fish populations) influence the capacity of a SES to deal with change at the individual and system level (Bodin et al., 2019).

Box 3
The SMILI Model (Lindkvist et al., 2017)

The way fishers in small-scale fisheries organise has implications for sustainable resource use and fishers' livelihoods. For example, fishers that self-organise in cooperatives are more likely to apply long term management strategies and provide equity in benefits while patron-client relations can be exploitative and focussed on short term goals. The aim of the SMILI model was to investigate why patron-client relationships dominate many small-scale fishing communities in north-west Mexico despite state support for cooperatives. In particular, it was developed to investigate whether heterogeneity of fishers' reliability, organisational characteristics of different self-governance forms (e.g. the dynamics of trust) and the fish population, through their dynamic interactions, may explain observed differences in self-governance arrangements.

The model was developed through a multi-year collaboration between agent-based modellers and SES researchers with a Mexican fisheries researcher interested in institutional dynamics in divers, local contexts. Generalising from knowledge on fishery organisation and the case of Northwest Mexico, the broader goal was to develop theory on how organisations emerge using the agent-based model as a tool for synthesising knowledge and unravelling key mechanisms for when cooperatives vs fisher-trader relations emerge in small-scale fishers. The model was thus empirically grounded in the realities of small-scale fisheries in Northwest, Mexico, but stylized in that it represented selected features of the system in a qualitative and slightly abstracted way. An empirical model based on quantitative data would not have been possible because of lack of data on key decision making or social processes. It would have also been of limited value because of its specificity for a particular case. A purely theoretical model for small-scale fisheries would not have been possible given the large gap in theoretical knowledge on the emergence of cooperative vs non-cooperative forms of self-governance in fisheries research.

The entire model design and analysis process was highly collaborative and took place over about two years with several in person workshops and weekly to monthly online meetings. The modelling team consisted of three core team members which enabled a close and frequent collaborative style where all model details and analysis was a team effort rather than left to individuals. The modellers and the case expert were thus part of the model design, analysis, and interpretation of the simulation outcomes in relation to the case.

When the empirical expert or other published data could now answer questions raised in the modelling process, additional data was collected thanks to the case expert frequently visiting the case study. The SES framework by (Ostrom, 2009) was initially used to identify key variables in the case study relevant for explaining self-organisation. In collaboration with the team, theory on cooperatives and patron-client relations were used to support, challenge and discuss the model design decision and its simulation outcomes. In the model development process the team realised they had limited knowledge on how patron-client relationships actually work in detail in small-scale fisheries around the world. This led to hiring a research assistant to investigate this phenomenon more broadly to understand implications of the simulation outcomes and how generalizable the implementation was.

The model analysis helped unravel an intriguing interplay between the macro- (the fish stock, the population of fishers, the numbers of coops and PCs), meso- (the success of cooperatives and PCs) and microlevels (fishers' reliability and loyalty), which would have been impossible to study empirically. The collaborative approach in combination with the empirical and theoretical knowledge strengthened the results and its contribution to middle-range theorising about self-organisation and collective action in common pool resources, particularly the interplay of different social and ecological processes across levels. Through the collaboration, the empirical expert was able to present insights to the Mexican government on the importance of understanding fishers and local context when pushing for e.g., cooperative forms of organisation in fisheries. In this way it also contributed more directly to action, not only to theorising.

two wedges of the outer circle in Fig. 1). The purpose of the model is specified when iterating between the questions of the case study and the conceptualisation of the model. Once defined, the choice of a purpose has a strong path-dependent effect on the remainder of the process, such as on the level of abstraction of the resulting model (Sun et al., 2016). For example, a model that aims to explore the consequences for fish provision of social ties between traders (SmallTrade) abstracts less from the details of human social interactions than a model that aims to explain the success of a particular actor in influencing policy (PoliSEA). Each BIM model emerges from a collaborative process that involves empirical researchers –who have investigated the phenomenon of interest through a SES case study in a specific location– domain experts, and modellers. They bring different types of knowledge to the process of conceptualizing the mechanism of interest and the overall structure of the empirically stylized model (arrows and inner circle of Fig. 1). These components interact at almost all stages of the modelling cycle, albeit in different ways at different stages (depicted as meandering lines differing in colour and line type in Fig. 1, in Fig. 2, and elaborated in Boxes 1-3).

In the context of BIM and Fig. 1, *case study* refers to the learning outcomes of an in-depth empirical study or a behavioural experiment that was conducted by members of the team. It represents the knowledge researchers gained from engaging with the empirical realities in a particular place or from observing how players play in behavioural experiments. This knowledge is rich and contextual; i.e. it includes observations of complex interrelationships and contextual details. *Empirical knowledge* refers to insights from the literature, either from published case studies or synthesized empirical knowledge from comparative research (Magliocca et al., 2015). We make a distinction between knowledge from in-depth empirical fieldwork in a particular place and published empirical knowledge in order to emphasise the importance of real-world experiences for developing ideas about possible explanations of an empirical explanation. Field research not only provides qualitative and quantitative data, but also tacit and experiential knowledge which influences the way a researcher conceptualises the question, an explanation or key social-ecological processes (Johansson et al., 2024).

Theoretical knowledge refers to knowledge from existing, often disciplinary theories, which help identify and specify (parts of) a mechanism and guide the selection of what details to include in an explanation that is valid beyond the particular case. For example, our research of traders in Mexican small-scale fisheries was inspired by the concept of social embeddedness from economic sociology (Box 2 SmallTrade), while theories of policy change informed the case study and the model of fisheries' policy making (Box 1 PoliSEA). Limitations of these disciplinary theories when it comes to social-ecological processes, such as the impact of feedback from the ecosystem (e.g. changes in resource availability), however, are one of the main reasons why it is important to combine theoretical knowledge with knowledge from an in-depth case study.

In the following, we present three features of the BIM approach that have emerged as common to all models, and serve as key principles for characterizing it. The distinction of the features is a purely analytical one. In the practice of modelling using a BIM approach, the three features do not follow each other in a linear fashion, but are intrinsically

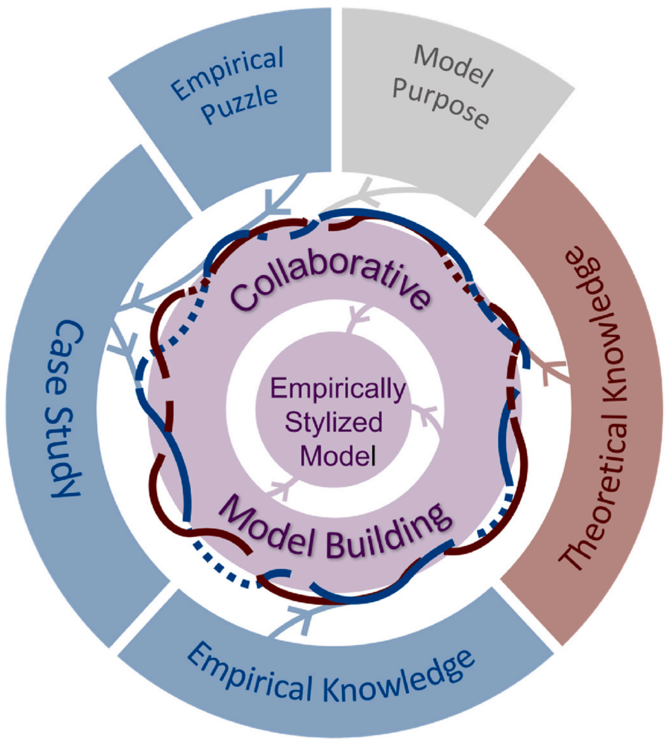

Fig. 1. Representation of the BIM approach and its three features: The outer circle represents its empirical embeddedness through building on a case study of a particular SES, as well as the different knowledge sources that are part of the abductive process of building the model (empirical knowledge in blue and theoretical knowledge in red). The middle circle represents the abductive and collaborative model building process, during which the different knowledge sources are brought into deliberations and reflections that result in the model structure. The meandering lines in different colours and types depict the dynamic process of integrating the different knowledge sources (colored lines), showing that the intensity of the input from the different sources can vary (dashed and full lines). The inner circle represents the resulting model which is both stylized and empirically grounded. The two wedges at the top show that the empirical puzzle identified in the case study and the model purpose (description, exploration or explanation) are the starting points for the BIM process. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

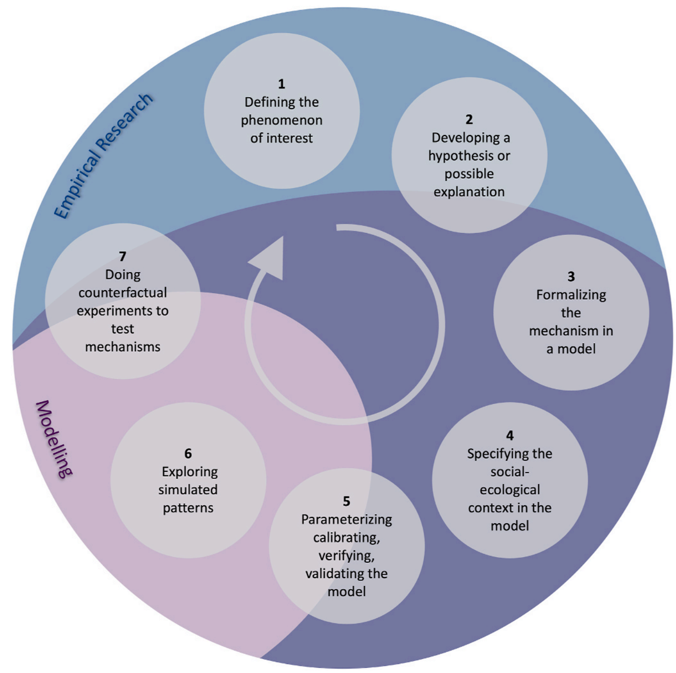

Fig. 2. Interactions between empirical research and modelling during the BIM process. The blue area indicates activities that primarily involve empirical research, the light purple area those that are largely related to modelling. The dark purple intersection contains those activities where empirical research and modelling strongly interact, e.g. through involvement of empirical researchers in the modelling or through complementary field research. The positioning of activities 5 and 7 indicate that they are largely in the domain of modelling, but are informed by the particular case, e.g. when setting parameter values, assessing the credibility of model outcomes or developing scenarios. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and intricately linked and continuously influence each other.

4.1. ***Feature 1: contextually embedded*** *– inspired and informed by in-depth empirical research in specific SES*

The feature *contextually embedded* refers to the tight connection between the modelling process and empirical research in a particular SES, such as small-scale fisheries in Northwest Mexico (see case study in Table 1). The interaction between empirical research and modelling is important to ensure that the model addresses an empirically relevant question and that the practice of theorising is situated in real-world social-ecological complexities. The case study is the origin of the empirical puzzle that initiates a BIM approach and it is essential for generating first ideas and hypotheses about possible causes and consequences of an observed phenomenon (Fig. 2, processes 1–4). By including researchers in the modelling process who have a relation with a particular place, the reasoning process is enriched by intuition and imagination that stems from their observations, experiences, insights and tacit knowledge (Agar, 2003; Swedberg, 2012). This helps develop conceptualisations that do justice to the social-ecological complexity and context-dependence of the phenomenon. These first conceptualisations direct the modelling process, both by defining its purpose and presenting a "hunch/potential explanation" that will be explored through the model development and analysis process.

The PoliSEA model (Box 1), for example, was inspired by the puzzle of the success of environmental interest groups in influencing EU Common Fisheries Policy despite their weaker economic and political position compared to industry groups. A member of the modelling team conducted an empirical study using process tracing which identified coalition formation as a mechanism that may explain this puzzle (Orach et al., 2017). The case study thus provided the phenomenon of interest – environmental interest group success in shaping policy adaptation towards more sustainable management – and coalition formation as a possible empirical explanation of it. The purpose of the model was to test whether coalition formation could indeed explain the success of environmental interest groups in influencing policy outcomes and to explore the functioning of the mechanism in a dynamic social-ecological environment. The empirical study of interest group involvement in the EU policy reform process was essential for identifying the mechanism, but also for providing contextual details about the institutional setting and interactions between key actors that were critical for its effectiveness.

The purpose and design of the SmallTrade Model (Box 2) was inspired by field research of a team member on the social embeddedness of trade relations in small-scale fisheries in Baja California Sur, Mexico. The fieldwork, which included interviews and participant observation at the local fish market as well as social and social-ecological network analyses, revealed the prominence of relatively stable trader networks which are shaped by moral commitments between traders (González-Mon et al., 2019). The study found that there are different types of traders with different connectivities, and hence abilities to exchange fish with other traders, which were hypothesised to affect traders' capacity to face times of fish scarcity and market gluts. This raised questions about the importance of social embeddedness for traders' ability to adapt to changing fish supply, and more generally, the importance of cross-scale social relations and networks for trading, which is often conceptualised solely as an economic exchange. The purpose of the model was to explore the effect of social embeddedness on the provision of fish to a regional market under conditions where fish availability varied spatially and temporally. The empirical study was essential for uncovering the social relationships between traders and their effect on fish trading and raising awareness about their potential role for the resilience of fish provision.

As indicated by the two examples, insights, experiences and data from in-depth empirical research are also an essential input to the abductive process of developing a representation of the hypothesis or explanation in the model, and for identifying which contextual factors or processes are relevant for the phenomenon of interest and thus need to be included (see Features 2 and 3). Throughout a BIM process, modelling and empirical methods are combined, which may require multiple iterations between the empirical case study and the modelling process. For instance, it may be necessary to go back to the field and apply different empirical methods to generate understanding of key processes or mechanisms, as in the SmallTrade modelling process (Box 2). In addition, the model building and analysis process itself is a way of interrogating the empirical data, e.g. by helping to examine the empirical evidence in more depth and identifying open questions and data needs for further empirical research. Validation of model structure and outcomes in a BIM approach is thus done at every single step of model development and analysis.

In summary, the feature *contextually embedded* highlights that a BIM approach always begins with an empirical puzzle from a case study and initial ideas and hypotheses about what constellations of social-ecological interactions may explain the puzzle. The in-depth case study is also critical for providing contextual knowledge for the process of abstracting the hypothesis or possible explanation into the virtual world of the agent-based model during the modelling and analysis process.

4.2. *Feature 2: collaboratively abductive – built and analysed through an abductive and collaborative process*

The feature *collaboratively abductive* refers to the process through which the model is developed and analysed. This includes conceptualizing the phenomenon of interest, identifying a potential explanation and formalising this explanation in an agent-based model (Fig. 2, processes 2–4). This process is **abductive** in that it starts with the observed phenomenon and seeks to explore or explain it using empirical and theoretical knowledge, as well as intuition and speculation (Sætre and Van de Ven, 2021; Swedberg, 2016). Tavory and Timmermans (2014) refer to abduction as 'pragmatic theorising with a focus on creativity as a logic of inference'. The BIM approach facilitates creative processes of abduction through providing spaces for dialogue across different types of knowledge (empirical, theoretical, tacit, experiential) from different knowledge sources (from a particular place, from empirical studies, from theory, and multiple disciplines). Throughout the modelling process diverse, multidisciplinary understandings of an observed phenomenon are negotiated, integrated or contrasted, which facilitates joint sense-making of the complexity of the real-world problem at hand (Alonso-Adame et al., 2024).

The abductive process of developing a possible explanation and formalising it in an ABM is carried out **collaboratively**. The co-construction of the model by empirical researchers and modellers ensures that the process builds on both a diversity of knowledge and a tight connection to the complexities of a real-world case. During this collaboration all participants are involved in making critical decisions about the design of the model (Gilbert et al., 2018; Schlüter et al., 2019c). The collaborative nature of this process is particularly important for dealing with three challenges: 1) boundary setting, i.e. making choices about what goes into the model and what not; 2) bringing together insights from the case study with generalized empirical and theoretical knowledge from different disciplinary perspectives; and 3) interpreting simulation results by drawing both on familiarity with the case as well as theory and insights from other cases. Defining the boundaries of a complex system is one of the most difficult tasks of developing an agent-based model (Lorscheid et al., 2019). Decisions about what elements and relations go into the model and what makes a difference in the kind of world that is modelled (Agar, 2003) are critical because they determine what the model can do and what knowledge will be generated. For BIM, it is important that boundaries are set in a way that is sensitive to context-specific details and ambiguities (Lazurko et al., 2023). This requires deliberation that puts all understandings and views on the table to discuss, reflect, contest and "negotiate" what goes into the model and what not.

The way we brought empirical and theoretical understanding to bear in discussions of boundary setting among all participants was unique to each BIM process. In the SMILI model (Box 3), for example, ideas about factors that may explain the dominance of fisher-trader relationships over fishing cooperatives were developed by building on observations of the empirical researcher in the team who has worked in Mexican fisheries for many years, as well as data from a two-year diary of a fish buyer, empirical literature on self-governance in small-scale fisheries and common pool resource theory (Basurto et al., 2020). The collaborative process started with frequent meetings of the modeller and the empirical researcher over many months to identify the research question, the purpose of the study, and relevant explanatory factors. The team identified history of cooperation, reliability of fishers and the dynamics of trust as key variables influencing why cooperatives or patron-client relationships emerge. When there were questions about how to formalise e.g., an agent behaviour or an interaction, that could not be answered by the team, additional research was performed, through literature studies or additional field work.

When building the PoliSEA model (Box 1), the team, composed of a political scientist, a social-ecological researcher and a researcher with a political science and social-ecological background, met regularly to move from the conceptual model "sketch" that was informed by the empirical process-tracing study to experimenting with different versions of the model in order to scrutinize and test the empirical causal mechanism. In doing so, the team iterated between the empirical mechanism of coalition formation, other empirical studies of interest group influence, and theories of interest group influence and the policy process. This ensured that choices about the agents and their attributes, their behaviour, (e.g. when an interest group would build a coalition) and interactions with the social-ecological environment (e.g. through the perception of a crisis in the fishery) were based on the best available knowledge that was plausible given the empirical case study. This iteration between rich empirical insights and theoretical knowledge of the phenomenon also enabled creativity in hypothesis generation and further exploration of the case-based causal mechanism, which in turn, assisted the 'discovery' phase of theorising (Swedberg, 2012).

Our experience has shown that such a dialogue between empirical researchers and modellers is both fruitful and challenging because it can create tensions and participants may feel uncomfortable (Freeth and Caniglia, 2020). Tensions and uncomfortableness may arise, for instance, when ambiguities in the empirical data need to be reduced to a rule or a number in order to operationalize a process in the model. For example, in the SmallTrade model (Box 2) there was no clear empirical answer about whether the trader offers to sell or requests to buy the different fish species, because depending on who was interviewed and where, both options were discussed. This raised questions about how to represent this decision in the model. In this case, the team chose to include both mechanisms in the model (top-down request for fish based on demand and bottom-up offering fish based on the fish available until all trade possibilities were exhausted). Such technical solutions are, however, not always possible or desirable. It is important that tensions are acknowledged and dealt with in constructive ways that do not brush concerns away, and that the process of model conceptualisation remains open as much and as long as possible (McDowall and Geels, 2017). Closing down on particular choices is not about removing ambiguities in order to develop unified theories, but rather, acknowledging that no theory or theory building approach can capture all aspects of and perspectives on complex SES (Hertz et al., 2024; Schlüter et al., 2024).

In summary, the feature "collaboratively abductive" highlights the importance of collaboration between empirical researchers and modellers to enable a creative abductive process that is sensitive to contextual complexities of SES phenomena and integrates insights from empirical evidence and disciplinary theories from different fields.

4.3. *Feature 3: empirically stylized – a level of abstraction between context-specific and fully stylized*

The feature *empirically stylized* refers to the level of abstraction of the resulting model, which can vary significantly, but will always lie between the level of detail of an empirical model and the simplicity of a theoretical one. We call the models that emerge from a BIM process empirically stylized because they differ from stylized models or stylized facts. Contrary to stylized models, BIM models are developed based on qualitative data from a particular empirical case study, and thus include more contextual details than stylized models that build on generalized insights from empirical literature. They are different from stylized facts, defined as empirical regularities in the need of explanation (Hirschman, 2016), because they are models that serve to develop and test explanations of empirical observations (not the observations themselves). Finally, they differ from stylized facts as a synonym for theories (Meyfroidt et al., 2018)) because of the collaboratively abductive process through which they are derived. *Empirically stylized* highlights that the models are stylized but that how they are stylized is determined by the empirical context in which they are embedded (Feature 1) and the careful process of abstracting from it (Feature 2).

A mid-level of abstraction is important in order to be able to analyse the dynamics of simulation runs and assess the workings of the mechanism. Through simulation experiments we can analyse the causal pathways that generate an observed model outcome (Fig. 2, process 6–7). Unpacking the causal structure of the model involves tracing agent interactions, collective outcomes and biophysical dynamics to develop a narrative explanation (Millington et al., 2012). In the PoliSEA model, for example, we investigated and compared simulation runs that led to qualitatively different outcomes. This enabled us to identify conjunctions of specific events, e.g. a particular activity of an individual or collective agent that coincides with a particular state of the environment or other agents in a way that creates a path dependency that moves the system onto a particular trajectory. Our analysis of the causal narratives of individual simulation runs also revealed a tug-of-war dynamic that was triggered by resource poor groups forming coalitions while resource levels were still high. This created a path dependency that stabilised the fish population. Analysing causality also involves doing counterfactual experiments where parts of the mechanism or its conditions are removed or changed to test whether the phenomenon would still emerge (Magliocca et al., 2023) (Fig. 2, process 8). For example, we conducted experiments with the PoliSEA model where conditions for industry influence were changed in order to test under which conditions the tug-of-war mechanism stabilises fish population dynamics.

In practice, finding the suitable level of abstraction requires experimentation and deliberation through iteration between case-specific insights, existing empirical and theoretical knowledge and the constraints and needs of the developing model (Fig. 1). Finding the right level of abstraction involves choices about what the elements are, which elements and processes to include and which not, and at what level of detail. In the SMILI model, for example, we simplified the diversity of self-governance forms in the Mexican fisheries into two prototypical forms, patron-client relationships and cooperatives, which are at opposite ends of a spectrum found in the field. We also simplified fish population dynamics to a population level process represented by a common bio-economic model, i.e. the Gordon-Schaeffer model. In SmallTrade, however, we slightly increased social-ecological complexity to include two different hypothetical fish populations that are located within two spatially separate regions in order to assess the effect of spatial variability.

This mid-level of abstraction implies not only a simplification of model structure to the key elements of the mechanism and its social-ecological context, but also that the model is not directly parameterised or calibrated with quantitative data from the case study (Fig. 2, process 5). Instead, parameter values are set to correspond in magnitude with empirical values, to be internally consistent among themselves, and with a reference scenario. In the PoliSEA model, for example, we gave industry interest groups twice the amount of resources and influence than environmental groups, to reflect their larger influence in the EU policy process. In the SmallTrade model, we did not directly use the empirical social networks of small-scale traders in La Paz, Mexico. Instead, we included simulated networks that have the same key properties as the empirical ones. This allowed us to manipulate the networks to investigate the consequences of changing particular structural features. Our models are typically calibrated against a theoretical reference scenario; for example, an economically optimal fishery where all fishers harvest at levels that correspond to maximum sustainable yield. The calibrated model then serves as a reference against which different initial conditions, parameterizations or alternative model structures are compared.

In summary, the feature "empirically stylized" indicates that a model that results from a BIM process has a mid-level of abstraction that is achieved through a careful, collaborative process of abstracting using different types of empirical and theoretical knowledge sources.

5. Discussion

Through articulating the BIM approach, we contribute insights from social-ecological modelling to discussions about theorising initiated by Lorscheid et al. (2019). BIM is an approach for building complexity-aware, social-ecological theories – that is, theories that conceptualize SES phenomena as emerging from complex social-ecological interactions (Schlüter et al., 2019). While there are other approaches that use modelling to arrive at empirically valid theory, such as synthesising empirical models of a certain class of systems (Antosz et al., 2023), e.g. through a systematic literature review (Achter et al., 2024); or starting with an empirical model and then modelling that model with a simpler one (Lafuerza et al., 2016); BIM is unique in its focus on developing theory through a collaboratively abductive process of building a model that involves modellers and empirical researchers to jointly explore and test an empirical hypotheses. By situating the process in real world contexts, BIM advances our ability to theorise in embedded ways that account for the context-dependent, dynamic and social-ecological nature of SES and produce theories that are useful for action (Miller, 2015; Schlüter et al., 2022).

The BIM approach contributes to SES research in multiple ways. First, it enables the discovery of new social-ecological interdependencies and their importance for theorising SES dynamics. Joint deliberation and critical reflection of assumptions among diverse participants of a BIM process can facilitate new ways of thinking about what determines the emergence of a particular phenomenon and how (Schlüter et al., 2025). Second, BIM provides an approach for navigating the tension between context-dependence and abstraction when theorising social-ecological phenomena. In this role, BIM serves as an approach to explore the middle-range when building middle-range theories, e.g. by supporting a process of careful abstraction from empirical cases, exploring hypothesised mechanisms in dynamic SES contexts and testing the conditions under which the proposed mechanisms hold (Schlüter et al., 2019c). Third, a BIM process supports explicit reflection on the interdisciplinary dialogue that brings insights from both theory and empirics together. Such reflection creates awareness about the situatedness of knowledge (Klein et al., 2024) and its consequences for the insights generated. Finally, by making explicit and transparent how a model was developed under the BIM approach, the modelling practice becomes both more rigorous and recognisable, but also open for questioning, validation and critique.

5.1. New avenues for discovering and theorising social-ecological interdependencies and building middle-range theories

The main aim of the BIM approach is to support the process of conceiving a theory, that is, the endeavour to articulate, flesh out and develop the potential of a theory (Schickore, 2022). The development of the empirical hypothesis, the collaboratively abductive process of building the model and its refinement through many iterations facilitate the making of a theory. This situates the BIM approach within the context of discovery (Schickore, 2022), which has traditionally received less attention. Yet, some activities within the BIM approach are also aimed at assessing the emerging theory (context of justification). For example, the theory and its epistemic support is assessed when making sense of the available evidence and existing theories, or when weighing different evidential support during the collaborative model development, or when doing counterfactual experiments or testing alternative mechanisms. This provides justificatory support to the model outputs and hence, the theory the model represents. As a result, the BIM process leads to more robust theories that are more coherent with both empirics and theory from multiple fields.

The building and analysing of an ABM is one step in the process of developing and refining an emerging theory iteratively with empirical research. The model is an implementation of a theorized empirical mechanism (such as coalition formation) in the context of the virtual world of the model (i.e. the social-ecological context of the mechanism). Exploring and testing the mechanism through simulations with the model serves two purposes: 1) it further develops the theory by specifying dynamic aspects which are rarely part of empirical theories but are critical for complex adaptive systems; 2) it facilitates validating the theory through testing whether the hypothesised mechanism can actually grow the phenomenon.

The interdisciplinary and cross-method dialogue a BIM approach enables, its embeddedness in real world contexts and its capacity to simulate and analyse the workings of hypothesised causal mechanisms are critical for its capacity to support theorising. Social-ecological research requires cross-domain and cross-method dialogue because of the social-ecological nature of the problems of interest and the need to bring together different types of evidence from different disciplines and approaches. In addition, intuition and speculation that is part of the abductive process benefit from a broad array of expertise and backgrounds. A dialectic group process of integrating multiple hunches, for instance, increases the likelihood of developing a "breakthrough idea" (Sætre and Van de Ven, 2021). Our experience has shown that the dialogue between empirical researchers and modellers enhances the knowledge that is produced and supports balancing the tension between empirical realism and a useful level of abstraction. The reflection and reflexivity that take place when participants with different backgrounds interrogate each other's assumptions, or when ambiguities in how to interpret empirical data are revealed, contribute to enhanced understanding of the phenomenon and the abilities of the emerging model. The deliberations also enable a deeper reflection on the available knowledge, which leads to more consistent and better-grounded assumptions and emerging theories. They may also enhance consistency between different perspectives (Antosz et al., 2023) and raise awareness about the situatedness of knowledge and its consequences for the generated theories (Klein et al., 2024).

The collaborative and abductive process is particularly useful for exploring and theorising about unknown or uncertain social-ecological interdependencies, such as the social-ecological relations of fish trading (SmallTrade). This is because BIM supports a reasoning process that is more open to possible, alternative explanations that differ from established, often disciplinary, knowledge. When the process of abstracting a hypothetical causal structure of the phenomenon builds on direct experience of studying a complex problem in the field (experienced complexities (West et al., 2019)), the discovery of factors that have not been theorised before becomes more likely. When this understanding is brought into critical dialogue with knowledge from other cases and theories through a modelling process, complexities and their consequences can be explored in ways that can be more open, diverse, integrative and systemic than if a modeller alone uses empirical data to develop a model based on commonly used representations of social or ecological processes.

5.2. How does BIM differ from other modelling approaches?

None of the individual parts of a BIM approach are necessarily unique. What is novel and different is how BIM brings these parts together into a methodology for theorising social-ecological phenomena by building on insights and approaches from empirical social and social-ecological sciences, from social simulation, ecological, social-ecological and participatory modelling. In its entirety, the approach differs significantly from dominant modelling approaches in social-ecological systems research. While it has commonalities with approaches from social simulation that merge qualitative and computational methods to explain highly contextual phenomena (e.g. Dirksen et al., 2022; Nespeca et al., 2023), BIM goes beyond using the in-depth, qualitative case study solely as the source of data for the model, but also as the source of the puzzle and initial theory and knowledge for careful abstraction into the model during collaborative model building.

There are key differences to other modelling approaches, particularly agent-based models of SES for policy or impact assessment in particular land- or seascapes (Grimm et al., 2024; Lorscheid et al., 2019). First, case-based empirical research is not relegated to serving the data needs of the ABM, it is an integral and equal partner to the theorising process and a stand-alone research project. Engagement with the empirics is necessary *before and during* the modelling process in order to recognize context dependencies. The importance of the empirical case study for defining the research question and purpose of the model also distinguishes it from many other modelling approaches that are developed through engagement with existing literature and theoretical frameworks (Dilaver and Gilbert, 2023).

Second, in a BIM approach all participants are involved in decision making and co-design throughout the entire modelling process, albeit with different intensities at different stages and in different implementations of the approach. This process of co-modelling is very different from expert elicitation, which is much more unidirectional and not about co-designing the model. In some ways BIM is similar to some forms of participatory modelling (Basco-Carrera et al., 2017), where the participants come from diverse disciplines and research traditions. The model-building process and the emerging model serve as boundary objects which can help address obstacles related to a lack of a shared language, ambiguities, different theoretical commitments, perspectives and research interests (Schlüter et al., 2019). It forces participants to be explicit about their assumptions and thus provides a platform for critically questioning them and negotiating what will be included in a model and what not. So far, we have largely engaged in collaboration between empirical researchers and modellers. The inclusion of stakeholders and their practical experience in the co-development of the model is a potential next step in developing the approach.

Third, the resulting models are abstract enough to serve as a device for thinking about theoretical possibilities (Ylikoski and Aydinonat, 2014), but detailed enough to incorporate important real-world complexities to make insights relevant for addressing sustainability problems in concrete locations. The empirically stylized models that result from a BIM process are a type of mid-level model (O'Sullivan et al., 2015) and similar in nature to typifications (Boero and Squazzoni, 2005), yet they differ from the latter in the process that generated them. Typifications, for example, are developed through synthesising some general features of a class of empirical phenomena and thus rely less on insights from a particular case study than a BIM model. The extent to which empirical research and researchers are a central part to a BIM modelling process, also distinguishes it from other stylized or toy models of SES.

5.3. How to use a BIM approach

Our models are a good illustration of the diverse ways in which a BIM approach can be realised. While they all share the three features, contextually embedded, collaboratively abductive and empirically stylized, they differ in the compositions of the teams, the way the collaborative process was realised and the level of abstraction of the resulting models. What underlies all our BIM modelling processes is the aim to account for the complex, context-dependent nature of social-ecological phenomena and the need for reflexivity when specifying social-ecological interactions and mechanisms that are hypothesised to be important drivers of SES dynamics. A BIM approach does not prescribe a particular way of realizing the integration between empirical research and modelling, the design of the collaborative process or the level of abstraction of the model. Our aim is to provide an approach for reflexive and rigorous theory building that builds on some core principles but is flexible in the details of its implementation. This breadth is important because it allows answering different types of questions, tackle different types of puzzles and accommodate different epistemologies, research contexts and practical limitations.

During all our BIM processes, there were frequent interactions between empirical researchers and modellers over an extended period of time and across all modelling stages. Key decisions about what to include in the model and how, were almost always taken together. In one case, each line of the core model code was co-developed (AgentEx - Table 1). In others, the conceptualisation of the model was co-developed during one or several workshops, followed by a series of meetings between the modellers and the empirical researcher(s) to discuss key decisions during implementation. The number of meetings is not decisive. What is important is that there are enough moments of interaction and dialogue to allow for building a shared language, and for enabling the critical and reflexive dialogue that is essential for the abductive process. It is also important for surfacing and working with differences in understanding, in perspectives and theoretical commitments and reflecting on the consequences of choices made when specifying the model.

In practice, the process of combining rich, empirical insights with modelling can be challenging. There is no set procedure for how to "translate from an explanation that rests on layers of tacit and fuzzy knowledge to a coded rule … " (Agar, 2003, section 1.1). Several social sciences have developed methodologies for theorising from case studies such as creative synthesis (Zittoun, 2017), interpretive comparative research (Chabal and Daloz, 2006), abductive reasoning (Sætre and Van de Ven, 2021), and mechanism-based theorising (Ylikoski, 2018) which can support this part of a BIM process. Yet, these methodologies do not involve modelling or a collaborative process between researchers that are rooted in different epistemologies which can create additional challenges (Elsawah et al., 2020).

A dialogue between researchers who differ with respect to the methods they use, their underlying assumptions and different perceptions regarding the validity, quality and meaning of data can be challenging (Elsawah et al., 2020; for an example of this tension see McDowall and Geels, 2017). When combining different perspectives it is thus important that their underlying assumptions are made explicit and potential (in-)compatibilities assessed (Hertz et al., 2024). Navigating the different epistemologies that participants bring to the collaborative model building process requires interdisciplinary skills, such as epistemic agility (Haider et al., 2018) and an ability to recognize and negotiate the ethical-political dimensions of research methods (West and Schill, 2022). BIM requires all participants to be open and respectful towards the respective other field and method and have some cross-domain competencies. For example, case study researchers should have some familiarity or at least appreciation of agent-based modelling; while modelers need to have some familiarity or at least appreciation of ethnographic and other qualitative case study methods. Principles such as those of situated modelling are useful guides for implementing open, reflective and reflexive modelling practices that accommodate different perspectives (Klein et al., 2024).

To be able to assess the emerging theory and the process that generated it, it is important that the justification for choices about what to include and the decision about what to leave out are transparent and clearly communicated. Yet, despite recent advancements in model documentation (Ayllón et al., 2021; Secchi et al., 2024), best practices and protocols to systematically document the model development process are still lacking (Grimm et al., 2024). In particular, it remains a challenge to document the process of bridging creatively between multiple epistemologies. One way forward to address this limitation could be to include questions about the positionality of involved researchers, and the research context of the modelling activity, as well as aspects that were discussed but left out into documentations such as the ODD and ODD + D protocols (Grimm et al., 2020; Müller et al., 2013).

Another challenge is the high demand on resources and time that the BIM approach may entail. Both empirical, field-based research and the development of agent-based models require a lot of work and different skill sets. Combining them thus easily explodes the need for time, skills and resources. This is another reason why collaboration is needed, so that multiple researchers can carry the burden and provide the skills for the different research components. The multi-method approach of BIM is also challenging when it comes to publishing the resulting insights, because of the need to describe the different methods used and the insights gained from the case study and the modelling. This easily goes beyond what can be presented in a single article. When publishing results from a BIM process, we often separate the work into several papers that describe particular parts of the theorising process and its outcome, such as the theory developed through the empirical case, the modelling, etc (see e.g. the PoliSEA model).

5.4. Research frontiers

Many important conceptual and technical frontiers remain for the BIM approach and ABM for theory building in general. A conceptual frontier for BIM lies in defining the scope of a theory and justifying its claims through additional fieldwork or modelling. The emerging theories are validated and tested throughout the process, particularly when doing counterfactual simulations. Yet, more work is needed to develop methods for assessing the types of configurational theories that result from a BIM process (Furnari et al., 2021). A related technical frontier lies in the development of methods to analyse how a particular model actually works (Grimm et al., 2024), i.e. identifying cause-effect relations and causal pathways that produce particular simulation outcomes and to develop criteria for counterfactual experiments to test causal assumptions. Furthermore, the empirical stylized nature of the models and the theorising purpose raises questions about what type of validation strategies are needed (Boero and Squazzoni, 2005), something we could only hint at; and about their contribution to addressing sustainability problems that warrant further work. Finally, more research is needed to better understand how insights that are generated through an empirically stylized model ultimately feed back into empirical realities, both in terms of enhancing understanding of particular places and informing policy and governance for sustainability. Being explicit about BIM allows researchers to reflect on their research process, raise awareness about challenges and tensions when modelling SES and move towards building middle-range theories.

6. Conclusions

We propose an approach of combining empirical research with simulation modelling to build theories of social-ecological phenomena through collaborative, abductive ways of navigating the space between complex, rich empirical realities and theoretical abstractions. The iterative process of stylizing empirical knowledge and contextualising theoretical knowledge through the model building process generates models that are context sensitive but not context specific. A BIM approach is particularly useful in cases where the empirical puzzle cannot be explained by existing (disciplinary) theories because of the complex and social-ecological nature of the phenomenon, or because existing theory is too abstract and thus neglects contextual factors that are highly relevant for the phenomenon of interest. It is also useful in cases where it is unclear which of multiple, alternative theories that provide viable explanations provides the best possible explanation.

While the use of ABM for exploration and explanation with the aim to theorise has been described and discussed before (Grimm et al., 2024; Lorscheid et al., 2019; Schlüter et al., 2019c; Secchi et al., 2024), we articulate a methodology that can support theorising in a rigorous and reflexive way. This methodology is grounded in a view of SES as complex adaptive systems that are characterised by context-dependence, adaptation, nonlinear dynamics and complex causation. We developed the three features – contextually embedded, collaboratively abductive and empirically stylized – to articulate the approach and be precise about what is particular to BIM compared to other modelling practices. While we developed this approach based on cases of natural resource governance using ABMs, we believe that it is useful beyond this particular application domain and can be applied to other types of modelling such as generalized modelling (Lade et al., 2015) or dynamical systems modelling (Lade et al., 2017; Radosavljevic et al., 2020). In general, BIM has the potential to facilitate interdisciplinary collaborations which are grounded in place-based research and aim for hypothesis generation and theorising.

CRediT authorship contribution statement

Maja Schlüter: Writing – review & editing, Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Nanda Wijermans:** Writing – review & editing, Project administration, Methodology, Investigation, Conceptualization. **Blanca González-Mon:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Emilie Lindkvist:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Kirill Orach:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation. **Hannah Prawitz:** Writing – review & editing, Visualization, Methodology, Investigation. **Romina Martin:** Writing – review & editing, Methodology, Investigation. **Rodrigo Martínez-Peña:** Writing – review & editing, Methodology, Investigation. **Kara E. Pellowe:** Writing – review & editing, Methodology, Investigation. **Udita Sanga:** Writing – review & editing, Methodology, Investigation.

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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