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Research

Eliciting the plurality of causal reasoning in social-ecological systems research

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ABSTRACT. Understanding causation in social-ecological systems (SES) is indispensable for promoting sustainable outcomes. However, the study of such causal relations is challenging because they are often complex and intertwined, and their analysis involves diverse disciplines. Although there is agreement that no single research approach (RA) can comprehensively explain SES phenomena, there is a lack of ability to deal with this diversity. Underlying this diversity and the challenge of dealing with it are different causal reasonings that are rarely explicit. Awareness of hidden assumptions is essential for understanding how the causal reasoning of an RA is constituted, and for promoting the integration, translation, or juxtaposition of different RAs. We identify the following elements as particularly relevant for understanding causal reasoning: methods, frameworks and theories, accounts of causation, analytical focus, and causal notions. We begin with the idea that one of these elements typically figures as an entry point to an RA. This entry point is particularly important because it generates a path dependence that orients causal reasoning. In a subsequent step, when an approach is applied, causal reasoning concretizes as a result of a particular constellation of the remaining elements. We come to these insights by studying the application of four different RAs to the same social-ecological case (the collapse of Baltic cod stocks in the 1980s). On the basis of our findings we developed a guide for the analysis of causal reasoning by raising awareness of the assumptions, key elements, and the relations between these key elements for a given RA. The guide can be used to elicit the causal reasoning of RAs, facilitate interdisciplinary collaboration, and support disclosure of ethical/political dimensions that underlie management/governance interventions that are formulated on the basis of causal findings of research studies.

Key Words: *Baltic cod collapse; causal reasoning; causation; interdisciplinary collaboration; social-ecological systems*

INTRODUCTION

As a multidisciplinary field, social-ecological systems (SES) research is characterized by a plurality of research approaches (RAs) that each have their own conceptualizations of particular phenomena and strategies for reasoning about their causes. Causal insights from RAs thus often differ, and if we do not understand what the causal reasoning shaped by an RA looks like, we risk unknowingly being directed and biased in our causal findings and corresponding interventions aimed at solving problems.

But what is it that allows making particular causal claims about SES phenomena, rather than other claims? This fundamental question goes beyond the familiar one about how to make causal claims, which has a strong methodological focus (Biesbroek et al. 2017, Ferraro et al. 2018). Indeed, we regard causal reasoning—and the claims and insights it allows—as more than just a methodological question. Causal reasoning involves many assumptions and choices that influence its direction, such as assessing and specifying the relevant causal aspects of a phenomenon, the causal configuration in which the phenomenon is embedded, or potential biases and alternative explanations (Schlüter et al. 2023, *unpublished manuscript*, https://doi.org/10.31235/osf.io/kn49v). These assumptions and choices are informed by the research interests, background knowledge, and theoretical commitments of those involved in a study. Although the field of interdisciplinarity research in particular has created awareness of and developed tools for uncovering these commitments, as well as for reflecting on the roles of values (Lélé and Norgaard 2005, Moon and Blackman 2014, Hazard et al. 2020, Moon et al. 2021), it is not immediately evident how they shape causal reasoning. In other words, we lack strategies for how to analyze, disentangle, and communicate the causal reasoning underlying RAs. This is critical for the multidisciplinary field of SES research, since SES scholars often need to engage with a diversity of causal reasonings in order to enhance our understanding of complex sustainability problems (Schlüter et al. 2023, *unpublished manuscript*).

In this paper we aim to address this gap by proposing a guide for uncovering the different elements that shape the causal reasoning of RAs. By RA we refer to typical ways and examples of how research within a certain scientific community can be conducted, and to a specific combination of analytical focus, particular frameworks and theories, methods, accounts of causation, and particular sets of causal notions that are chosen for a given study. These elements influence the selection of possible entities and processes involved in claimed causal relations, and how causal relations are identified and justified. When members of a scientific community consistently choose the same or similar combination of elements, they engage in broadly similar forms of causal reasoning, which become adopted as a part of their scholarly culture, often reinforcing a crystalized set of views and practices.

We demonstrate the relevance of our guide for SES scholars in four concrete ways. First, our guide raises awareness of path dependencies between elements of an RA in constituting causal reasoning. This proves important because, secondly, RAs often

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need to be adapted to the changing and complex nature of SES phenomena, and our guide can support this process. Third, the guide allows disclosing and understanding the assumptions that particular interventions rest on. This is important because, for many sustainability problems, even the very problem formulations themselves are contested and perhaps RA-dependent. Thus, revealing these assumptions allows their discussion and may clarify the implications, ethical or political, of a corresponding intervention (for example, what it means from an ethical perspective to focus on one scale rather than another). Fourth, our guide provides groundwork for combining RAs to serve interdisciplinary research toward a more comprehensive understanding of SES phenomena. Although thoroughly developing this last point goes beyond the scope of this paper, we argue that our guide facilitates disclosing and comparing the assumptions on which different RAs rest. This allows, for example, exploring their compatibility by drawing on the notions of commensurability/incommensurability of RA elements. In turn, this helps orient interdisciplinary scholars toward different ways of collaborating when using causal knowledge generated by different RAs.

We arrive at this guide by synthesizing insights from four different causal analyses of the same social-ecological case (the collapse of Baltic cod stocks in the 1980s), each following a different RA. These RAs come from analytical sociology, ecological modeling, dynamical systems analysis, and process-relational analysis, which are explained in further detail throughout this paper. We do not take these RAs to fully represent the diverse and dynamic field of SES research, in which new RAs continuously emerge. Instead, these four RAs from the natural sciences, social sciences, and humanities serve as examples. They reflect the diversity in how the multidisciplinary SES field reasons about causation.

ANALYZING CAUSAL REASONING OF RESEARCH APPROACHES

Causal reasoning refers to the cognitive activities involved when determining the effects of specified causes (e.g., the effect of a new policy), the causes of specified effects (e.g., the drivers of fisheries collapse), or how causes bring about these effects (Schlüter et al. 2023, *unpublished manuscript*). In the diverse and rich literature on causation, many efforts have focused on methodological issues, that is, on developing appropriate methods for causal inference (Ferraro et al. 2018) and multi-method approaches (Biesbroek et al. 2017). Indeed, causal reasoning has a strong methodological dimension, but other aspects are also crucial (Illari and Russo 2014). It is essential to make these additional components of causal reasoning more explicit in order to improve our understanding of the causes of social-ecological change. To this end we disclose how elements such as analytical foci, frameworks and theories, methods, accounts of causation, and particular sets of causal notions together "assemble" as part of an RA and function to orient causal reasoning (Table 1).

The characterization of RAs is key to this analysis. Although RAs have origins in disciplinary traditions, it is not useful to simply equate a given RA with a single discipline. First, there can be a considerable diversity of RAs within a particular discipline. Second, many RAs are not easily associated with one discipline but are instead interdisciplinary. This holds especially for the young and still developing field of SES research, which is often described as truly inter- if not transdisciplinary (Pricope et al. 2020, de Vos et al. 2021). Thus, we prefer to say that RAs are associated with particular research communities, beyond disciplinary divides.

An RA typically comprises several key elements (Table 1). The analytical focus concerns the realm (e.g., social or ecological), the system boundaries, and the units selected for analysis (e.g., agents, activities, populations, ecosystems) as well as scales, which are the objects of theoretical attention. The analytical focus may include cross-scale interactions and also specifies which kinds of items are related in a causal analysis, and how, i.e., the particular relations and relata (e.g., relations between agents, states of affairs, variables, or processes). Further, an RA encompasses as key elements particular frameworks and theories, methods, accounts of causation (e.g., based on regularities or mechanisms), as well as a supporting set of causal notions.

We consider this set of elements (Table 1) appropriate to disclose and dissect how causal reasoning constitutes for quite diverse RA. In what follows, we demonstrate how, for a given RA, analyzing these elements—and, importantly, how they influence each other—supports dissecting and understanding what constitutes causal reasoning. First, we introduce the concept of entry points, which allow identifying path dependencies in causal reasoning that are common across different applications of the same RA. However, such common characteristics are general and still allow for significant variation and flexibility in how causal reasoning concretely constitutes in the application of RAs. Therefore, second, case-specific conceptual maps (CoMap) spell out the concrete characteristics of the different elements, and the relations between these elements. Thus, the CoMaps clarify what orients and determines causal reasoning as part of the case-specific applications of RAs.

Entry points orient causal reasoning of research approaches

To characterize RAs at a general level and identify path dependencies in causal reasoning that are common across different applications of the same RA, we use the concept of entry points. An entry point designates a particularly important element of an RA that orients or exerts influence on the other elements, in that these need to "align" with the entry point. The demands to align can be narrow or rather open. For example, for a theory as entry point, the analytical focus might just need to remain within the substantive domain of the theory. Alternatively, a certain method as entry point might require very specific relations and relata, but no commitment to particular theories at all. Each element of causal reasoning (Table 1) can provide the entry point to an RA, and the selection is not necessarily straightforward. Researchers, although familiar with a particular RA, might sometimes consider different elements as having most influence on others. However, such disagreement can also be productive and disclose underlying assumptions about what makes an RA distinctive and orients causal reasoning.

Entry points largely determine what, in principle, we can or cannot identify as possible factors in a causal explanation. However, even with the same entry point, causal reasoning still allows for considerable flexibility. In other words, different applications of the same RA often differ in certain respects even though the entry

Table 1. Elements of research approaches (RAs) that characterize commitments for how causal reasoning can unfold.

Element of RA	Description
Analytical focus	Focus realm (social, ecological, social-ecological), system boundaries (limits and scales that define the system for the analysis), relations and relata (items of the studied system and how they potentially are connected in a causal analysis), units of analysis (objects of theoretical attention, may include cross-scale interactions)
Frameworks and theories	Key concepts and the relations between them—both frameworks and theories—identify concepts and relations between them to be considered in an analysis, but theories are usually more specific about particular relations and under what conditions they hold (Ostrom 2011)
Methods	Systematic procedures for identifying and analyzing causes
Accounts of causation	Philosophical accounts to identify causes and make causal claims, expressed in terms of, e.g., regularities (regular succession between causes and effects; Hume 1985), manipulability (manipulating causes produces effects; Pearl 2000), mechanisms (explicit, often stepwise, links between causes and effects; Hedström and Ylikoski 2010), or intra-actions (entanglement of causes and effects; Barad 2007)
Causal notions	Expressions and their context, which are used to describe causation, ranging from common (e.g., "give rise to," "lead to," "enable") to specific (e.g., "proximate and ultimate cause," "necessary and sufficient condition")

point is the same. Therefore, we need to go beyond entry points and their implicit role for causal reasoning toward concrete applications of the RA.

Purpose of analysis and relations between elements specify causal reasoning in the application of research approaches

The purpose of analysis and the motivation for the study concretize causal reasoning. The purpose of analysis and motivation could relate to, for example, a given research question, a researcher's interest in exploring or applying particular elements of an RA (or competence and familiarity with it), or simply to the available data for elucidating a given problem (which might suggest the use of, e.g., a particular method).

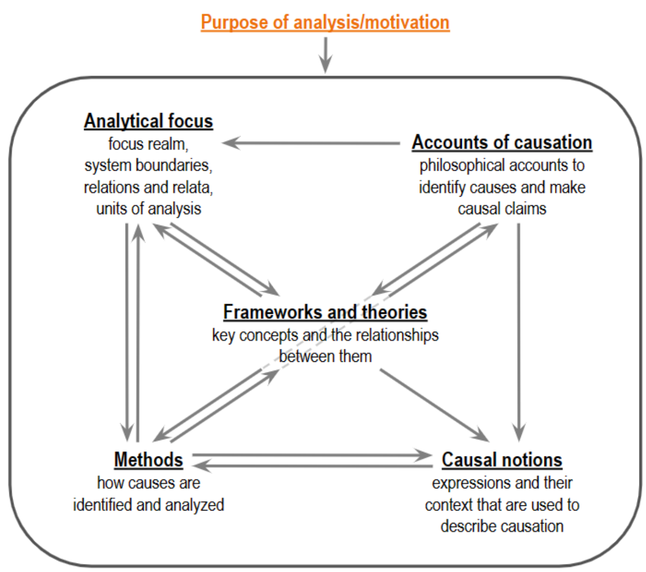
The order in which the concept of entry points and purpose of analysis were introduced above is not intended to represent a linear sequence according to which causal reasoning of an RA is composed. Some might begin with a clear purpose for a study in mind and then select an RA that is well suited for the purpose. Conversely, a researcher might also already have a particular RA in mind, which then shapes the purpose of the study. Thus we argue that, given the purpose and the general constraints imposed by the entry points, the elements of an RA (Table 1) and their particular influences and dependencies on each other together form the causal reasoning of an RA.

A conceptual map for disentangling causal reasoning

To elicit the process of how the causal reasoning of an RA forms, we have developed the CoMap (Fig. 1). This map allows researchers to dissect the elements that matter for how a particular causal analysis is conducted, and to understand the role of each element in relation to others.

The CoMap represents the option space for possible relations of dependency between the elements. Irrespective of what one begins with (i.e., methods, accounts of causation, frameworks and theories, causal notions, or the analytical focus), this will have implications for the other elements of the map. Thus, when an RA is applied, specific relations of dependency among the many options come into play and inform causal reasoning. The CoMap allows us to make sense of such processes. We now turn to the empirical case, the collapse of Baltic cod stocks in the 1980s, and apply the CoMap to case-specific applications of the different RAs.

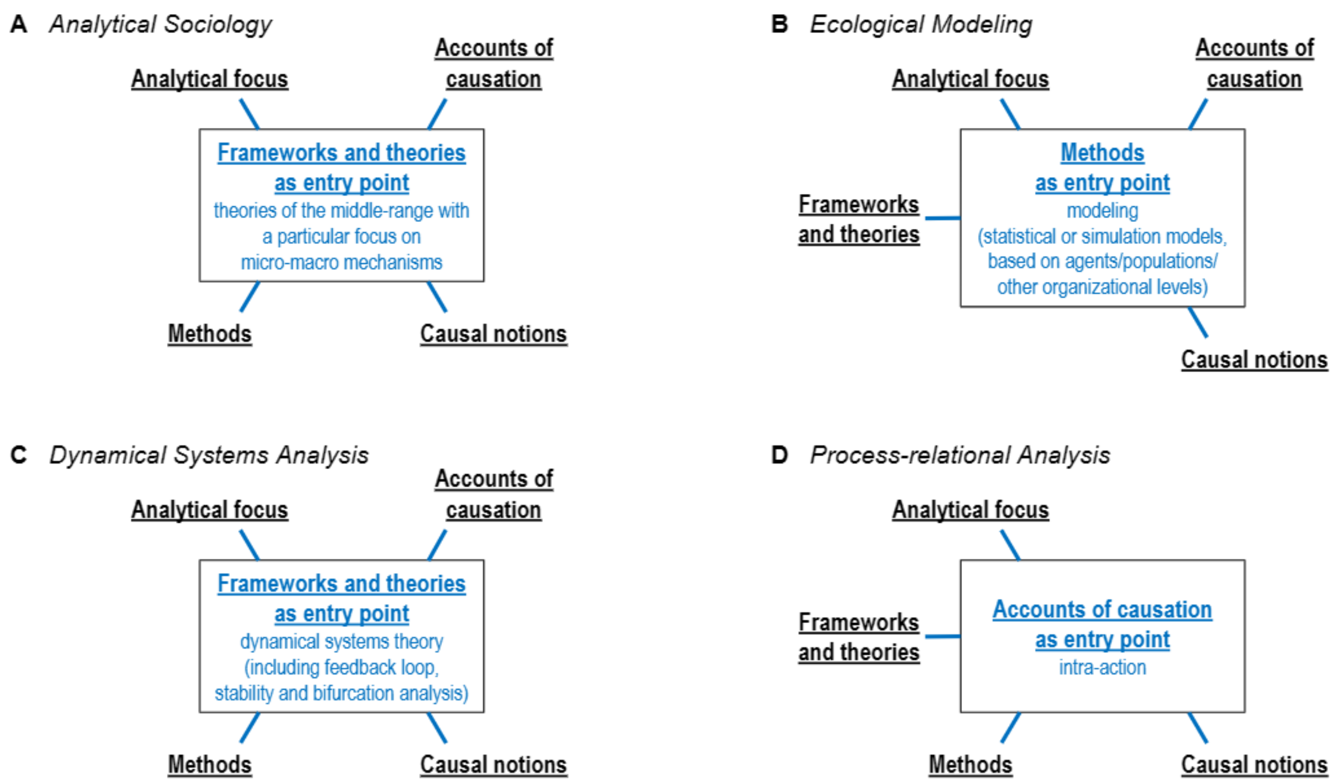
Fig. 1. The CoMap shows the elements of causal reasoning of a research approach (RA) and the potential relations between these elements. An arrow from one element to another denotes that the choice of the first element influences the choice of the second. Dashed lines indicate that arrows between Methods and Accounts of causation can also be direct. The causal reasoning of an RA is also strongly influenced by the research purpose it is applied to (top orange element).



EXAMPLE APPLICATIONS: CAUSAL REASONING FOR THE COLLAPSE OF BALTIC COD STOCKS

The collapse of Baltic cod stocks in the 1980s has been studied extensively, and many different explanations proposed (e.g., Möllmann et al. 2008, Lade et al. 2015, Casini et al. 2016). We could thus draw from a large number of studies that were also very diverse in kind. We also consulted several experts from the natural and social sciences with long records of researching the Baltic cod collapse. We exemplify our guide with the help of four RAs. Because the research purpose or motivation form part of

Fig. 2. Entry points for (A) analytical sociology, (B) ecological modeling, (C) dynamical systems analysis, and (D) process-relational analysis.



how causal reasoning is composed in a particular application of an RA, these were specifically formulated to adequately reflect the aims of each application. On the basis of literature reviews and expert interviews, we built our own models for analytical sociology and dynamical systems analysis, developed narratives for process-relational analysis, and referred to an existing published study on ecological modeling.

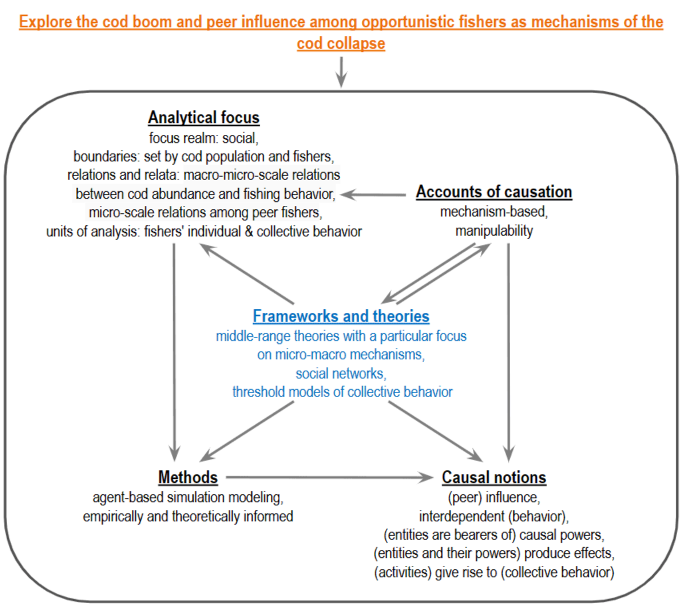
Analytical sociology

During the 1980s, an abundance of cod in the western Baltic Sea was followed by increased fishing effort, partly because of opportunistic fishers entering the fishery, which is thought to have contributed to the subsequent collapse of cod stocks (R. Martinez-Peña, *unpublished manuscript*). The purpose of the analytical sociology study was to provide a mechanism-based hypothesis formalized in an agent-based model (ABM) linking cod boom, increase in opportunistic fishing, and cod collapse. The proposed explanation is that the cod boom significantly increased the profitability of cod fishing. Then, people with fishing skills and access to boats and gear, but presently engaged in alternative occupations, learned about the opportunity provided by fish abundance, which created a dilemma: to remain in their current occupation, or switch to an activity more profitable in the short term but uncertain in the longer term. To decide, they paid attention to the choices of others in a similar situation. An increase in the numbers of fishers had the effect of reducing uncertainty and so encouraging others to follow suit. As more opportunistic fishers joined, uncertainty declined amongst the remainder, leading to a cascade throughout the network of opportunistic potential fishers. As more actors took up fishing, pressure on the cod population increased until reaching the highest sustainable fishing effort, which led to a reduction of cod abundance and reduced profitability. Finally, alternative income opportunities determined the moment when opportunistic fishers exited the sector.

We consider frameworks and theories as the entry point for the analytical sociology RA (Fig. 2), particularly the mechanism-based idea that explanations of phenomena can be given by spelling out the dependencies between parts and the whole. This results in two distinct but related analytical micro and macro scales, which are summarized in the so-called Coleman's diagram (Hedström and Ylikoski 2010). Macro-scale change influences agents' behavior by modifying their context, cognitive processes, and agential capacities; in turn, interdependent micro-scale behavior gives rise to macro-scale outcomes. Analytical sociology also holds that causal knowledge obtained about micro-macro interactions can be generalized. However, because these generalizations are not universal but hold under specific circumstances, they are called theories of the middle range (Hedström and Udehn 2011).

Data availability strongly influenced the RA. Analytical sociology relies on different methods to study the consequences of individual agents' interactions, including network analysis, experiments, statistical analysis, and agent-based modeling (Manzo 2021). Given the lack of agent-level data about opportunistic fishers' behavior in the 1980s, and the availability of case experts instead, the possibilities of conducting analytical sociology research narrowed to an ABM informed by theory and qualitative information. ABM is used in many disciplines interested in modeling interaction between entities, like biochemistry, ecology, and physics (Wilensky and Rand 2015). We chose it because it enables exploring the macro-scale consequences of micro-scale behavior. We aimed to produce a middle-range hypothesis of dynamics between opportunistic fishing and changes in fish population size (Fig. 3). Both the selected method and the micro-macro view of analytical scales are compatible with the mechanism-based account of causation. To this account, entities, properties, activities, and organization of their interactions are bearers of both causal powers and susceptibilities. This view oriented decisions on the units of analysis: individual opportunistic fishers (entities), properties (thresholds of influence), switching occupation (activities), and social networks (organization).

Fig. 3. CoMap for analytical sociology. Blue element denotes the entry point, orange element denotes the purpose of the analysis/ motivation.



Previous theories shaped how the model was designed. Decision making was operationalized as a threshold model, according to which agents prefer one of two alternatives when a given environmental factor matches an individual threshold value (Granovetter 1978). In this case, there were two coupled thresholds: one sensitive to the number of network neighbors, and the other to income opportunities from fishing (Centola and Macy 2007, Watts and Salganik 2009). The definition of relevant relata was oriented by these models that align with prescriptions from analytical sociology: high cod abundance modified income opportunities (macro-scale context affects agents' situations), agents affected each other through information and peer influence (micro-scale interdependencies), which unfolded to produce cascades of adopting and then quitting opportunistic fishing (micro-scale behavior to macro-scale outcome). The focus realm remained social. However, the mechanism-based account of causation enabled integration of the ecological dimension as an exogenous macro-scale cause of change; underlying mechanisms of ecological change were not addressed. The system boundaries were delineated by the criterion of including as few actors, relations, and factors as possible. The causal reasoning that emerged from the combination of CoMap elements served to decompose the phenomenon under study and recompose it through an ABM. This approach attributes causal relevance to agents' properties, decision-making processes, interdependencies, and activities. These categories were used by the researcher to draw from both empirical findings and theory, and then incorporate them into the design and parameters of the model.

R. Martinez-Peña (*unpublished manuscript*) showed that when total fishing effort from full-time fishers is below the maximum sustainable fishing effort, it is plausible that additional fishing effort from opportunistic fishers responding to a sudden increase of fish abundance will not collapse the fishery even if it exceeds the maximum sustainable fishing effort, provided that they have access to profitable alternative sources of income when the fishery declines (cf. Lade et al. 2015). In such a situation, the fishery can recover. Likewise, when agents are less susceptible to social influence, the behavioral cascade of opportunistic fishers might be dramatically smaller and thus not result in fishery collapse. These insights indicate that in the case of the boom and collapse of the Baltic cod, opportunistic fishers may not have had access to good opportunities for alternative employment that would have facilitated their return to other occupations.

Ecological modeling

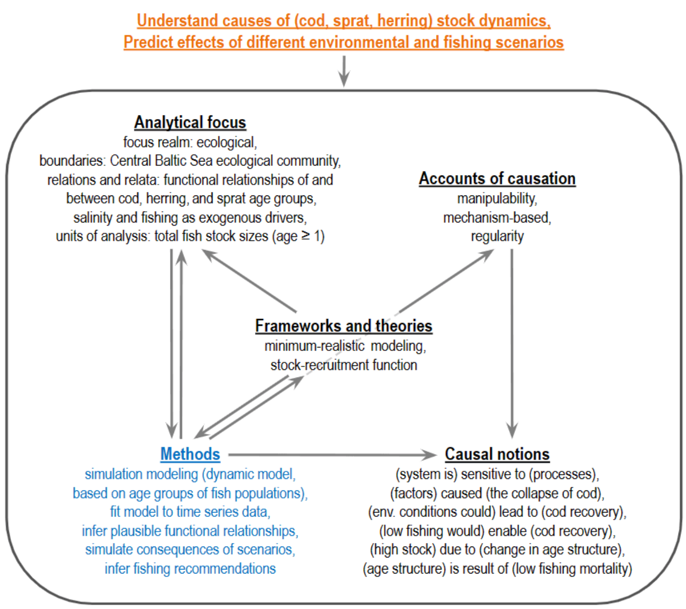
Heikinheimo (2011) utilized ecological modeling for two purposes: understanding causes of cod and prey species stock dynamics, and predicting those dynamics for different environmental and fishing scenarios. The entry point for the study is the selected method of ecological modeling (Fig. 2), here a dynamic simulation model that can produce stock dynamics (time series) based on selected entities representing the Central Baltic Sea ecosystem (environment in terms of deep-water salinity; cod, sprat and herring stocks structured by age groups; fishery of these three species) and processes that change and link these entities (recruitment, natural mortality, predation, cannibalism, fishing). This system conceptualization inherently influences the causal findings that can be derived through the ecological model (cf. Banitz et al. 2022). Certain model process assumptions and parameter values were fixed according to previous knowledge, whereas others were determined by fitting the model dynamics to the data.

The selected method makes three accounts of causation (cf. Table 1) feasible (Fig. 4), which were applied as follows: manipulability via changing model definition or simulation scenarios and observing consequences of such manipulations for stock dynamics; mechanism-based via observing which mechanistic assumption (on functional relationships between entities) best fits the data; and regularity via observing average outcomes (and variation) of multiple stochastic simulation runs. The method allows applying a theoretical concept called "minimum-realistic" modeling (cf. Heikinheimo 2011), which refers to developing as simple a model as possible while still allowing reproduction of real data. Another concept employed is stock-recruitment functional relationships, which in turn affected specific decisions on model design. One can also assume that these concepts affected the analytical focus on functional relationships within and between species. They also guided the focus on a simplified representation of the complex ecosystem, including the most important entities and processes, at the spatial scale of the whole Central Baltic Sea (without lower-resolution differences). This focus influenced the specific structure of the model, while the initial decision for a dynamic ecological simulation model constrained which kinds of analyses could be performed. The causal notions used to express causal findings strongly reflect the method of simulation modeling and the applied accounts of causation (Fig. 4).

Causal reasoning was done by (1) showing that the admittedly simple simulation model can, after calibration, reproduce empirical data (taken as support that the model captures the major control relations of the ecological dynamics); (2) testing the responses (changes and reasonability of simulated dynamics, match to data) to different forms of one functional relationship in the model (taken as support that a certain type of predation function, i.e., a mechanism, is realistic); and (3) simulating under different environmental and fishing scenarios (making predictions for the consequences of these scenarios).

For the Baltic cod collapse of the 1980s, the model with high fishing mortality and decreasing deep-water salinity as the main external drivers of fish stock dynamics was found to reproduce the historical biomass data well, although with some deviations (e.g., the simulations overestimated the cod collapse in response

Fig. 4. CoMap for ecological modeling. Blue element denotes the entry point, orange element denotes the purpose of the analysis/ motivation.



to decreasing salinity). Thus, assuming that the processes within and between species are adequately captured by the model, one can infer that the combination of unfavorable salinity and high fishing pressure caused the collapse. This is supported by model predictions when changing one of these factors alone: reduced fishing or improved salinity both led to cod recovery in the simulations. It is noteworthy that the author considered deep-water salinity as a proxy for other environmental conditions that changed synchronously, i.e., reflecting the general state of the Baltic ecosystem.

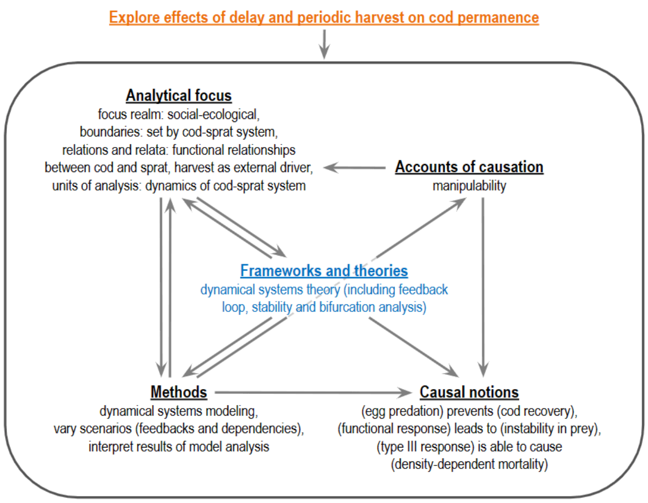
Dynamical systems analysis

The purpose of dynamical systems analysis is to increase understanding of how the structure of a dynamical system brings about its dynamics (cf. Radosavljevic et al. 2023). A dynamical systems model relates variables (relata) through rules of interaction in ways that describe the evolution of the system, for instance the co-evolution of a predator and prey population. Dynamical systems analysis is also one approach used in ecological modeling, particularly in theoretical studies. Here, however, we regard dynamical systems analysis as a separate RA because it is a broader approach that is defined by dynamical systems theory and applied to a wide range of systems, not only ecological ones.

Thus, we consider frameworks and theories as being the entry point of the RA (Fig. 2). Dynamical system theory is the major distinctive element of this RA. This abstract theory focuses on the evolution of a system if interactions between its components are known. Components of a system are state variables that are understood as variables in a mathematical sense and interactions between them are understood as mathematical dependencies. The rule of evolution, represented by a set of differential or difference equations, allows computation of consecutive states of the system given its initial state. Modeling begins by choosing appropriate state variables and specifying interactions between them using empirical or theoretical knowledge about the real world. In this way, a real-world system is formalized as a system of equations, which can then be analyzed using established mathematical methods such as stability and bifurcation analysis. Implications for the real world can be obtained by mapping the state variables to their meaning in the social-ecological context.

Having frameworks and theories as the entry point profoundly shapes the RA. It determines what kind of problem it is possible to study, how to analyze it, and what type of results to expect. For example, in order to use dynamical systems theory, state variables must be quantifiable and a certain flow, e.g., of energy or information, must exist between them. This limits the kind of relata that can be studied and, in turn, shapes analytical focus. On the other hand, analytical focus influences which part of dynamical systems theory will be used in a model formulation and analysis. For example, one may choose delay differential equations instead of ordinary differential equations to account for time lags. The methods in Figure 5 represent mathematical methods that are used in social-ecological research. They are partially derived from dynamical systems theory and the mathematical notions that are part of it (e.g., stability and bifurcation). Systems of differential equations provide no information on causal relationships. However, in addition to systems of equations, methods also enable interpretation with regard to SES knowledge and empirical assumptions that establish causal mechanisms between components of a system. Exploration of dynamic outcomes through manipulation of assumptions and their formalization (e.g., developing model scenarios with different feedback structure or functional dependencies, and comparing their dynamics) is an integral part of methods. A unidirectional relation between frameworks and theories and methods stems from the fact that frameworks and theories include deductive mathematical theory, whose results do not depend on their application in case studies, while scenario development depends on mathematical formalization.

Fig. 5. CoMap for dynamical systems analysis. Blue element denotes the entry point, orange element denotes the purpose of the analysis/motivation.



Empirical research shows that delays in human behavior, learning, and decision making contribute to social-ecological dynamics. Lindegren et al. (2009) suggested that the Baltic cod collapse could have been avoided by adapting harvest levels to changing environmental conditions and food web interactions. Brown et al. (2012), Lade et al. (2015), and Fulton (2021) point out that harvest levels can vary for a number of reasons, including economic, social, political, or psychological. Their delayed adaptation to observed stock size may have adverse effects on the exploited population. Therefore, in our example of a dynamical system analysis of the Baltic cod collapse (Fig. 5), the purpose of analysis is to understand how time lags in fishers' responses to observed size of the cod stock affect the fishery dynamics and eventually lead to cod collapse. The analytical focus is on a system constituted by cod and sprat under a variety of assumptions about their interactions in the food web and responses to the environment. All food web interactions and responses to the environment are represented by their average values, thereby aggregating spatial and individual heterogeneity and eliminating cross-scale interactions. According to empirical findings, food web interactions are relatively stable, and the strongest interactions between humans and cod come through fishing.

These assumptions are formalized as a variable harvest rate that either depends on the past adult cod level or is time-dependent and reflects the seasonality of fish population behavior and harvesting practices. Time delay in the harvest rate can create qualitative change in the system dynamics. Short time delays may lead to periodic behavior, which can be understood as oscillations in fish populations due to processes in the food web and harvest. If the time delay is sufficiently long, periodic solutions can turn into declining solutions that represent cod collapse and increase in sprat numbers.

Dynamical systems models provide limited explanations for outcomes in particular case studies, including the one exploring fishery collapse. According to the model, fish stocks collapsed because the combined influence of ecological dynamics and time lag in adaptation created a trajectory that converged to a state of cod extinction. Why this happens is beyond the scope of the model of the RA. The reasons for fishery collapse may include rigid policies, persistent fisher habits, lack of appropriate fishing gear, or other factors. Although the model can pinpoint interactions that are responsible for the outcome, it provides no answer as to why these interactions occurred in the real world. This highlights the importance of causal assumptions and the connection between dynamical systems analysis and empirics.

Process-relational analysis

Process-relational analysis differs radically from the other RAs because it does not start from a separation between entities and processes but considers them as constituting each other. This adds, in our opinion, an important dimension to the analysis of SES, but this approach is inherently difficult to explain because our everyday thinking is usually based on seeing entities and processes, such as interactions, as being separate. Process-relational analysis thus uses its own terminology, which can at times be unusual, but there is growing interest in the approach for SES research (Preiser et al. 2018, 2021; Hertz et al. 2020; Mancilla García et al. 2020; West et al. 2020).

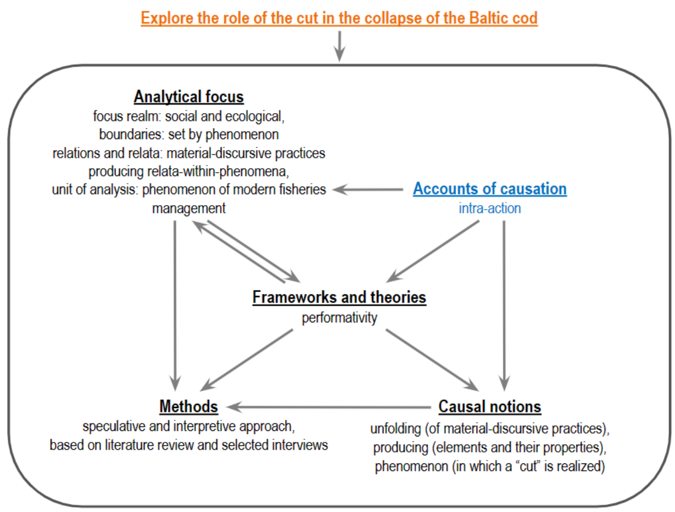
We identified the entry point for the process-relational analysis in SES research as the intra-active account of causation (Fig. 2). Intra-action captures the idea that entities such as things or actors do not exist as independent entities before they act on each other, but rather that they are constituted through their relations. Relations are thus considered to be "performative" (i.e., have the power to constitute what they relate) and the motivation for this study was to explore a Baradian understanding of performativity for causal reasoning (Barad 2003, Barad 2007, Barad and Gandorfer 2021). This led us (Hertz and Mancilla García 2021) to study (1) the performative material-discursive practices producing the phenomenon of modern fisheries management and the "cut" it entails; and (2) the role that this "cut" played in the collapse of the Baltic cod.

The term "cut" is specific to the work of Karen Barad. It is proper to a phenomenon and designates the process by which "part of the world becomes determinately bounded and propertied in its emergent intelligibility to another part of the world" (Barad 2007:149). This understanding abolishes the distinction between observer and what is observed (as compared to the more familiar understanding of phenomenon as something that happens separate from an observer). Instead, those distinctions become determinate within the phenomenon. According to this view, fundamental distinctions, such as "subject" or "object," or "social" and "ecological" are proper to a phenomenon instead of pre-existing it, and these distinctions are what the "cut" refers to: a certain way of experiencing and making sense of the world. Consequently, "cuts" vary with material-discursive practices that enact them. For example, some material-discursive practices perform a "cut" that might be characterized as an "anthropocentric," "biocentric," or "pluricentric" worldview (see IPBES 2022 for definitions).The notion of material-discursive practice means not only that both the discursive and material dimensions of practices together enact "cuts" within phenomena, but also that they mutually entail each other, that is, that they intra-act. For example, the notion of "subject" becomes intelligible only in its intra-action with notions such as "object" as well as in its intra-action with a particular material arrangement.

An intra-action account draws on theories of performativity and, accordingly, also influences the analytical focus and leads to an understanding of relations and relata in which relations are seen as prior to relata, or to use Barad's (2007:334) words, where "relata do not preexist relations; rather, relata-within-phenomena emerge through specific intra-actions." In turn, the analytical focus, theories, as well as the motivation for the study suggested the use of a particular research method, or rather speculative practice, that we see aligned with a Foucauldian "critique" drawing on literature and selected interviews. The application of this RA culminated in the development of a narrative drawing on specific causal notions (unfolding, phenomenon, production, mutual constitution, etc.) tracing the emergence of the phenomenon of modern fisheries management, the "cut" it embodies, and its contribution to the collapse of the Baltic cod (Hertz and Mancilla García 2021).

Making sense of the role of the "cut" in the collapse of Baltic cod required understanding the distinctions enacted by the "cut," that is, why elements materialize the way they do as part of the phenomenon of modern fisheries management. For this we discussed the role of models from philosophy, natural resource economics, international relations, and fisheries science defining modern fisheries management, and how reality was enacted in their image via an unfolding (i.e., a continuous building on each other) of corresponding performative material-discursive practices (see Fig. 6). This unfolding enacted a "cut" aligned with the distinctions inherent in a modernist ideal (Nightingale et al. 2020), which includes the tendency to conceptualize sustainability problems by reference to particular "scales" such local, national, or international. This "cut" set the conditions for a process of ever-increasing productivity to take hold in the framework of the raison d'état of national development. This process of ever-increasing productivity created dangerous overcapacities of fishing fleets (Johnsen et al. 2009) and is considered a major factor contributing to overfishing and collapse of the Baltic cod. At the same time, this process also drove this very unfolding of performative material-discursive practices. Put differently, processes of ever-increasing productivity (e.g., modernizing the capacity of fishing fleets as part of the raison d'état of national development) also drove the unfolding of a "cut" or at least kept it in place (e.g., the process solidified cod manifesting as a pure natural resource). We associate "cut" and "process" with constitutive (what something consists of) and causal (why something happened) dimensions of causal reasoning respectively (for distinction between constitutive and causal explanations see Johansson et al., in press). We take "cut" and "process" to be intra-active and argue that neither could be given priority in matters of causation (Hertz and Mancilla García 2021). Indeed, many (though not all) process-relational analyses go beyond the distinction between constitutive and causal dimensions of an explanation (Ylikoski 2013; Johansson et al., in press), highlighting the usefulness of both for causal reasoning about complex sustainability problems (Fig. 6).

Fig. 6. CoMap for process-relational analysis. Blue element denotes the entry point, orange element denotes the purpose of the analysis/motivation.



DISCUSSION

We now discuss the potential of our guide, and to what extent it helps to disclose causal reasoning, especially when adapting and revising RAs, elicit the assumptions on which corresponding interventions rest, and lays the groundwork for combining approaches to serve interdisciplinary research. Finally, we discuss some of the specific challenges encountered during the development and application of the guide, and identify areas for future research. Overall, we believe the guide can make differences between RAs more explicit and foster their thoughtful application both within and in collaboration between different disciplines. However, using the guide will not lead to all-encompassing, fully comprehensive, and coherent causal analyses because it neither can nor shall resolve the existing diversity and plurality of RAs into a single, monolithic approach suited to answering all kinds of questions.

A guide for eliciting causal reasoning

We summarize the insights gained from applying our guide (Table 2), that is, how the four RAs reason causally about phenomena (as manifested in the analyses of the Baltic cod collapse), as well as how they derive causal insights for the various goals of scientific activity (explanation, prediction, intervention, etc.). We learn that the RAs evoke very different ways of reasoning about the collapse, which lead to diverse explanations of it. The causes were found in micro-scale behavior (analytical sociology), in particular functional relationships between system components (ecological modeling and dynamical systems analysis), and in continuously unfolding material-discursive practices (process-relational analysis). Focus realms emphasize the social (analytical sociology), the ecological (ecological modeling), or both domains (dynamical systems analysis and process-relational analysis). Accounts of causation, theories and frameworks, and corresponding causal notions also differ. As a consequence of these various differences, potential SES interventions derived with the RAs also vary.

It is by applying our guide, that is, via the elements of CoMap, the concept of entry points, the role of the purpose of an analysis, and the conceptual mapping of how the elements influence each other, that we can elicit how causal reasoning constitutes and explains the above differences between RAs. This means that when using the guide to analyze certain RAs, and especially their application as in the example of Baltic cod, it becomes obvious which choices can

Table 2. Insights into causal reasoning from applying our guide regarding how the different RA explain change, the causal inferences it allows and, in addition, what kind of intervention or governance actions might be associated with the different explanations.

	Analytical sociology	Ecological modeling	Dynamical systems analysis	Process-relational analysis
Purpose/motivation	Explore the cod boom and peer influence among opportunistic fishers as mechanisms of the cod collapse	Understand causes of (cod, sprat, herring) stock dynamics; Predict effects of different environmental and fishing scenarios	Explore effects of delay and periodic harvest on cod permanence	Explore the role of the "cut" in the collapse of the cod
Entry point	Frameworks and theories: middle-range theories with a focus on micro-macro-scale interactions	Methods: modeling	Frameworks and theories: dynamical systems theory	Accounts of causation: intra-action
Causes that can be identified	Macro-scale change is explained by the underlying (micro-scale) behavior of agents, interdependent on each other	Characteristics of and interactions between ecosystem elements	Particular functional relationships between state variables	Unfolding of performative material-discursive practices (these practices produce constitutive spaces of intelligibility for causal processes to take hold)
How are causal insights derived?	Given assumptions of micro-scale behavior (and background structures), and using appropriate tools (e.g., ABM), macro-scale consequences are derived	By deriving and disentangling mechanisms, by manipulation/scenario comparison (with the model), by identifying regularity (esp. for model development)	By structural understanding, i.e., understanding how structure gives rise to dynamics of a system	By disclosing the intra-active nature of constitutive and causal dimensions of phenomena, it is possible to explain under what (constitutive) conditions particular causal processes take hold
Suggested interventions based on causal findings	Changing agents' opportunity space (e.g., restricting fishing and/or opening alternative income sources), interventions aimed at changing influential agents' behavior (e.g., targeted participatory processes)	Any possible interventions that change identified factors, such that their effects change toward desired directions	Any intervention that changes initial conditions or interactions between state variables	Promoting participatory processes and practices that enact different constitutive spaces (see, e.g., Savransky and Stengers 2016)

and need to be made by researchers. In so doing, the guide raises awareness of path-dependent effects between elements of a RA and tracks their roles in constituting causal reasoning.

A guide for adapting RAs and exploring the effects on causal reasoning

Researchers continuously adapt RAs for a variety of reasons. SES problems and phenomena are complex and intertwined, constantly changing, and evolving, and RA may therefore need to adapt to better account for, e.g., social-ecological intertwinedness, to study novel aspects, or simply when there is the need/desire to increase focus on particular aspects of a phenomenon as opposed to others. For this, researchers might revise/adapt, for example, the analytical focus or use different theories. Our guide supports this process and helps understanding the implications on causal reasoning.

For instance, for analytical sociology let us suppose that in order to gain a better understanding of integrated social-ecological intertwinedness, the focus realm changes from exclusively analyzing the social aspects with high resolution to also increasing the resolution of the ecological aspects. This would require including ecological theory about what affects fish population growth, such as food web relations, migration, or food availability. The system boundaries could comprise additional marine species such as sprat and herring, constituting new relata, such as those involved in predator-prey or fishing relations. The units of analysis could expand from the behavior of fishers to potential ecological drivers of cod collapse such as trophic relations or environmental effects on fish populations. Certain CoMap elements could remain unchanged, such as the mechanism-based and manipulability accounts of causation, the basic causal notions, or the method of an ABM. However, to inform the model, more empirical biological information would be needed. This setting would not necessarily change the principle of explaining macro-scale phenomena by micro-scale behavior, but could also include ecological micro-scale activity. Finally, the modified RA would also expand the range of suggested interventions. For example, an analysis could lead to the suggestion of changing fishing efforts on sprat and herring, as an alternative or in addition to suggestions for influencing cod fishers' behavior (cf. Table 2).

As another example, let us suppose that the process-relational RA weakens the theoretical stance that processes and relations are fully performative, and adopts a theoretical stance in which entities have some autonomy. This might respond to a need/desire of a researcher to "zoom in" on particular aspects of a problem and where it is less relevant to understand why entities manifest the way they do, but to instead understand what they can do at a particular moment (i.e., the capacities of entities). Accordingly, modified RAs would reason with different time scales and draw on, for example, assemblage theory as put forward by DeLanda (2006) where relata have a certain autonomy. This would change the analytical focus in that relations would not pre-exist relata, but relata would instead, to some degree, pre-exist relations. This would mean that what particular relata, such as entities or actors, can do (i.e., their causal capacities) is determined by their organization, that is, by how they are arranged vis à vis each other, which determines their capacity to affect as well as be affected

(DeLanda 2018). For example, a fisher having access to finance, technical expertise, equipment, and global markets following a profit maximization rationale might have different capacities than a fisher engaged in traditional forms of community-based fishing following a subsistence rationale. In turn, modifying the RA would have consequences for what causes are identified and for how causal insights are made (see Table 2). The former variant of this RA tracks the unfolding of material-discursive practices producing entities as well as their properties, and infers how the intra-active nature of these practices create the conditions for certain causal processes to take hold. The latter, modified variant would instead take these entities as given and infer how a particular arrangement of these vis à vis each other determines the causal capacities that are exercised. Therefore, doing both would draw on a largely overlapping body of causal notions but might use different methods (the modified variant could also draw on computational methods; DeLanda 2011). This would manifest in different intervention points: modifying a "cut" as compared to modifying the capacities that entities can exercise according to a "cut."

As seen from these examples, changing a particular CoMap element can have very different implications for causal reasoning; our guide helps us to track and make sense of these. We hypothesize, however, that these roles and potentials of particular CoMap elements for changing causal reasoning can vary from case to case. Their role depends on how CoMap elements are assembled and related as part of an RA (and particularly on the entry point).

A guide for eliciting assumptions on which interventions rest

Our guide is not only of academic interest but also of practical relevance. It reveals the particular elements of an RA, their constellation, and the path dependence that follows from entry points and subsequent choices. Thus, it makes apparent the context and the hidden assumptions that contributed to the causal insights generated. This knowledge matters for SES governance or management practices that build on these causal insights (cf. Grimm et al. 2020, Will et al. 2021, Banitz et al. 2022). Indeed, from our own analysis, we see that proposed interventions not only vary across different RAs (see Table 2) but also as part of the same RA that evolves and adapts (see previous section). Our guide makes explicit where these differences come from, for example, by disclosing the analytical focus underlying the causal reasoning, that is, the focus realm, system boundaries, relations and relata, the objects and scales of an analysis.

Making such elements, on which potential interventions rest, transparent is important, particularly because many sustainability problems are "wicked" problems (Rittel and Webber 1973) in which problem formulations are often contested and where "optimal" or "right" solutions rarely exist (Bardwell 1991). For example, clarifying whether an SES study, its causal findings, and implications apply to a time frame of several years or several decades, cover a local area with specific conditions or a much larger region, take into account social aspects as elaborate representations of human behavior or as rather fixed external drivers and so forth, ultimately helps in designing or implementing better interventions (e.g., policies that are supported by a wide variety of stakeholders, academic and non-academic). This is because making transparent the commitments on which scientific problem formulations and causal reasonings of research studies rest allows discussing, assessing, and comparing these broadly, together with the ethical and political dimensions they raise when acted upon.

The guide lays the groundwork for a collaboration of RAs in view of a more comprehensive understanding of SES phenomena

The literature on decoding human-environment approaches (e.g., Bousquet et al. 2015) and supporting interdisciplinary collaboration (e.g., Hazard et al. 2020, Graham et al. 2023) is rich and diverse. Although there are, of course, overlaps between these initiatives and our work in that they all aim to tease out underlying commitments that may or may not hinder interdisciplinary collaboration, our guide focuses explicitly on causation. Thus, we see our guide as a complement to existing initiatives.

Collaboration could mean, for example, combining methods or theories from different RAs into a new RA with its own entry point and set of decisions shaping causal reasoning. It could also mean applying different RAs individually and then considering them together. But what to do when RAs that are meant to collaborate are "radically alien" to each other (Gregory 1996), that is, when there is no "theoretical perspective from which we can reconcile their differences, their otherness to each other" (Bernstein 1991:225, see also Gregory 1996)? By disclosing the basic elements of causal reasoning, our guide could help to settle this question. Comparing the different CoMaps allows us to explore, for example, whether RAs look at different pieces of the same puzzle (e.g., when different RAs explore different aspects of a phenomenon using elements that are commensurable and thus comparable) or whether they look at pieces from different puzzles that cannot be put together (e.g., when different RAs conceptualize an SES phenomenon using elements that are incommensurable and thus not comparable).

The essential question is whether elements (such as causal notions or theories) of different RAs "can be "reconciled" through a framework which acts as an organizing schema" (Gregory 1996:616). Such a schema can be understood as a shared vocabulary and shared set of standards that define how research should be conducted (Holbrook 2013; Holbrook 2018, *unpublished manuscript*) and hence with which causal reasoning is rendered. When the elements can be reconciled, this means that they are commensurable and comparable; still, they may or may not be compatible (they are not, for example, if they occupy comparable but opposing theoretical stances). When they cannot be reconciled through such an organizing schema they are incommensurable, thus not comparable and, by definition, incompatible. This is particularly relevant for SES research because the field studies a variety of knowledge systems, including local and indigenous ones, that use radically different concepts and framings, which might be incommensurable with one another (Tengö et al. 2014, 2021). Accordingly, RAs in SES research are highly diverse. Overlooking this diversity and instead assuming commensurability in interdisciplinary collaboration (or trying to generate it) might mean that differences are neglected and some aspects get lost (Gregory 1996). Therefore, SES research might also require forms of interdisciplinary collaboration for causal reasoning that are not based on assumptions of commensurability. Instead of, for example, integrating RAs and the causal knowledge that different RAs generate, these forms might emphasize and explore similarities and differences between RAs, that is, retaining ambiguities and tensions without seeking to reconcile or integrate them "away." Such forms of collaboration, the argument goes, enable more nuanced decision making (Gregory 1996). Identifying commensurability/incommensurability is challenging, to say the least, but we believe our guide provides a basis for this process by identifying and relating individual elements across RAs.

An in-depth exploration of potential combinations of the example RAs for studying the Baltic cod collapse is beyond the scope of this paper. However, we propose an example by focusing on a CoMap element that has received less attention to date: the causal notions. For the case of the Baltic cod collapse, and following Holbrook's (2013; 2018, *unpublished manuscript*) definition, we clearly find some form of incommensurability, especially when comparing the process-relational with the other RAs. By systematically disclosing the elements of causal reasoning we can see that causal notions such as "cut," "intra-action," or "unfolding" are specific to process-relational analysis, and even when notions are shared between RAs they seem to have different meanings. Consider, for example, the notion of "phenomenon." For the process-relational variant presented above, this notion conveys the idea that entities do not pre-exist but that they become determinate within a phenomenon (which refers to the "cut"). This points to the inseparability (or intra-active nature) between an observer and what is observed, and draws attention to the material-discursive practices producing phenomena. This is clearly different to how the term "phenomenon" is used as part of the other RAs, where it tends to have a much less specific meaning. For the most part, it simply designates that something happens and the observer is seen as being separate from studying it. If one were to reconcile these different meanings in view of generating commensurability, then one would most likely lose the specificity of the process-relational meaning of the phenomenon (which, unlike for the other RAs, is of causal significance).

However, we could nevertheless envision productive forms of interdisciplinary collaboration, especially when comparing the different analytical foci, theories, and accounts of causation of the RAs, as well as how these connect in the supporting narratives. We then see that the analytical focus of the process-relational RA is quite different from the other RAs in that the focus lies on the material-discursive practices that realize the phenomenon of modern fisheries management and the "cut" it enacts. The focus lies thus not on, e.g., what agents, ecosystem, elements, or variables to choose for a study and on exploring how they are causally connected, but instead on enquiring about why we reason using such agents, ecosystem elements, and variables in the first place. By applying our guide, we thus see that we are not dealing with pieces of the same puzzle (to extend the metaphor introduced above), but rather with how, on the one hand, puzzle pieces are produced and, on the other hand, how they are subsequently put together. Thereby, the process-relational RA could connect the causal explanations of the cod collapse from analytical sociology, ecological modeling, and dynamical systems analysis to a wider network of historical and philosophical developments. This could possibly lead to enlarging the space of possible interventions (see Table 2), and perhaps lead to designing interventions that mutually support each other, as it is there, as others have already noted, that the greatest potential for transformation lies (O'Brien 2018).

Challenges and ideas for future work

We also encountered some challenges and limitations in developing our guide. First, although we consider the concept of entry points and their role in orienting causal reasoning highly useful, additional work is needed to make it operational. For example, our guide lacks a process for identifying the entry point of a particular RA when applied to a particular case and how to justify it. For our cases, we consulted scholars familiar with the RAs, but nevertheless opinions might diverge. Second, although our guide allows us to articulate causal reasoning, something "more" is needed to comprehensively make sense of it, which may be obtained through aspects as diverse as background conditions, scientific trends, norms, or personal experiences that are constitutive of the positionality of the researcher. Researchers' positionalities, as Foote and Gau Bartell (2011:46) note, "influence what researchers may bring to research encounters, their choice of processes, and their interpretation of outcomes." Put differently, the "social-historical-political location of a researcher influences their orientations, i.e., that they are not separate from the social processes they study" (Darwin Holmes 2020:3). A positionality statement, specifically tailored to how positionality influences causal reasoning, might be a useful complement to our guide. Although the positionality of researchers manifests via the elements of our CoMap, how this happens is less explicit, thus potentially limiting our understanding of the causal reasoning of the RAs. These additional aspects influence causal reasoning at various stages, from what shapes the interest and motivation in the first place (e.g., certain scientific trends, norms, or questions), to the choice between different, perhaps equally suitable, methods (e.g., because some methods are the standard in a particular community, etc.).

CONCLUSION

We have developed and presented a guide to the study of causation in SES research. Not only does this allow disclosing causal reasoning and tracking how it changes when CoMap elements change, but it can also be useful for comparing different RAs in the framework of interdisciplinary collaboration in view of serving a variety of purposes, such as achieving a more comprehensive and interdisciplinary understanding of causation, discovering unknowns, generating learning, articulating theories, or simply supporting reflexivity. Although more research along the lines identified is necessary, we believe that the guide can ultimately be useful not only for SES research but also beyond, that is, for any kind of interdisciplinary collaboration.

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Data Availability:

We did not collect primary data. Throughout the paper we refer to data sources, which are published papers.

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