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Improving network approaches to the study of complex social-ecological interdependencies

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Abstract

Achieving effective, sustainable environmental governance requires a better understanding of the causes and consequences of the complex patterns of interdependencies connecting people and ecosystems within and across scales. Network approaches for conceptualizing and analyzing these interdependencies offer one promising solution. Here, we present two advances we argue are needed to further this area of research: (i) a *typology of causal assumptions* explicating the causal aims of any given network-centric study of social-ecological interdependencies; (ii) unifying research design considerations that facilitate conceptualizing exactly *what* is interdependent,

through what *types* of relationships, and in relation to what *kinds* of environmental problems. The latter builds on the appreciation that many environmental problems draw from a set of core challenges that re-occur across contexts. We demonstrate how these advances combine into a *comparative heuristic* that facilitates leveraging case-specific findings of social-ecological interdependencies to generalizable, yet context-sensitive, theories based on explicit assumptions of causal relationships.

Introduction

The numerous ways in which people and ecosystems interact create complex patterns of social-ecological interdependencies. Social-ecological interdependencies are characterized by unidirectional or bidirectional relationships within and between people and nature. These relationships create mutual dependence, where actions and outcomes in one component of a social-ecological system can lead to actions and outcomes in another (either intentionally, or unintentionally) [1]. For example, changes in forest conservation policies in one country can, through far-reaching social-ecological interdependencies, lead to deforestation in another country[2]. The ways in which people and ecosystems currently interact are many, including extraction and trade of natural resources, various land uses, and the maintenance and utilization of local to global ecosystem services. Human population growth, coupled with, for example, continual increase of trade, economic development, and human- and species migration ensure that social-ecological interdependencies will continue to increase at scales ranging from local to global[1,3,4].

The crucial importance of such interdependencies in understanding causes, consequences, and possible solutions to environmental problems has long been recognized within the interdisciplinary scholarship on social-ecological (or coupled human-environment) systems[5–7]. Nonetheless, progress in precisely measuring and theorizing complex patterns of social and ecological interdependencies has been limited. The boundaries of scientific disciplines often define which interdependencies are taken into account; hence, either social or ecological interdependencies tend to be over-simplified, or even disregarded[8,9].

Network approaches, i.e. a perspective where a system is described and analyzed as a set of nodes and the various types of relationships that exist among them are described and analyzed as links, offer one solution for conceptualizing and analyzing complex social-ecological interdependencies (this does not, however, imply other approaches are unfeasible). As early as the 1930s, Moreno and Jennings demonstrated how basic social preferences among individual people concerning who they interacted with socially could lead to the formation of larger (community-level) social networks that exhibited strong, non-random patterns[10]. Within studies of ecology, antagonistic and mutualistic interactions among species, as well as species dispersal in landscapes, have long been analyzed as networks[11–13].

Recently, scholars have begun to conceptualize and analyze previously separated social- and ecological networks in concert to assess and theorize complex social-ecological interdependencies[14–16]. These 'social-ecological networks' explicitly represent social-ecological interdependencies; i.e., complex relationships within and between components of social-ecological systems (Box 1). Hence, the precise pattern of interdependencies becomes the subject of empirical enquiry. Using this approach, empirical studies have, for example, demonstrated that certain re-occurring patterns of social-ecological interdependencies among local resource users seem to be associated with more sustainable resource uses[17]. This type of research implies a shift away from social-ecological models and frameworks solely based on relationships within a set of variables (cf. ref. [6]) towards an approach strongly emphasizing interdependencies (links) between various different system components (nodes); hereby constituting an important addition to the existing rich social-ecological scholarship.

BOX 1 - A social-ecological network approach

As an integrative and interdisciplinary approach, a network representation of a social-ecological system incorporates a range of social and ecological/biophysical entities (nodes), as well as their interdependencies (links), in one model simultaneously[18] (Fig. 1a).

The choice of appropriate nodes and links varies from case to case depending on the phenomena under study. This critical step in the research design will be further elaborated in subsequent sections. Social nodes could be, for example, individual resource extractors, governments, NGOs, or non-physical actors such as institutions. Ecological nodes could be specific components of the biophysical environment, such as specific species or spatially separated habitat patches, but they could also represent higher-order and more aggregated biophysical forms or phenomena which do not necessarily exhibit a one-to-one mapping to a specific biophysical entity (e.g., eutrophication, climate change, etc.)[19]. If emphasizing the latter, the ecological network resembles a set of biophysically derived *issues* that could be more or less interdependent (Fig. 1b).

Examples of links in a social-ecological network include collaboration (between actors), competition (between species, e.g., preying on the same species; between firms, e.g., competing on the same market), and resource extraction (actors harvesting ecological resources). Numerous types of links can be investigated, either selectively one-by-one, or in a more combined fashion (‘multiplexed’ in network terminology, see Supplementary Information).

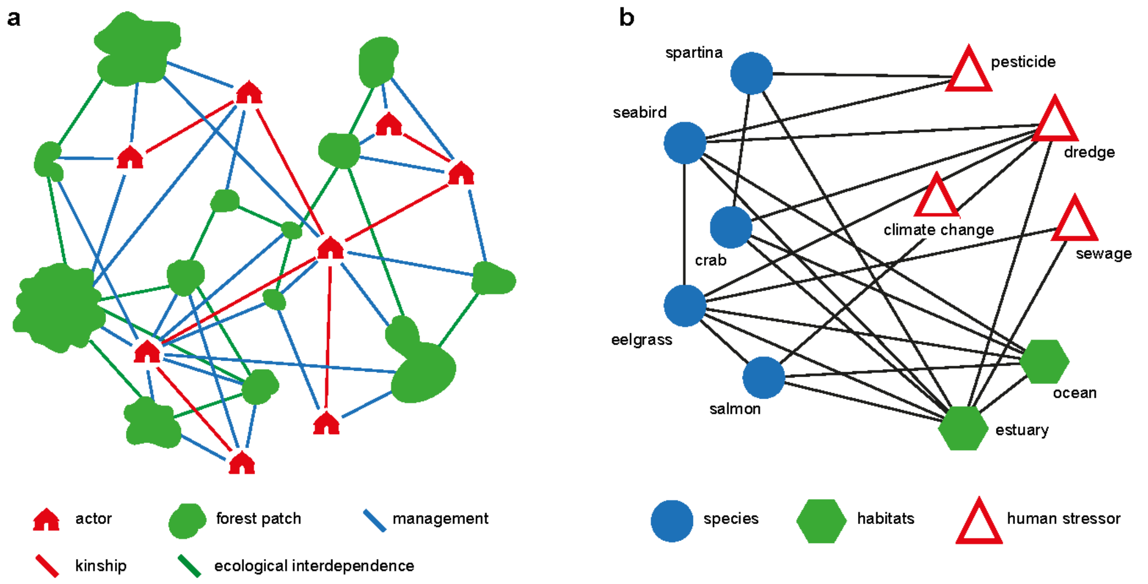


Fig. 1. Describing social-ecological systems as social-ecological networks. (a) An example from Madagascar, where actors (red nodes) represents clans, and where forest patches (green nodes) represent the forest patches that the actors are set to manage/utilize[16]. The links represent social ties based on e.g., kinship (red), ecological interdependency through species dispersal across the landscape (green), and social-ecological ties based on ownership or management authority of certain forest patches (blue). (b) A more abstract and aggregated description of a social-ecological system (coastal California, Oregon, and Washington, adapted from ref.[20]) where social nodes (red-white triangles) are defined as an institution/policy devised to address certain problems, and ecological nodes (blue circles and green hexagons) are defined as key components of the ecological system entangled with other key components. The key components are conceived as management and governance targets; thus they constitute a series of interdependent ‘issues’ forming a ‘issue network’.

The challenge now is to advance social-ecological scholarship beyond its early achievements. To develop a causal and theoretically grounded understanding of how social-ecological interdependencies drive or mediate outcomes in social-ecological systems[21], and/or how interdependencies derive from different social-ecological processes, we emphasize the need to move beyond only measuring and describing patterns of social-ecological interdependencies. Studies expressing an explicit ambition to elaborate causal assumptions, and to empirically test clear hypotheses about causality, with the aim to build and develop theory are, however, still rare[22–25].

Building generalizable theory involves, among other things, aggregating insights about causality across a large body of studies. This endeavor encompasses disentangling idiosyncrasies of case-specific findings and insight by taking various contextual and research design factors into account. Thus, seeking an all-encompassing causal relationship between even two factors is a daunting task when investigating a series of cases in heterogeneous contexts at different scales. Inappropriate case comparisons can lead to misleading or irrelevant conclusions. Moreover, perceived and real heterogeneity among cases can deter scholars from engaging in comparative analyses, thereby leading to missed opportunities to develop broader insights.

To address this gap, we provide two key advances: (i) *a typology of causal assumptions* explicating the causal aims of any given network-centric study of social-ecological interdependencies; and (ii) a set of *unifying research design considerations* applicable when conceptualizing complex patterns of social-ecological interdependencies as networks. The former also involves elaborating what research methods and analytical approaches are suitable for what causal aims. The latter encompasses a set of considerations on how to best describe the study object as a network of nodes and links, and an analytical perspective that builds from a realization that there are certain core aspects of environmental problems that re-occur across multiple contexts and scales. Acknowledging these core aspects facilitates the development of *middle-range* theories[26] that are generalizable, albeit only within certain bounds. We draw from previous studies to demonstrate how these advances combine into a *comparative heuristic* that facilitates leveraging case-specific findings of social-ecological interdependencies to generalizable, yet context-sensitive, theories based on explicit assumptions of causal relationships

Towards causal understanding

We acknowledge that defining, assessing and thinking about causality is approached differently across disciplines and research traditions. Here, we elaborate causality in a strict network context and in its simplest and broadest form, i.e., when A (the cause) gives rise to B (the effect). Social-ecological networks can be causally linked to social and ecological outcomes in both directions. For example, a landscape where species are confined in certain patches of habitat and where species' abilities to disperse across the landscape is limited (but not impossible) implies that their genetic composition tends to be more or less locally clustered[27]. The structural characteristics of a network representing such a landscape, where habitat patches are defined as nodes and where species' abilities to disperse between pairs of patches are defined as links, thus captures a *cause* for how genes are distributed (the *effect*).

Conversely, sometimes the network itself may be the phenomenon or outcome of interest, in other words, the dependent variable. Seeing the network itself as an outcome (the effect) implies a different directional assumption about causality. Here, the structural characteristics of the network – the patterns of nodes and links – are typically treated as the observable empirical fingerprint left by latent, and often unobservable, processes. Depending on the directionality of the causal assumption, different analytical methods in analyzing the networks are preferable (Supplementary Information).

To advance a network-centric causal understanding, we therefore argue that a network lens needs to involve more than measuring and describing patterns of social-ecological interdependencies. To this end, we clarify a *typology* of different causal relationships linking various social-ecological patterns with different social-ecological processes and outcomes that researchers can use to clearly situate their causal assumptions (Table 1). We argue that this typology represents a first important step to begin unlocking the potential of the network approach to link empirical investigations of social-ecological interdependencies with more fundamental theoretical understandings of how such patterns came about, and/or how they can lead to certain social-ecological outcomes.

Table 1 – Typology of causal relationships and whether the network represents the cause or the effect (first four types of causality adapted from ref.[28])

Type of causality	**Direction of causal influence**
Basic types of causality	
Influence/diffusion. Network ties influence how individual entities/nodes are influenced by other entities/nodes (e.g., diffusion of knowledge and norms, spread of diseases or movement of species populations, etc.)	Network->Individual node (Macro->micro)
Selection. Individual entities/nodes choose network partners based on other individuals' attributes (e.g., similarity in educational background, species abundance in food webs, etc.).	Individual node->Network (Micro->Macro)
Global network outcome. The structure of the network, and the distribution of nodal attributes, give rise to certain global outcomes (e.g., people being part of dense social networks are more apt and able to engage in collective action, a food web composed of different clusters is more robust to perturbations)	Network->System level social-ecological outcome (Macro->Macro)
Compounded causalities	
Co-evolution. Network structures (*selection*) and individual attributes (*influence*) co-evolve over time (e.g., fishermen select certain species as targets based on whether they are catchable given their current set of gears. The targeted fish stocks decline as a response to the fishing pressure, thereby influencing food web dynamics in the marine environment).	Individual node<->Network (Micro<->Macro)
Global outcomes derived from and mediated by individual choices and behaviors in networks. Individual entities engage with other individuals to meet certain objectives (i.e., objectives that are not confined solely to what individual entities can accomplish by themselves). The specifics of these objectives partly explain choices of network partners (*selection*), but the aggregation of these choices influence network structures, thereby affecting both individuals' behaviors (*influence/diffusion*), and collective outcomes[a] (*global network outcome*).	Individual->Network->System level social-ecological outcomes (Micro->Macro)

[a] *An example from the social domain is coordination, when actors perceive a need to connect socially to better synchronize their efforts to effectively solve a commonly agreed-upon collective problem. A coordination problem is distinct from a cooperation problem, where the collective problem is characterized by incentives to free-ride on others' efforts and/or the existence of disagreements on how to best address the collective problem. Actors' perceptions of which type of collective problem they face will determine their preferences in how they choose to engage with other actors ('Risk hypothesis'* [29]*). Thus, this type of causal assumption involves but extends beyond "selection" since it assumes that individual choices to form specific network ties is partly based on other factors that others' attributes. Further, the form and shape of the social networks that emerge as the result of these choices also determines how well they, as a community, are able to address the coordination problem ("global network outcome").*

It is important to note that real world phenomena are typically not explained through a single, clear, unidirectional path linking a cause to an effect. In any complex social-ecological system, there can be multiple causal processes operating simultaneously (e.g. compounded causality, Table 1). One might observe equifinality (multiple pathways leading to the same end state), multifinality (a causal pathway can, depending on the context, lead to different end states), intertwined causal pathways, and various feedback and co-evolution mechanisms can blur the distinction between causes and effects[2530]. Of course, it is desirable to simplify complex research problems to enable tractability and ease of interpretation, but there may be a fine line between an overly complex and opaque explanation and an oversimplification that hides deeper underlying conclusions. For this reason, we think it is essential to theorize carefully about basic causal processes, in order to ensure that their combinations in any particular social-ecological system may be better understood and parsed out empirically. We argue that the use of our typology of causal relationships facilitates such a process, and makes assumptions about causality more transparent.

Any full consideration of causality will require longitudinal data, and thus it is desirable for researchers to collect such data to the extent it is possible. There are a variety of analytical methods available from different scientific disciplines studying networks that can readily be adapted to analyze integrated social-ecological networks longitudinally (or otherwise), including methods that seek to disentangle network selection and influence causal effects (Table 1, Supplementary Information). However, we also acknowledge the many practical difficulties and the high costs associated with gathering longitudinal social and ecological network data. Consequently, assessing causality and developing generalizable theories is strengthened by applying a multitude of approaches, and by triangulating insights drawn from different methods[31,32].

Small-scale experiments, either in a laboratory environment or in the field, are very useful in testing detailed causal assumptions empirically, such as human behaviors in relation to environmental issues[33]. Although experiments are the "gold standard" in science, they can, however, suffer from reduced realism and generalizability to other contexts. Another approach that can aid investigation of causes and effects is simulation studies, where the potential implications of various assumptions about causal relationships can be formally modelled and explored in a virtual testbed[25,34]. Finally, in some cases it might be possible to conduct large-scale experiments through on-the-ground interventions (or via 'natural experiments' such as when new policies are being implemented). For example, by deliberately creating new social network ties, it may be possible to directly observe the social-ecological outcomes these ties are responsible for with data collected both before and after the change was induced[35].

Unifying research design considerations

While clearly acknowledging the value of all efforts made to collect longitudinal data and in applying methodological triangulation (or just methodological pluralism[36]), we still emphasize the value of cross-sectional real-world empirical case studies. Albeit burdened with difficulties in quantitatively assessing causality, case studies will nonetheless remain of crucial importance in moving this research forward. One key reason is that case studies allow the researcher to gather complementing quantitative data and rich qualitative data that not only helps to contextualize the study, but also to infer causality. For example, isolating network effects will require additional information on potentially competing explanations for observed outcomes. Similarly, when the network itself is the object of study (i.e., the dependent variable), information on contextual factors contributing in shaping the formation of the network will also be needed. In this section, we therefore elaborate a number of research design considerations and analytical perspectives that, if followed, would not only help individual researchers interested in conducting case studies using a social-ecological network approach to overcome initial barriers, but also build towards a common heuristic facilitating cross-case comparisons in a post-hoc manner.

Aggregation – defining adequate nodes and links

The social-ecological network approach describes objects or phenomena under study as nodes and links (Fig. 1). Obviously, the ways in which this description is done must be driven by the underlying assumptions and theories associated with the research objectives. Thus, every study needs to carefully consider its own empirical and theoretical specifications and act accordingly. Nonetheless, unifying research design considerations – applicable across contexts and scales – could make it possible and feasible to construct a research protocol providing guidance on how to define nodes and links in a context-sensitive and flexible way, while paving the way for social-ecological network research to provide insights that reach beyond the idiosyncrasies of single case studies (cf. ref. [37]).

A starting point is to define what kinds of human-nature relationships are in focus. These social-ecological links represent interactions between a social entity or issue (social node) and a biophysical entity or issue (ecological node). Thus, defining these interactions is inherently tied to defining what the most relevant social and ecological nodes are (this is further elaborated in the Supplemental Information). Prototypical examples of environmental problems often arise when human users (over)harvest units of common-pool or open-access resources, e.g., timber, fish species, or large mammals. In such cases, it is often pragmatic to define these natural resources as ecological nodes, the actors primarily engaged in their extraction as the social nodes, and their extractions as links connecting social and ecological nodes (cf. Fig. 1a). However, social-ecological interactions are often tied to specific functions that are produced by assemblages of biophysical entities and processes. In these cases, a more inclusive or aggregated approach in defining ecological nodes may be more appropriate[15] (Fig. 1b). One example of such aggregation is the concept of ecosystem services, which is increasingly being used in environmental management and governance. Other examples of when a higher-order aggregation may be more appropriate are, for example, when more systemic biophysical phenomena typically being addressed (and possibly also defined) at higher societal and administrative levels are the focus of the investigation (e.g., invasive species, climate change, biodiversity loss, eutrophication, see Fig. 1b and ref.[20,38]).

Often, the most appropriate level of aggregation of ecological/biophysical entities will coincide with geographic scale, yet it can also be related to the degree of complexity of underlying ecosystems. In particular, the relevance of specific individual biophysical entities in a highly complex system with many different types of ecological interdependencies may be low, and in such cases, it may be more useful to define ecological nodes at an aggregated level (analogous to not being able to see the forest for the trees). Similar reasoning is applicable to what constitutes a relevant definition of a social node. It could range from the conceptualization of a node being an individual farmer, to various forms and sizes of aggregated social entities ranging from organizations, firms and public agencies, to more abstract social forms such as practices and institutions (Fig. 1B, Supplementary Table S1).

Naturally, everything that humans derive from nature is produced by ecosystems, and not by one specific type of biophysical entity in isolation. Thus, even if single biophysical entities are defined as ecological nodes by themselves, these nodes are dependent on other ecological nodes. Thus, it is important that these key ecological interdependencies are also captured in the network model as links connecting ecological nodes (see Fig. 1). This of course also applies in cases with ecological nodes being defined as aggregates (for example, ecosystem services result from numerous types of interactions across many different ecological entities, and therefore ecosystem services are themselves interdependent to a varying extent[39]).

The issue of defining social links also affects issues of case comparability. This involves an informed understanding of the type of relations (or interdependencies) that are important to consider for a given case (Supplementary Table S1). In much of the existing network-centric research on governance and management, various types of collaborative relationships between actors are often at focus. These types of relationships, however, do not always lead to desired outcomes. Instead, less ‘pro-social’ relationships between actors building on power asymmetries and various conflicts of interest may sometimes be more important to consider[40,41].

This unifying logic (i.e. the conceptualization of social-ecological interdependencies as the starting point and the appropriate levels of aggregation that follows from there) facilitates telescoping in and out across multiple geographical scales and levels of social and ecological aggregation. Even more importantly, it promotes comparability, although it does not imply that the same results are to be expected despite the type(s) and level(s) of aggregation. Rather, it reduces the possibility that any revealed substantive differences between cases are not just artifacts derived from applying different guiding principles when conceptualizing what constitutes nodes and links, at similar and/or different levels of aggregation. For example, are individuals’ behaviors comparable with the behaviors of nation states? Perhaps in some specific cases; yet certainly not in all cases. A benefit from being clear on the issue of aggregation when defining nodes and links is that it makes it possible to avoid making any such indirect or unintended assumptions of scale invariably, while also making it possible to empirically test if, when, and why scale invariability might indeed be in place.

Disentangling recurring sets of core governance challenges

Every environmental problem has its own history, and is situated in its own specific social- and ecological context. Despite this, we argue that the *nature* of an environmental problem in any given case is not inherently unique, but instead reflects a series of core *governance challenges* that occur repeatedly across many different cases and contexts (cf. ref.[38]). For example, it has been demonstrated over the last several decades that common-pool or open access natural resources (e.g., local or migrant fish stocks, clean water or air, etc.) present what we here define as a core governance challenge that occurs across many places and geographical scales, albeit in widely different forms and shapes [42].

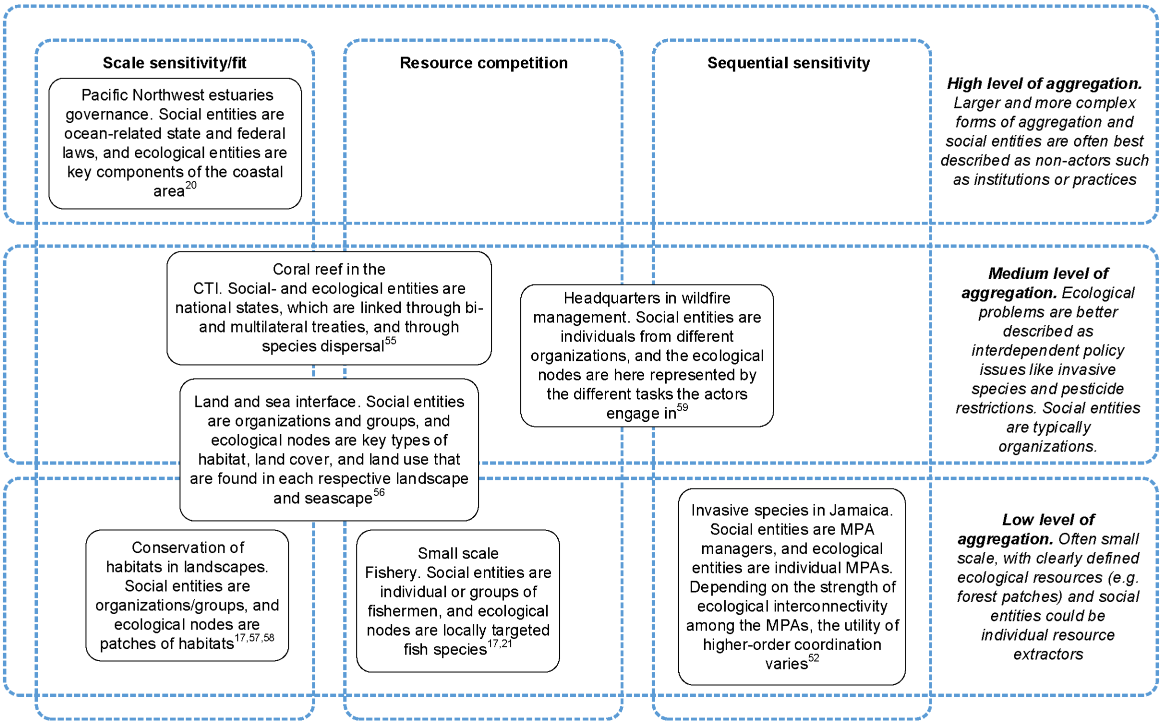
A given case often experiences a range of such core challenges simultaneously, although the relative intensity of individual challenges may differ. For example, even if a specific case partly suffers from unresolved common-pool resource dilemmas, the potentially most devastating environmental threat (and therefore most pressing and dominating governance challenge) might be the possible intrusion of invasive species [43]. Hence, most, if not all, real world environmental problems can be understood as a composition of one or more of these core governance challenges[18,38,44–47]. Furthermore, our previous arguments on equifinality, multifinality, and complex causalities also apply here. For example, different cases facing similar environmental problems can nonetheless experience substantial differences in terms of what specific core governance challenges prevail.

Increased precision in comparative analyses could thus be accomplished by disentangling the idiosyncrasies of case-specific environmental problems in order to place them into sets of comparable core governance challenges. This applies irrespectively of the specific reasons why a given case experiences a certain set of core governance challenges. Hence, this approach would not only help to avoid inappropriate and potentially misleading comparisons, it would enable case-specific knowledge spanning diverse and heterogeneous social-ecological systems to accumulate. In that way, it facilitates the development of middle-range theories (e.g. ref.[26,48]). Middle-range theories are applicable and generalizable only within certain bounds, defined by contextual differences[49]. In other words, focusing on specific sets of core governance challenges when conducting social-ecological network-centric studies implies taking a middle-range theory approach to try and maximize the generalizability of insights across contexts, but without compromising the validity of such generalizations.

Here, we elaborate three different core governance challenges that have been the focus of many existing network-centric studies in the environmental domain. First, we emphasize "scale sensitivity/fit," a core challenge that arises from the multiscale characteristics of both ecosystems and societies. It derives from the long standing realization that social-ecological systems are characterized by different social and ecological processes operating at different temporal and spatial scales (often referred to as social-ecological, or scale, mismatch[50]). Importantly, if these processes are not reasonably aligned – implying a lack of social-ecological *fit* – attempts to govern for sustainability will struggle since managing actors are inherently limited in their abilities to address environmental problems at appropriate scales. Often, ecological structures and processes operates at scales beyond the reach or jurisdiction of managing actors, thereby limiting their abilities to apply measures at scales where they would be most effective[51]. "Resource competition" represents the second core governance challenge, and essentially captures all cases where a multitude of actors are extracting or utilizing limited and shared/common ecological resources[42]. Lastly, the third core governance challenge is that of "sequential sensitivity," which describes cases where the order in which different management activities are executed is important for effectively addressing a specific environmental problem. An example of this could be how to stop the spread of an invasive species in the most effective way, where the applied sequence of different eradication measures is crucial for success and therefore poses challenges regarding coordination among managers[52–54].

A comparative heuristic

By combining these considerations of recurring core governance challenges with our research design considerations related to levels of aggregation, we arrive at a two-dimensional structure suitable for situating multiple cases in cross-case comparisons (Fig. 2). We have focused here on the three core challenges represented in much of the network-centric literature of environmental governance to date. Yet, what is considered a suitable categorization of core challenges should evolve as more studies are conducted and new insights made; as should a more precise definition of aggregation levels. Therefore, we expect this structure to be refined over time – what is present here is a foundation for guiding cross-case comparative studies.



Pacific Northwest estuaries governance. Social entities are ocean-related state and federal laws, and ecological entities are key components of the coastal area[20]

High level of aggregation. *Larger and more complex forms of aggregation and social entities are often best described as non-actors such as institutions or practices*

Coral reef in the CTI. Social- and ecological entities are national states, which are linked through bi- and multilateral treaties, and through species dispersal[55]

Headquarters in wildfire management. Social entities are individuals from different organizations, and the ecological nodes are here represented by the different tasks the actors engage in[59]

Land and sea interface. Social entities are organizations and groups, and ecological nodes are key types of habitat, land cover, and land use that are found in each respective landscape and seascape[56]

Medium level of aggregation. *Ecological problems are better described as interdependent policy issues like invasive species and pesticide restrictions. Social entities are typically organizations.*

Conservation of habitats in landscapes. Social entities are organizations/groups, and ecological nodes are patches of habitats[17,57,58]

Small scale Fishery. Social entities are individual or groups of fishermen, and ecological nodes are locally targeted fish species[17,21]

Invasive species in Jamaica. Social entities are MPA managers, and ecological entities are individual MPAs. Depending on the strength of ecological interconnectivity among the MPAs, the utility of higher-order coordination varies[52]

Low level of aggregation. *Often small scale, with clearly defined ecological resources (e.g. forest patches) and social entities could be individual resource extractors*

Fig 2. A heuristic for facilitating comparable social-ecological network studies. *The matrix serves as an initial foundation, together with the typology of causal relationships in Table 1, for gathering and synthesizing studies across contexts in an effort to develop empirically informed insights regarding the causal relationships between social-ecological structures, processes, and outcomes. The columns capture different core governance challenges, and the rows different levels of aggregation. Comparisons within a matrix element (i.e., a row and a column) can reveal insights across different contexts for a given level of aggregation and core governance challenge. Comparisons across core governance challenges for a given level of aggregation (an entire row, or certain sets of individual core challenges) can reveal generic insights valid across different core governance challenges. Comparison across levels of aggregation for a given type of core governance challenge can provide insights both within and across aggregation levels, and also get at cross-level interdependencies (or identify possible "scale breaks" where e.g. insights applicable at a certain level do not hold as the level of aggregation changes). There are more core governance challenges than what is depicted here, and future research might described/categorized them in other ways. Further, any given case often experiences more than one core governance challenge; thus some cases will apply to (and thus appear in) more than one column (observe that a case might appear in two core challenges not next to each other as they are visually presented here).*

Furthermore, the core governance challenges depicted here derive from different biophysical and human-nature characteristics of social-ecological systems. Other types of governance challenges that derive from, for example, the socioeconomic domain are also important (e.g., asymmetric power relations, exclusion of user groups, lack of adequate institutions, etc.). These other challenges are to be seen as either contributing explanatory factors, factors to explain (i.e. dependent variables), or factors that can be associated with certain core challenges, patterns of social-ecological interdependencies, and/or social-ecological outcomes. An example on how other factors can be associated with certain network patterns derives from current research on conflicting coalitions. Conflicting coalitions can be described, understood and analyzed in a social network context as subgroups of actors that are socially tied to each other but not to other subgroups[60].

Ordering cases according to their level of aggregation and their core governance challenges significantly reduces the chance of cross-case comparisons not taking key contextual and research design differences into account. However, it will not necessarily enhance an elaborated causal understanding when conducting social-ecological network research. Our typology of causal assumptions, instead, contributes to elaborated causal understanding. Hence, by combining our research design considerations leading up to the two-dimension structure for case comparisons (Fig. 2) with our typology of causal assumptions (Table 1), we arrive at a *comparative heuristic*. This heuristic can significantly further our causal understanding of the role and impact of complex patterns of social-ecological interdependencies in understanding causes, consequences, and possible solutions to environmental problems.

Applying the heuristic

To demonstrate the applicability of the proposed heuristic, we used it to retrofit a series of previous network-centric case studies and investigate the core challenge of 'scale sensitivity/fit' (Fig. 2). We investigated (i) if these studies explicitly tried to understand why and how different social and ecological nodes aligned (or not) in certain ways ("Selection", Table 1); and/or (ii) if they sought to explain social-ecological outcomes ("Global outcomes", Table 1). The issue of scale sensitivity/fit has been a key focus for numerous studies over the last couple of decades[51]. In spite of this, we still lack a commonly agreed upon definition of what exactly constitutes a good fit, and how it could be measured. Accordingly, it remains to be seen to what extent mismatch is important in explaining social-ecological outcomes[61]. Our comparative analysis, encompassing different levels of aggregation and contexts, thus also provides an indicative synthesis of studies addressing social-ecological mismatches.

A set of seven studies using explicit social-ecological network models was identified through a series of searches (Table 2). First, we looked at studies referring to an early article that to our knowledge was the first to explicitly elaborate integrated social-ecological networks[14]. Secondly, we relied on web searches using keywords such as "social-ecological networks", "social-ecological", and "institutional fit". Finally, all authors did their own inventories of their personal libraries of published studies. Given that this type of network-centric research is still in an early phase, in combination with our substantive focus on social-ecological fit, these searches capture the bulk of relevant studies.

Table 2 – The studied cases and (statistical) propensities for social-ecological alignment[a]

Case locality	Propensity for closed four cycles[b]	Propensity for closed triangles[c]
Highest level of aggregation		
Pacific Northwest region of the USA[20]	Not tested statistically, however large variation observed. There were qualitative indications of deliberate efforts to increasing social-ecological alignment.	Not tested nor elaborated
Middle level of aggregation		
Indo West Pacific[55]	Not tested statistically, however some variation observed. A qualitative assessment suggest mostly fairly good alignment.	Not tested nor elaborated
Lesser Antilles[56]	Overall neither positive or negative, but there was a positive tendency to form closed four cycles across the critical sea-land interface. However, there was also a negative overall	Not tested

	tendency of actors with a sea versus land focus not to engage with each other.	
Lowest level of aggregation		
Western Australia[57]	Negative	Positive
Southern Madagascar[17]	Negative	Positive
Coastal southern Kenya[17]	Not tested	Negative
County of Stockholm, Sweden[62]	Neither positive or negative	Not tested

[a] *Propensity for social-ecological alignment implies a selection process where, for example, actors prefer to engage with other actors and ecological entities in ways to enhance the social-ecological fit.*

[b] *Two linked social entities are linked to two interdependent ecological entities, see Fig. 3b*

[c] *Same social entity is linked to two interdependent ecological entities, see Fig. 3c*

We found that the studies differed substantially in their causal aims, and causal assumptions were often not clearly articulated. Only one study expressed an explicit ambition to elaborate causal assumptions where the social-ecological network could potentially explain social-ecological outcomes (the “Global network outcome” and “Global outcomes derived from and mediated by individual choices and behaviors in networks”, Table 1). This illustrates the need for future research in this domain that more explicitly elaborates causality and causal assumptions.

One study fits to the highest level of aggregation, and is based in the coastal Pacific Northwest of the USA[20]. Two studies fit in the middle level of aggregation. The first spans the coral triangle and beyond in the Indo West Pacific and includes 13 states[55]. The second is based in the Lesser Antilles in the Caribbean Sea and focuses on two regions: the southwest coast of Dominica and the southeast coast of Saint Lucia [56]. Three studies fit in the lowest level of aggregation. The first encompasses two cases: an agricultural landscape in Madagascar, and a small-scale fishery in Kenya[17,63]. The second study is based in Western Australia and analyzes a large-scale conservation program[57]. The third study is based in and around metropolitan Stockholm in Sweden.

Social-ecological alignment was assessed using two kinds of network constructs at various levels of aggregation – at the lowest level, an analysis of full-fledged social-ecological networks (Fig. 1 and 3a), and at the highest level, a compressed version in which social and ecological nodes were merged into one combined node (Fig. 3d, see also section in Supplementary Information on multiplex networks). In the former, the identified studies all analyzed their respective network in terms of the prevalence of certain micro-level configurations (“motifs”)[10] (Fig. 3b & c). It is not our intention to delve deeply into exactly how social-ecological networks could and should be analyzed given different study aims and empirical considerations (the Supplementary Information provides some suggestions of suitable analytical methods for different purposes). Nonetheless, these studies illustrate different analytical possibilities all aiming to reveal how patterns of social-ecological interdependencies can be theoretically and empirically associated with, in this example, differing capacities to effectively address environmental problems at appropriate scales.

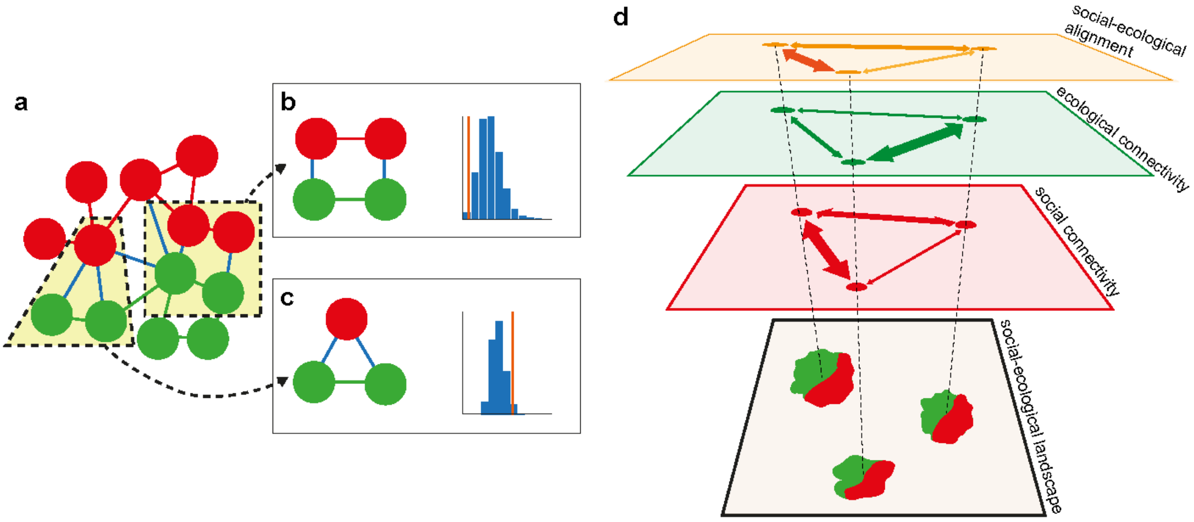


Fig 3. Social-ecological alignment in social-ecological networks. *(a) represents an example of a social-ecological network (social nodes are red, ecological nodes are green), and (b) and (c) represent two micro-level configurations present in the network that capture distinct aspects of social-ecological alignment. In (b), two linked social entities are separately linked to two interdependent ecological entities, hence this configuration represents a closed loop where social- and ecological links are aligned horizontally (closed four cycle). In (c), the same social entity is linked to two interdependent ecological entities, thus forming a closed loop (closed triangle, representing vertical alignment). The histograms in (b) and (c) depict how frequent these configurations appear in the social-ecological network compared to what we would expect by chance (i.e., the blue bars represent the results from a large number of simulated random networks, and the red bar represents the empirical network)*[16]*. In (d), a more simplistic social-ecological network is formed, where the nodes represent both social and ecological entities, but the social and ecological links are preserved as separate links (here laid out in the two planes named 'ecological connectivity' and 'social connectivity')*[55]*. The top plane captures to what extent the social and ecological links are aligned, i.e., the degree of social-ecological alignment, where an orange link implies a high degree of mismatch.*

Our schematic comparative analysis (presented more in-depth in the Supplementary Information) suggests that horizontal social and ecological alignment (Fig. 3b, d) are more common among higher levels of aggregation (Table 2). The propensities of actors to strive towards a tight alignment between an actor and any two interdependent ecological entities (vertical social-ecological alignment, Fig. 3c), however, seems to vary from case to case (Table 2). The one study attempting to examine whether global outcomes (Table 1) related to social-ecological structure relied on a two-case cross-sectional comparison at the lowest level of aggregation. Nonetheless, results from this study indicate that vertical social-ecological alignment (Fig. 3c) is associated with more desirable outcomes.

Based on the small number of cases, we refrain from drawing any far-reaching conclusions about social-ecological mismatch. In addition to the low number of cases, a full-fledged comparative analysis should ideally also address how exogenous macro social-political variables condition the effect that structures of social-ecological networks can have on outcomes (as well as control for the implication of other core governance challenges potentially also being present). However, we argue that the heuristic showed utility in enabling useful cross-case analyses. Ultimately, the full strength of the heuristic can only be unlocked if applied also a priori upon *initial study design*, and not only post priori as here.

Conclusions

The crucial importance of a better understanding of the causes and consequences of complex patterns of social-ecological interdependencies in social-ecological systems is frequently advocated. Integrated social-ecological network approaches have recently been proposed and applied in furthering this line of research, and early achievements are encouraging since they shift the research focus towards investigating and theorizing the precise pattern of interdependencies. Early work along these lines has delivered some substantive albeit pending insights, thereby demonstrating these network approaches provide a valuable addition to the broad methodological and theoretical toolbox that is needed to further sustainability research. The work has, however, concentrated on individual case studies given the substantial costs of collecting both social and ecological data needed for this type of research, although the use of online data could in some cases be utilized at lower costs[64]. Our goal in this paper is to begin the work of setting out a direction to help researchers using an explicit social-ecological network approach to orient their own research projects, and/or inspire others to, in one way or another, engage with this emerging research. Our aspiration is that the field encompassing social-ecological network research can, over time, build a corpus of empirical data with the intent to seek generalizations across multiple case studies.

To accomplish this, we argue two key advances are needed. First, there is a need to be more clear on assumptions of causality. To that end, we propose a typology of causal relationships in order to facilitate a research process where causal assumptions are made clear, and where the choices of applied analytical methods are congruent with these assumptions. Second, there is a need to rapidly move beyond the possible idiosyncrasies inherent in single cross sectional case studies. Instead, research programs coordinating worldwide and systematic efforts to gather data facilitating comparability and synthesis of insights across different cases and context are paramount to the generation of cumulative knowledge (cf. ref.[63,28]). To that end, we present some unifying research design considerations to facilitate comparisons across case studies taking on a social-ecological network approach. These considerations are also useful in their own right in helping researchers to elaborate some critical decisions in defining the study object. Further, based on the assumption that any given environmental problem is not inherently unique, but instead typically reflects, to a varying extent, a series of re-occurring features, a set of core *governance challenges* that occur repeatedly across many different cases and contexts are defined.

These advances are combined into a comprehensive heuristic suitable for cross-case comparisons with the objective to advance generalizable theory developed within relevant, and theoretically and empirically defendable, bounds. Using a small set of previous studies, we illustrate the potential for our heuristic. This comparative analysis does yield some new insights in relation to the core governance challenge *scale sensitivity/fit*, even though the number of relevant cases is small. Our heuristic expands the existing toolbox of research approaches, thereby advancing progress towards empirically revealing the root causes and effects of complex social-ecological interdependencies across different scales and contexts.

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Author contributions

Ö.B. designed and performed the research, led the collaborative work and the writing of the paper. All other authors contributed to the research, the analyses and the writing based on their specific expertise.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information is available for this paper