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Toward a methodology for explaining and theorizing about social-ecological phenomena

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Explanations that account for complex causation, emergence, and social-ecological interdependence are necessary for building theories of social-ecological phenomena. Social-ecological systems (SES) research has accumulated rich empirical understanding of SES; however, integration of this knowledge toward contextualized generalizations, or middle-range theories, remains challenging. We discuss the potential of an iterative and collaborative process that combines generalizing from case studies with agent-based modelling as an abductive methodology to successively build and test explanations rooted in complexity thinking. Collaboration between empirical researchers, theoreticians, practitioners, and modellers is imperative to accommodate this process, which can be seen as a first step toward building middle-range theories.

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Introduction

As social-ecological systems (SES) research is maturing, calls for moving beyond describing toward explaining and theorizing social-ecological phenomena are becoming more frequent [1–3]. In the last few decades, SES research has accumulated a rich body of empirical knowledge about how the interplay between human agency, social networks, and ecological dynamics shapes social and ecological outcomes [4,5]. This in-depth, mostly place-based knowledge, together with the increasing availability of generalized knowledge from synthesis studies [6], provides a valuable source for the development of explanations and theory. Generalization and theorizing in SES, however, face many challenges because of complex causation, emergent processes, social-ecological intertwinedness, and context dependence that characterize SES [7•,8–10].

Recent advances in the use of agent-based modelling (ABM) for explanation and theory development in several natural and social sciences provide interesting opportunities for overcoming some of these challenges. ABM is grounded in complexity thinking, allows studying emergent processes and has proven to be a valuable tool for interdisciplinary and transdisciplinary collaboration [11,12]. While ABM is becoming increasingly popular in SES research it is mainly used for exploring social-ecological dynamics and global change or policy implications in particular places, to support participatory processes or as a conceptual tool [11]. We argue that ABM could also be a valuable tool for facilitating a transdisciplinary process of theory development that builds on existing empirical knowledge, particularly recent attempts to develop generalized knowledge claims [6,13••]. Yet, combining generalization from case studies with ABM to develop and test explanations of social-ecological phenomena is not often done (but see Ref. [14] for an example and Ref. [15] for a discussion of how meta-studies can support the development of process-based land change models).

For this purpose, we introduce here a methodology that combines case-study research with ABM to facilitate developing generative explanations, that is, explanations that specify the causal mechanisms and processes that bring about a phenomenon of interest [16]. Contrary to deductive approaches of theory building and testing, this methodology builds theory from empirical understanding in an abductive manner. The resulting theories are so-called middle-range theories [17], or 'contextual generalizations' [18] that apply to a delimited set of cases specified by the conditions under which the proposed mechanisms are effective (see Box 1 for a glossary of terms).

We aim to advance the development of middle-range theories of social-ecological phenomena by proposing a transdisciplinary process of theorizing that iterates between empirical knowledge integration and modelling. The approach is inspired by the mechanism-based approach from Analytical Sociology [16], but extends

Box 1

Glossary of key terms

Term	Definition
Explanation	Explaining means finding causes of observed phenomena and causal links between those causes and the phenomenon of interest [56••].
Generative explanation	An explanation that postulates a process or a set of mechanisms that generate the phenomenon [41].
Possible explanation	An explanation that tells us how the effect could in principle be produced [16].
Plausible explanation	A possible explanation is turned into a plausible one through empirical validation [16].
Abduction	Inference to the best possible explanation to generate and justify hypotheses. Abduction departs from empirically observed phenomena and tries to explain them, but does not aim at developing a general law as an inductive approach.
Middle-range theory	An approach that, in contrast to grand theorizing, aims to develop theory situated between a local working hypothesis and general theories that aim to explain all observed instances of a phenomenon [17].
Mechanism	A mechanism consists of entities, the activities they engage in or processes they trigger. These activities or processes bring about change [16]. In SES entities can be social or ecological. A mechanism does not have to be deterministic.

beyond it by incorporating diverse knowledge sources and ways of knowing through a collaborative process of developing, testing, and refining explanations. This methodology requires empiricists, theorists, practitioners, and modellers to work together across disciplines and methods. ABM can be used as a tool to collect, contest, compare, and integrate these various types of knowledge and understanding. In this article, we first discuss current trends in generalizing from case studies in SES research and review the potential of ABM for developing explanations of phenomena recently put forward in several natural and social sciences. We then propose four steps to combine empirical synthesis with ABM and discuss their potential for supporting an abductive and iterative process of theorizing that moves from empirics to theory and back.

Case study methods for finding commonalities and generalizing across cases

Synthesizing empirical evidence across cases to identify common patterns, mechanisms or drivers of SES outcomes has recently received increased attention, particularly in the subfield of land system science (see Figure 4 in Ref. [13••] for a review of studies in land system science from 1995–2012). These studies have applied a variety of qualitative and quantitative case study and synthesis methods. A review of a subset of the most commonly found methods in SES research provides insights into their use, as well as their potential to support theorizing (Table 1). One important feature is the level of explanation, that is, the extent to which an analysis with a particular method can establish causality between the outcomes of interest and hypothesized causal factors [6].

Synthesis or case comparison methods provide opportunities for theorizing but also have important limitations when it comes to identifying causal mechanisms, dealing with complex causation and the dynamic, out-of-equilibrium nature of SES. They can contribute different aspects to an explanation, from identifying key factors, such as trust, to elaborating conditions, such as institutional settings or social or ecological network structures (see also Ref. [13••] for strengths and limitations of synthesis methods). While they provide valuable clues about causal effects and can test predefined hypotheses, standard case comparison and synthesis methods can provide little insight into the causal mechanisms or pathways that generated the phenomenon [19]. Common statistical methods used for quantitative meta-analysis, moreover, are based on assumptions such as excludability or no interference, that are violated in SES because of feedbacks between social and ecological processes or other issues of endogeneity [7•,20]. Endogeneity refers to a situation where dependent variables may also act as independent variables. Structural equation modelling and longitudinal analysis can overcome some of these limitations; however, the former has so far little been used in SES. Finally, comparative methods are constrained by the available case studies [21], and are mostly static which limits their ability to capture how processes leading to a SES phenomenon unfold.

Novel methods such as Qualitative Comparative Analysis (QCA) and network analysis can capture more complex causation through establishing combinations of causes (QCA) or identifying structural characteristics of social and ecological interactions that are associated with a phenomenon of interest (network analysis). These methods, however, can only capture a small set of drivers and can be very data intensive [20,21]. They are also limited in their ability to uncover causal mechanisms. Here, in-depth qualitative case studies become instrumental as they can provide insights into causal mechanisms when related to theories or existing knowledge [22••]. A few recent studies have applied process tracing, for instance, to identify and test causal pathways that lead to an outcome of interest, such as the emergence of a new policy framework [23]. In-depth case study methods focus on within-case inference, and thus require case selection techniques, be based on theoretical ideas about mechanisms or combined with case

Table 1

Overview of case study and synthesis methods. The list of methods is not comprehensive but presents a subset of methods that have recently been used in SES research for explanation and theory building. We acknowledge that the description of the procedure may not represent all applications of the respective method.

Method	Procedure	Levels of explanation	Examples from SES research
Framework/ typology-building	Synthesis of empirical insights with the purpose of identifying concepts and processes that are part of explanations. Often developed from literature.	Providing guidance for further empirical investigations about concepts, variables, mechanisms or causal relationships that may explain a phenomenon.	Social-ecological system transformation constitutes change in two core elements – natural capital and ecosystem services, and includes subprocesses clustered in four phases [26]. Social-ecological collapse is defined by fast loss of identity and social-ecological capital, with lasting consequences and can occur through 14 alternative mechanisms [3].
Quantitative meta-analysis	Statistical analysis of explanatory power of independent variables for explaining variance in outcomes. Usually involves a large number of cases.	Establishing the conditions, factors or attributes that contribute to a phenomenon.	Leaders and robust social capital combined with incentives (e.g. catch shares) contribute to successful fisheries co-management [27]. Slow, path dependent institutions with exclusive access to the resource contribute to alternative stable states – conservation or overharvesting [28].
Qualitative meta-analysis	Often a systematic review of qualitative case data and coding of key variables, for example, process components, causes and outcomes. Systematic approach allows for comparison across cases and establishing patterns. Usually performed in medium-N studies.	Establishing a set of key causes and conditions, associations between causes and outcomes, causal patterns or processes common across cases, that can contribute to explaining a phenomenon.	Adverse livelihood outcomes of large-scale land acquisitions frequently occur through a range of processes such as elite capture or competitive exclusion, while sustainable outcomes occur through for example, benefit creation, adaptation and co-existence [29]. Involvement of resource users in governance and contextually appropriate policies are associated with effective governance of squid fisheries [30].
Longitudinal studies	Analysis of repeated measures or observations of a set of variables through time. Performed in a single case or in small number of cases.	Establishing and testing causal effects through analyzing how quantitative or qualitative variables change through time.	Domestication of fire by humans has over time resulted in change in social and social-ecological interactions (e.g. human interactions with predators or burning of landscape) and humans' ecological niche, which led to a large-scale social-ecological regime shift [31]. Funding collaborative Watershed Councils in the state of Oregon is linked to improved water quality over short-term horizon. The relationship is mediated by attributes of the Council (e.g. operating budget, staff size) [32].
Qualitative comparative analysis (QCA)	Method relies on Boolean algebra to represent each case as a set of cause-outcome relationships and systematically compare the sets. It occupies a methodological space in-between qualitative and quantitative meta-analyses. Involves a small to medium number of cases or longitudinal data.	Establishing combinations of causes that are necessary and sufficient for the phenomenon of interest across cases.	A set of multi-level governance linkages (e.g. presence of research-oriented partnerships) have determined emergence of local autonomy in Costa Rica biodiversity governance; however, a different combination of linkages were important for its endurance [33]. Three types of outcomes of small-scale fisheries interactions with international seafood trade are mediated by a combination of conditions (e.g. stock decline and rising conflict result from lack of institutions and patron-client relationships) [34].
Social or social-ecological network analysis	Analysis of how structure/ structural conditions influence the phenomenon of interest across cases. Performed in single-case or small-N studies.	Establishing associations between patterns of interdependencies of actors and/or actors and different ecological components or resources and the phenomenon of interest. Identifying social-ecological processes that generate a specific structure.	Different types and structures of social-ecological networks are associated with varying capacities to face different governance challenges [35•]. For example, when two or more actors are managing (or competing for) the same ecological component, their joint ability to manage it sustainably increases if they are socially connected [36]. Pre-existing collaboration structures were found to positively impact legitimacy of natural resource co-management, while various networking strategies (e.g. deliberative attempts to influence collaboration) can have further positive effect [37].

Table 1 (*Continued*)

Method	Procedure	Levels of explanation	Examples from SES research
Process tracing	Tracing causal processes and conditions that brought about a phenomenon. Applications of the approach are diverse and different in terms of their conception of causality (deterministic, probabilistic, configurational). Typically, an in-depth, single case analysis.	Establishing causal mechanisms that link cause and outcome, and its context.	Environmental interest groups influenced the 2013 EU Common Fisheries Policy reform through obtaining information, resources and access by building lobbying coalitions [23]. Emergence of self-organization under presence of conflict in Georgian Bay region is explained through a set of four causal mechanisms – perceived problem severity, institutional emulation and entrepreneurship and fear of marginalization [38]

synthesis methods to strengthen generalization [22••,24]. A recent interesting development is the application of process tracing in combination with QCA in comparative case study designs [25].

To overcome limitations of individual methods and increase the strength of their causal inference, SES scholars often use mixed method approaches that combine quantitative with qualitative methods [20]. The combination of quantitative studies of causal effects with qualitative single case studies on causal mechanisms, however, faces epistemological challenges [6]. Furthermore, not all methods can be combined because they may be based on incommensurable ontologies and epistemologies, which is a critical limitation of multi-methods approaches that needs to be carefully considered.

In summary, using and combining multiple approaches of within-case and cross-case analysis are thus fundamental for developing understanding of causes of social-ecological phenomena [7•]. At the same time there remain critical limitations and gaps regarding the analysis of complex SES that are difficult to overcome with empirical methods alone. These include the ability to: (i) deal with complex causation resulting from interacting social and ecological processes that unfold over time through mutual influence; (ii) study processes of emergence [20]; (iii) test causal claims through interventions or counterfactual analysis [19]; and (iv) compare alternative explanations for a particular phenomenon of interest. Some of these limitations can be overcome by combining these empirical methods with ABM.

Developing explanations of complex system phenomena through agent-based modelling

ABM is a computational method that represents different types of agents, their attributes, interaction structures and behaviors and simulates their interactions with each other and their environment over time. Agent-based models are used to study emergent, meso-level and macro-level outcomes and perform experiments to test whether changes in the action logics of agents, their relational structures or the environment are likely to change the outcome [39,40]. ABM provides generative explanations; an observed phenomenon is explained by postulating a process or a set of mechanisms that generate the phenomenon [41].

The potential of ABM as a method to contribute to explanation and theory development has recently been highlighted in several natural and social science disciplines (Table 2). All disciplines highlight the ability of ABM to simulate features of complex systems, particularly: (i) the emergence of system-level or macro-level outcomes from dynamic, micro-level interactions between heterogeneous agents; (ii) the temporal evolution of the system, including path dependence and feedbacks resulting from interactions between agents; and (iii) the embeddedness of agents in bio-physical and social environments which they shape through their actions and interactions. These abilities make ABM a relevant tool for developing explanations of emergent social-ecological phenomena. The different disciplines highlight different potentials of ABM including their use as, for example, virtual laboratories (ecology), for studying micro–macro links (sociology, psychology), or improving existing theory through introducing more complexity (ecology and economics). These differences can in part be explained by different foci of the disciplines, such as a strong focus on micro–macro interactions in sociology versus a focus on general theory in ecology and economics.

The usefulness of ABM for explanation lies in its ability to serve as a tool for reasoning about how a phenomenon could possibly have been brought about [42] and for counterfactual analysis [43]. A simulation, however, can only provide a possible explanation because multiple mechanisms can bring about the same phenomenon (equifinality) [44]. The explanatory power of an explanation thus needs to be validated with empirical knowledge and data [45•,46]. Some fields have highlighted the ability of ABM to support knowledge integration for theory building, both through, for example, combining quantitative and qualitative aspects of cause-effect chains in the model itself (ecology, [47]) and through processes that support dialogues between different meta-theoretical foundations (economics, [42]). The latter is supported by the flexibility of ABM which is not based on a particular theory and can accommodate many different assumptions and types of knowledge [48].

In summary, ABM has been established as a tool to develop generative explanations of complex system phenomena across disciplines. It allows to test whether the hypothesized mechanisms give rise to the phenomenon, to unravel the generative process, to test causal claims through counterfactual analysis, and compare competing hypotheses. To realize its potential for explaining SES phenomena it needs to, however, be combined with empirical knowledge about possible explanations.

Combining empirical synthesis with agent-based modelling in an iterative, transdisciplinary process

We propose a four-step, iterative methodology for combining empirical synthesis with ABM to advance explanation and theorization of social-ecological phenomena (Figure 1). The methodology builds on the insights presented above and our experiences with combining empirical synthesis and ABM in collaborative research processes that involved empirical scientists, theoreticians, and modellers [14,59,60]. The steps are as follows:

Table 2

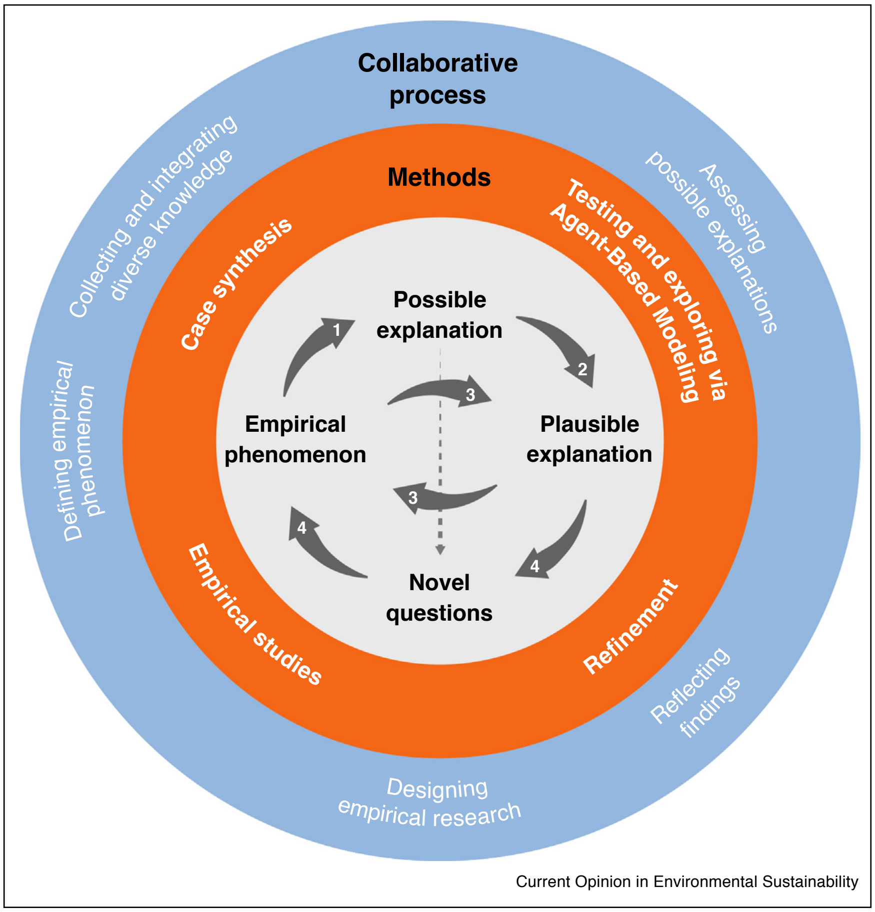
Overview of the use of agent-based modelling (ABM) for explanation and theory development in the natural and social sciences. The psychology entry combines literature from social psychology [41], organizational psychology [49] and social sciences in general [50•]

Field	Procedure	Potential highlighted by the field	Limitations highlighted by the field
Ecology	Models serve as virtual laboratories to investigate which micro-level interactions cause macro-level patterns [45•].	Models can connect quantitative and qualitative aspects of cause–effect chains across different hierarchical levels and investigate how population structure, spatial heterogeneity, and local interactions create a complex interplay of feedback processes across levels [47].	Many parameters require detailed system knowledge and imply susceptibility to errors [47].
	Empirical patterns at different levels are used to design and parameterize models with the aim to predict ecosystem behavior (pattern-oriented modelling [45•,51]). Models of different levels of complexity are compared to identify key mechanisms [47].	Causal relationships are represented and can be confronted with empirical data in more informative ways than statistical associations alone [52,53].	For the purpose of theory building, which should go hand-in-hand with solving applied problems [45•], the general validity of the model is still often derived from the 'goodness-of-fit' with empirical data [52]. This, however, is often impossible in the strict sense since the macro-level patterns cannot be measured directly [47].
Economics	Agent-based models are complementary to equation-based models. Their combination supports plurality of schools of thoughts and methods [54,55]. Theoretical and empirical ABMs are both useful; theoretical ABMs express and extend existing theories; empirical ABM synthesize mechanisms and explore their empirical validity.	Agent-based models allow to explore more dimensions than equation-based models. They improve explanatory power because the similarity of model and reality can be better assessed, and more opportunities to calibrate and validate models with empirical data exist [54]. Models are tools for how-possibly reasoning [42]. ABM is a flexible framework that can support a dialogue between different meta-theoretical foundations [48].	ABM alone cannot contribute to good theory development but needs to be triangulated with other methods [42]
Analytical sociology	A hypothesis about a generative mechanism, that is, a set of actors, their attributes and interactions, is formulated in a model that can then be run to engender the process that may generate the phenomenon. The model is used to (1) test the generative sufficiency of the identified mechanism, and (2) describe the generative process that was triggered by the model and produces the outcome [56••].	ABM allows generative explanation [46]. It facilitates an analysis of the complex social dynamics of evolving, heterogeneous and interacting agents. It is a powerful tool for addressing the 'transformation problem', that is, the link between the micro-levels and macro-levels, because of the way in which it enables the modelling of low-level entities' behavior and their interdependence.	There is a risk of falling back onto reductionist, individualist construction, and analysis of the model without considering macro-level structures and cross-level causation [57].
		Connection between ABM and empirical data is essential for explaining real word phenomena [46].	Understanding the processes in the simulation that produced the phenomenon of interest is difficult, however, if they are not specified the explanation is incomplete [56••].

Table 2 (*Continued*)

Field	Procedure	Potential highlighted by the field	Limitations highlighted by the field
Psychology	ABM is used to understand dynamic interactions among agents that underlie social phenomena [41].	ABM is the only approach that can facilitate analysis of sets of heterogeneous agents interacting and communicating in different ways [50•]. It moves beyond static relationships between variables [41] and allows investigating development over time, feedbacks and path dependence [49].	It is challenging to get the right balance between simplicity and complexity when specifying a model.
	Agent societies are (1) operational platforms where theories get converted into falsifiable hypotheses; (2) experimental laboratories where theories get gradually and thoroughly controlled; (3) multilevel worlds where the level of the agent is clearly distinct from the macro-level, and unforeseen effects and emergent properties of interaction can be observed [50•].	ABM forces the researcher to think about interactions across levels and scales (macro–meso–micro, past–current–future) [41,49,50•]. It allows for representing and studying human behavior in the contexts it is situated in (cognitive, affective, interpersonal, and cultural) [41].	Difficult to switch perspective to agents and interaction for researchers who have been trained to think and perform variable-based modelling (Anova, regression, and causal modelling) [41]. ABM can only provide a sufficient explanation of the phenomenon of interest, not a necessary one [58].

Figure 1



Current Opinion in Environmental Sustainability

A transdisciplinary process of combining generalized empirical knowledge with agent-based modelling (ABM) to develop explanations of SES phenomena. The orange circle indicates the steps and methods applied through the process of developing, testing and refining explanations. The blue circle shows the collaborative nature of each step. The dotted line indicates the generation of novel questions during the process of developing possible explanations.

- Step 1: Developing possible explanations of the empirical phenomenon through generalizing empirical knowledge.
- Step 2: Formalizing each explanation in a model and testing whether it generates the phenomenon in the simulations (generative sufficiency). Analyzing the causal processes that have produced the phenomenon in the simulation.
- Step 3: Validating the possible explanation with empirical data and expert knowledge to turn it into a plausible explanation.
- Step 4: Refining the explanation and the conditions under which it holds through further testing, for example, in different contexts and conducting novel case studies or data analyses to address novel questions that arose throughout the process.

All steps are embedded in a collaborative process that ideally involves disciplinary and interdisciplinary scientists as well as practitioners (Figure 1, outer blue circle). A diversity of participants is essential for providing different empirical, theoretical and tacit knowledge and perspectives in order to critically reflect upon, accumulate and triangulate understanding and evidence about causal effects and mechanisms [7•]. Step 1 of such a process is the joint identification and definition of the phenomenon of interest and the development of conceptual diagrams or conceptual models representing one or several possible explanations thereof [71]. These explanations are developed based on knowledge from case studies using methods outlined above as well as experience and expertise of the participants. Often a combination of synthesis and case study methods will be required to develop an understanding of possible causal relationships and mechanisms at play.

The resulting conceptual models or causal diagrams represent possible explanations, that is, hypotheses about social and ecological entities, their attributes, behaviors, relations and interaction structures that jointly may have produced the phenomenon, as well as the conditions under which they hold. Conceptual models and diagrams have proven to be useful tools for facilitating processes of interdisciplinary collaboration [61•,62]. The process of co-developing one or several conceptual diagrams facilitates making assumptions, understandings and worldviews explicit and supports a process of reflection. In doing so, different understandings do not necessarily need to be integrated; it is often more valuable to develop alternative, possible explanations and learn through comparison.

Step 2 involves the formalization of the possible explanation, or explanations, in one or several agent-based models. This entails not only formalizing the causal mechanisms and components of the possible explanation as identified in step 1, but also designing other elements of the artificial world, in which the social and ecological agents interact. Different explanations may share elements, but the combination of factors and interconnected processes is unique to an explanation. Choices about the components of alternative explanations and their conditions should ideally involve the entire team. Model formalization also involves collaborative decisions on the system boundaries and the level of complexity of the model, that is, choices about which details matter for the question under study. Once the model is designed and verified, simulation experiments are carried out to test whether it can generate the phenomenon of interest and, if so, under which conditions. These experiments involve turning elements of the mechanism and supporting conditions on and off to test how outcomes are affected. Further experiments focus on unravelling the processes, feedbacks and structural conditions that generate the phenomenon through counterfactual and sensitivity analysis. These experiments are used to test the impact of parameter value variation as well as the impact of the choice of critical structural assumptions, such as the model of agent decision making, that may or may not be a key component of the explanation.

In step 3, the empirical validity of the possible explanation(s) is assessed which, together with the refinement in step 4 is another collaborative endeavor as all participants reflect on, refine or refute the explanation(s) based on their knowledge and empirical evidence. The empirical validity of the explanation(s) can also be assessed using pattern-oriented modelling [51].

Throughout the process, particularly during explanation development and refinement, new questions may be triggered which can inform a new data collection or analysis. The sequence of steps and the entry point presented here are only indicative as each process will be unique. Most likely some steps take place iteratively and in parallel, and practical constraints may make some more prominent than others. Overall, it is a continuous process, through which possible explanations are generated, tested, refined, tested again to gain confidence about when, that is, under which conditions, causal explanations hold.

Concluding reflections

Recent advances in generalizing from SES case studies and explaining complex phenomena through ABM provide novel opportunities for theorizing social-ecological phenomena. Combining generalized empirical knowledge with ABM in a transdisciplinary process allows building evidence and confidence of causal claims and provides an empirically grounded, complexity-based methodology for developing middle-range theory. The use of ABM is particularly interesting for SES research because it is one of the few methods that allows simulating processes of emergence (bottom up) as well as macro-to-micro, top–down effects [50•]. Both are relevant for understanding the complex causality that characterizes SES. Empirical, case-based research and ABM complement each other and jointly facilitate establishing causal mechanisms and the contexts in which they are effective if used iteratively in a reflexive, collaborative process. The transdisciplinary process lies at the interface between empirics and modelling when at different stages possible explanations are developed, contested and scrutinized or model results are analyzed and discussed.

Some combinations of case study or case synthesis methods and ABM are particularly interesting, such as process-tracing with ABM [59], qualitative typologies with ABM [63], mixed method approaches and ABM [14] or network analysis and ABM [64]. Field experiments, that is, behavioral experiments conducted in field settings, are also interesting as ABM can test the causal relations identified through the experiments (see Ref. [65] for an example of combining lab experiments and ABM). These combinations are promising because they allow developing and testing causal mechanisms (process tracing), capturing diversity of human behavior (qualitative typologies, behavioral experiments) or interactions among multiple factors (mixed method approaches), or establishing the effect of network structure for a phenomenon and *vice versa* of the phenomenon on changes in network structure. They also allow developing and comparing alternative explanations.

The link between empirical knowledge and ABM described here is different from most commonly found model applications. Contrary to empirical models, the empirical research is not primarily the source of data to specify functions, or parameterize and validate the model [66], instead the empirical research is used here to hypothesize, select and identify the causes and causal processes that may have generated the phenomenon of interest. The ABM is thus not aimed at prediction or assessment but a tool for formalizing and testing causal analysis. This use of ABM is similar to the mechanism-based approach proposed by Analytical Sociology [16] and recently put forward for SES research [1] but extends it in three important ways: (1) the development of possible explanations and their exploration with ABM are based on a synthesis of empirical knowledge, which can be informed by different theoretical foundations but is not *a priori* based on a particular theory; (2) the models are stylized as they build on synthetic insights not individual case studies, (3) the development, validation, and refinement of explanations are carried out in interdisciplinary or transdisciplinary teams in order to integrate disciplinary knowledge and practical experience, but also to capture a plurality of perspectives.

This combination, however, does not come without challenges and is not a silver bullet. The scope and validity of the generalized knowledge used for developing possible explanations need to be carefully assessed [6]. There is also no procedure for how to incorporate knowledge from the many existing descriptive SES case studies into ‘elements that can play a crucial role in causal narratives about other concrete cases’ ([22••], p. 7). In general, more work is needed to better understand how to link different types of empirical explanations with the requirements of generative explanation in ABM, that is, a representation of a possible explanation in terms of the social and ecological entities, their properties, relations, behaviors, interaction structures and environments that may have brought about the phenomenon. Finally, unravelling the complex causal processes that bring about an emergent phenomenon in an agent-based model is not straightforward; however, the development of more sophisticated model analysis techniques is an active research frontier [67]. Finally, the interdisciplinary or transdisciplinary process we propose is time demanding, may be confronted with ontological or epistemological incompatibilities and other common challenges of such processes [68].

Despite these challenges, we find the advancement of explanations and ultimately middle-range theories of social-ecological phenomena through synthesis and integration of knowledge from continuous, iterative, abductive, and transdisciplinary processes promising. Participatory model development and analysis have already proven to be a valuable tool for processes of co-developing sustainable solutions [12]. We extend this point to argue that modelling is equally valuable in collaborative processes for theory development [14,69,70]. The process of generating and sharing knowledge to co-construct a conceptual model affects how we identify and address social-ecological phenomena. If carried out carefully, it can foster open discussions that enable sense making and unravelling the complexity of SES in a way that acknowledges and builds on a plurality of perspectives. Such an empirically driven process should engage with the theoretical backgrounds of participants but not be restricted by particular theories. It should rather embrace plurality and allow for the development of complementary explanations that can be tested and compared through ABM. However, some guidance for incorporating different evidence and knowledge is essential. Lastly, experience so far proves that research that aims to explain and theorize the causal complexity of SES phenomena typically goes beyond the scope of an individual research project or a PhD thesis, and needs to be embedded in larger research programs or collaborative networks to mobilize the diversity and critical capacity of interdisciplinary work.

Conflict of interest statement

Nothing declared.

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References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. Biesbroek R, Dupuis J, Wellstead A: **Explaining through causal mechanisms: resilience and governance of social–ecological systems**. *Curr Opin Environ Sustain* 2017, **28**:64-70.

2. Cox M, Villamayor-Tomas S, Epstein G, Evans L, Ban NC, Fleischman F, Nenadovic M, Garcia-Lopez G: **Synthesizing theories of natural resource management and governance**. *Glob Environ Change* 2016, **39**:45-56.

3. Cumming GS, Peterson GD: **Unifying research on social–ecological resilience and collapse**. *Trends Ecol Evol* 2017, **32**:695-713 http://dx.doi.org/10.1016/j.tree.2017.06.014.

4. Österblom H, Folke C: **Emergence of global adaptive governance for stewardship of regional marine resources**. *Ecol Soc* 2013, **18**:4.

5. Wiek A, Ness B, Schweizer-Ries P, Brand FS, Farioli F: **From complex systems analysis to transformational change: a comparative appraisal of sustainability science projects**. *Sustain Sci* 2012, **7**:5-24.

6. Magliocca NR, Ellis EC, Allington GRH, de Bremond A, Dell'Angelo J, Mertz O, Messerli P, Meyfroidt P, Seppelt R, Verburg PH: **Closing global knowledge gaps: producing generalized knowledge from case studies of social-ecological systems**. *Glob Environ Change* 2018, **50**:1-14.

7. • Ferraro PJ, Sanchirico JN, Smith MD: **Causal inference in coupled human and natural systems**. *Proc Natl Acad Sci USA* 2019, **116**:5311-5318 http://dx.doi.org/10.1073/pnas.1805563115.

This paper discusses how feedback across social and environmental dimensions that characterize coupled human and natural systems (CHANS) create challenges for causal inference because assumptions about excludability and the absence of interference may not hold. Structural knowledge, multiple approaches and transdisciplinary collaborations are needed to elucidate causal relationships in CHANS.

8. Levin S, Xepapadeas T, Crépin A-S, Norberg J, de Zeeuw A, Folke C, Hughes T, Arrow K, Barrett S, Daily G *et al.*: **Social-ecological systems as complex adaptive systems: modeling and policy implications**. *Environ Dev Econ* 2013, **18**:111-132.

9. Boonstra WJ, de Boer FW: **The historical dynamics of social–ecological traps**. *AMBIO* 2014, **43**:260-274.

10. Folke C, Biggs R, Norström AV, Reyers B, Rockström J: **Social-ecological resilience and biosphere-based sustainability science**. *Ecol Soc* 2016, **21**.

11. Schulze J, Müller B, Groeneveld J, Grimm V: **Agent-based modelling of social-ecological systems: achievements, challenges, and a way forward**. *J Artif Soc Soc Simul* 2017, **20**.

12. Etienne MC: *Companion Modelling: A Participatory Approach to Support Sustainable Development*. Springer Science & Business Media; 2013.

13. •• Magliocca NR, Rudel TK, Verburg PH, McConnell WJ, Mertz O, Gerstner K, Heinimann A, Ellis EC: **Synthesis in land change science: methodological patterns, challenges, and guidelines**. *Reg Environ Change* 2015, **15**:211-226.

The authors develop a typology of generalized knowledge claims (GKC) about causes and patterns of change in social-ecological systems. They propose a standardized protocol and an approach for assessing the validity, purpose and strength of GKC. The validity of a claim is assessed based on an alignment of case evidence with the characteristics of the claim, for example, the prior state of knowledge, the logic of generalization and the methodology used and its agreement with prior claims.

14. Lindkvist E, Basurto X, Schlüter M: **Micro-level explanations for emergent patterns of self-governance arrangements in small-scale fisheries—a modeling approach**. *PLoS One* 2017, **12**: e0175532.

15. Magliocca NR, van Vliet J, Brown C, Evans TP, Houet T, Messerli P, Messina JP, Nicholas KA, Ornetsmüller C, Sagebiel J *et al.*: **From meta-studies to modeling: using synthesis knowledge to build broadly applicable process-based land change models**. *Environ Model Softw* 2015, **72**:10-20.

16. Hedström P, Ylikoski P: **Causal mechanisms in the social sciences**. *Annu Rev Sociol* 2010, **36**:49-67.

17. Merton Robert K: *Social Theory and Social Structure*. NewYork: Simon & Schuster: The Free Press; 1949.

18. Meyfroidt P, Roy Chowdhury R, de Bremond A, Ellis EC, Erb K-H, Filatova T, Garrett RD, Grove JM, Heinimann A, Kuemmerle T *et al.*: **Middle-range theories of land system change**. *Glob Environ Change* 2018, **53**:52-67.

19. Walters BB, Vayda AP: **Event ecology, causal historical analysis, and human–environment research**. *Ann Assoc Am Geogr* 2009, **99**:534-553.

20. Young OR, Lambin EF, Alcock F, Haberl H, Karlsson SI, McConnell WJ, Myint T, Pahl-Wostl C, Polsky C, Ramakrishnan P *et al.*: **A portfolio approach to analyzing complex human-environment interactions: institutions and land change**. *Ecol Soc* 2006, **11**:31.

21. Cox M: **A basic guide for empirical environmental social science**. *Ecol Soc* 2015, **20**.

22. •• Ylikoski P: **Mechanism-based theorizing and generalization from case studies**. *Stud Hist Philos Sci A* 2018 http://dx.doi.org/10.1016/j.shpsa.2018.11.009.

The author argues that generalization from case studies can provide a more explicit theoretical contribution if based on ideas of stylized causal mechanisms. These can serve as building blocks for constructing explanations. Case studies are important for theory building because they provide elements that may be relevant in causal narratives in other cases. The author stresses that the mechanism-based approach can be used as a bridge between disciplines and methodologies.

23. Orach K, Schlüter M, Österblom H: **Tracing a pathway to success: how competing interest groups influenced the 2013 EU common fisheries policy reform**. *Environ Sci Policy* 2017, **76**:90-102.

24. Beach D, Pedersen RB: *Process-Tracing Methods: Foundations and Guidelines*. University of Michigan Press; 2013.

25. Beach D, Rohlfing I: **Integrating cross-case analyses and process tracing in set-theoretic research: strategies and parameters of debate**. *Sociol Methods Res* 2018, **47**:3-36.

26. Moore M-L, Tjornbo O, Enfors E, Knapp C, Hodbod J, Baggio JA, Norström A, Olsson P, Biggs D: **Studying the complexity of change: toward an analytical framework for understanding deliberate social-ecological transformations**. *Ecol Soc* 2014, **19**.

27. Gutiérrez NL, Hilborn R, Defeo O: **Leadership, social capital and incentives promote successful fisheries**. *Nature* 2011, **470**:386-389.

28. Tekwa EW, Fenichel EP, Levin SA, Pinsky ML: **Path-dependent institutions drive alternative stable states in conservation**. *Proc Natl Acad Sci USA* 2019, **116**:689-694 http://dx.doi.org/10.1073/pnas.1806852116.

29. Oberlack C, Tejada L, Messerli P, Rist S, Giger M: **Sustainable livelihoods in the global land rush? Archetypes of livelihood vulnerability and sustainability potentials**. *Glob Environ Change* 2016, **41**:153-171.

30. Aguilera SE: **Measuring squid fishery governance efficacy: a social-ecological system analysis**. *Int J Commons* 2018, **12**:21-57.

31. Biggs R, Boonstra W, Peterson G, Schlüter M: **The domestication of fire as a social-ecological regime shift**. *Past Glob Change Mag* 2016, **24**:22-23.

32. Scott TA: **Is collaboration a good investment? Modeling the link between funds given to collaborative watershed councils and water quality**. *J Public Adm Res Theory* 2016, **26**:769-786.

33. Basurto X: **Linking multi-level governance to local common-pool resource theory using fuzzy-set qualitative comparative analysis: insights from twenty years of biodiversity conservation in Costa Rica**. *Glob Environ Change* 2013, **23**:573-587.

34. Crona BI, Van Holt T, Petersson M, Daw TM, Buchary E: **Using social-ecological syndromes to understand impacts of international seafood trade on small-scale fisheries**. *Glob Environ Change* 2015, **35**:162-175.

35. Bodin Ö: **Collaborative environmental governance: achieving**
• **collective action in social-ecological systems**. *Science* 2017, **357** eaan1114.

This paper reviews and summarizes how a social-ecological network perspective can be used to make precise assertions about how, and under what conditions, collaboration improves governance of complex and boundary-spanning ecosystems.

36. Barnes ML, Bodin Ö, McClanahan TR, Kittinger JN, Hoey AS, Gaou OG, Graham NAJ: **Social-ecological alignment and ecological conditions in coral reefs**. *Nat Commun* 2019, **10**:1-10.

37. Sandström A, Crona B, Bodin Ö: **Legitimacy in co-management: the impact of preexisting structures, social networks and governance strategies: legitimacy in co-management**. *Environ Policy Govern* 2014, **24**:60-76.

38. Baird J, Schultz L, Plummer R, Armitage D, Bodin Ö: **Emergence of collaborative environmental governance: what are the causal mechanisms?** *Environ Manage* 2019, **63**:16-31.

39. Manzo G: **Variables, mechanisms, and simulations: can the three methods be synthesized?** *Revue francaise de sociologie* 2007, **48**:35-71.

40. Gilbert GN: *Agent-Based Models*. Sage; 2008.

41. Smith ER, Conrey FR: **Agent-based modeling: a new approach for theory building in social psychology**. *Pers Soc Psychol Rev* 2007, **11**:87-104.

42. Gräbner C: **How to relate models to reality? An epistemological framework for the validation and verification of computational models**. *J Artif Soc Soc Simul* 2018, **21**.

43. Meyfroidt P: **Approaches and terminology for causal analysis in land systems science**. *J Land Use Sci* 2015, **11**:501-522.

44. Poile C, Safayeni F: **Using computational modeling for building theory: a double edged sword**. *J Artif Soc Soc Simul* 2016, **19**.

45. Grimm V, Ayllón D, Railsback SF: **Next-generation individual-**
• **based models integrate biodiversity and ecosystems: yes we can, and yes we must**. *Ecosystems* 2017, **20**:229-236.

The paper stresses the potential of individual (agent-) based models to develop theory for individual behavior just detailed enough to explain observed patterns at the system level. The authors view theory development and solving applied problems going hand-in-hand and make a plea for more structural realism in models for prediction.

46. Manzo G: **Potentialities and limitations of agent-based simulations**. *Revue francaise de sociologie* 2014, **55**:653-688.

47. Breckling B, Middelhoff U, Reuter H: **Individual-based models as tools for ecological theory and application: understanding the emergence of organisational properties in ecological systems**. *Ecol Model* 2006, **194**:102-113.

48. Gräbner C: **The complexity of economies and pluralism in economics**. *J Context Econ* 2017, **137**:193-225.

49. Smaldino PE, Calanchini J, Pickett CL: **Theory development with agent-based models**. *Organ Psychol Rev* 2015, **5**:300-317.

50. Conte R, Paolucci M: **On agent-based modeling and**
• **computational social science**. *Front Psychol* 2014, **5**.

This article presents a critical reflection of agent-based modelling. It highlights how little its generative powers have been used so far. A truly generative explanation needs to model complex social dynamics by considering both how a macro-phenomenon is generated from the micro (emergence) as well as how the emergent phenomenon affects micro-processes.

51. Grimm V, Railsback SF: **Pattern-oriented modelling: a 'multi-scope' for predictive systems ecology**. *Philos Trans R Soc B: Biol Sci* 2012, **367**:298-310.

52. Connolly SR, Keith SA, Colwell RK, Rahbek C: **Process, mechanism, and modeling in macroecology**. *Trends Ecol Evol* 2017, **32**:835-844.

53. Cabral JS, Valente L, Hartig F: **Mechanistic simulation models in macroecology and biogeography: state-of-art and prospects**. *Ecography* 2017, **40**:267-280.

54. Gräbner C, Bale CSE, Furtado BA, Alvarez-Pereira B, Gentile JE, Henderson H, Lipari F: **Getting the best of both worlds? Developing complementary equation-based and agent-based models**. *Comput Econ* 2019, **53**:763 http://dx.doi.org/10.1007/s10614-017-9763-8.

55. Aydinonat NE: **The diversity of models as a means to better explanations in economics**. *J Econ Methodol* 2018, **25**:237-251.

56. León-Medina FJ: **Analytical sociology and its 'syntax' for**
•• **explanation**. *Soc Sci Inf* 2017, **56**:502-525.

The author argues that in order to build an explanation using an agent-based model a focus on generative sufficiency is not enough. It is important to understand the generative process that is triggered by the model and through which interacting agents in a given environment combine to produce the phenomenon of interest.

57. O'Sullivan D, Haklay M: **Agent-based models and individualism: is the world agent-based?** *Environ Plann A* 2000, **32**:1409-1425.

58. Epstein JM: *Growing Artificial Societies: Social Science from the Bottom Up*. Princeton University Press; 2006.

59. Orach K, Duit A, Schlüter M: **Sustainable natural resource governance under interest group competition in policy making**. *Nat Hum Behav* 2019. [Submitted for publication].

60. Wijermans N, Schlüter M, Boonstra WJ, Orach K, Hentati-Sundberg J: *The Human Factor for Sustainable Fisheries – Representing Fisher Behavioural Diversity in Models*. 2019. [In preparation].

61. Schlüter M, Müller B, Frank K: **The potential of models and**
• **modelling for social-ecological systems research – the reference frame MODSES**. *Ecol Soc Ecol Soc* 2019, **24**:31 http://dx.doi.org/10.5751/ES-10716-240131.

The paper highlights the diversity of models and model purposes and presents a reference scheme to situate models and their application along two gradients: the degree to which they are grounded in empirical data and the degree to which they engage different disciplinary or non-scientific knowledge systems. The authors highlight stylized structural realistic models (agent-based models) as particularly suitable to support interdisciplinary knowledge integration and social learning in trans-disciplinary processes.

62. Axelrod R: **Agent-based modeling as a bridge between disciplines**. In *Handbook of Computational Economics*. Edited by Tesfatsion L, Judd KL. Elsevier: Agent-Based Computational Economics; 2006.

63. Wijermans N, Boonstra WJ, Orach K, Hentati-Sundberg J, Schlüter M: **Careful what you fish for**. *Fish Fish* 2019. [Submitted for publication].

64. Dobson ADM, de Lange E, Keane A, Ibbett H, Milner-Gulland EJ: **Integrating models of human behaviour between the individual and population levels to inform conservation interventions**. *Phil Trans R Soc B* 2019, **374**:20180053.

65. Schill C, Wijermans N, Schlüter M, Lindahl T: **Cooperation is not enough—exploring social-ecological micro-foundations for sustainable common-pool resource use**. *PLoS One* 2016, **11**: e0157796.

66. Smajgl A, Barreteau O: *Empirical Agent-Based Modelling – Challenges and Solutions: Volume 1, The Characterisation and Parameterisation of Empirical Agent-Based Models*. New York: Springer; 2014.

67. Lee J-S, Filatova T, Ligmann-Zielinska A, Hassani-Mahmooei B, Stonedahl F, Lorscheid I, Voinov A, Polhill G, Sun Z, Parker DC: **The complexities of agent-based modeling output analysis**. *J Artif Soc Soc Simul* 2015, **18**.

68. Hertz T, Schlüter M: **The SES-framework as boundary object to address theory orientation in social–ecological system research: the SES-TheOr approach**. *Ecol Econ* 2015, **116**:12-24.

69. Lade SJ, Niiranen S, Hentati-Sundberg J, Blenckner T, Boonstra WJ, Orach K, Quaas MF, Österblom H, Schlüter M: **An empirical model of the Baltic Sea reveals the importance of social dynamics for ecological regime shifts**. *Proc Natl Acad Sci U S A* 2015, **112**:11120-11125.

70. Lindkvist E, Wijermans N, Daw T, González García-Mon B, Giron-Nava A, Johnson AF: **Navigating complexities: agent-based modeling to support research, governance and management in small-scale fisheries**. *Front Mar Sci* 2019. [Submitted for publication].

71. Schlüter M, Haider L, Lade S, Lindkvist E, Martin R, Orach K, Wijermans N, Folke C: **Capturing emergent phenomena in social-ecological systems: an analytical framework**. *Ecol Soc* 2019:24.