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

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Supplementary Information

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Supplementary Methods

Suitable analytical methods for different assumptions of causal relationships

There is an enormous breadth of analyses and metrics, developed across scientific disciplines, that are applicable when studying and analyzing networks. Hence, the challenge facing an analyst is most often to choose the most appropriate analysis given the specific objectives of the study, and the constraints and assumptions associated with the study object. Below we present a non-exhaustive list of analytical approaches that could serve as a starting point for further inquiry. The choice of suitable analytical methods depends, among other things, on whether the social-ecological network is considered an independent or dependent variable (Table 1). If the network is treated as a dependent variable, Exponential Random Graph Models (ERGM) or Stochastic Actor Oriented Models (SAOM) are very useful since they assume that the empirical network is formed based on processes that could be captured as different micro-level configurations ("motifs")[1]. SAOMs, in particular, use longitudinal network data to infer how networks change over time, and attempt to disentangle the node-level factors that can explain these changes (each node's creation, maintenance, and destruction of links over time form the empirical basis). Thus, SOAMs provide a method for direct empirical assessment of causality (assuming all relevant variables are observed), whereas ERGMs build on the modeling assumption that the observed (cross-sectional) network structure emerges from certain propensities to form certain micro-level configurations.

As advocated for here, a social-ecological network can often be favorably described as a multilevel network (one level represents the actors and their relationships, and one level the ecological entities and their interdependencies, and the links across these levels represent social-ecological interactions of various kinds (Fig. 1 & 3)). Using this model, a recent multilevel extension to ERGM is particularly useful for analyses since it allows the analyst to, for example, apply and explicate different assumptions on what kinds of structures (links) should be considered as structuring/influencing the creation/maintenance/extinctions of other types of links[2]. Further, it also enables hypothesis testing and development through elaborations on micro-level networks and their possible causes and consequences ("motifs", see Fig. 3).

If the network is treated as an independent variable (if and how macro-level network properties influences specific outcomes), the analyst could still use ERGMs and/or SAOMs since they also provide a means to define the whole network as the sum of its micro-level configurations. It would however also be suitable to look at the network's macro-level properties such as density, cohesiveness, degree distribution, clustering, centralization, factions, etc.[3]. The general idea would be to select and/or define relevant measures capturing some structural characteristics (i.e. patterns) of the social-ecological networks that are hypothesized to explain or capture how the characteristics of the social-ecological system relate to different social-ecological outcomes. Defining such characteristics could however also be the result of an explorative examination of a set of empirical networks. For example, an explorative analysis could be conducted on a high number of networks to see if highly centralized networks tend to give rise to certain social-ecological outcomes.

Social-ecological systems are, as stated, characterized by multiple, interacting types of relationships. Hence, there are many different types of links that potentially strongly influence specific outcomes. Individuals and organizations, for example, can share information and knowledge as well as opinions, but also participate in resource or financial exchanges that may impact the ecological system or have conflictual relationships due to different objectives and cultures. Further, within the ecological system, one can e.g. think of certain habitats found in a specific landscape to be of crucial importance for some species but not for all species. Given such multiple interdependencies, *multiplex* (often referred to as *multilayer*) network analysis can allow to assess the overall structural properties of a social-ecological system without separating the complexity into one social and one ecological network (as in the multilevel approach described above), hence giving a sometimes more adequate picture of how the overall structural properties influence social-ecological outcomes [45].

To clarify, when using multiplex/multilayered networks, we assume that each type of relationship forms a "layer" of the overall network (see Fig. 3d). The use of multilayer networks to analyze social-ecological systems can help revealing certain macro-level structural properties affecting specific outcomes. Such relationships are, in general, not possible to infer only by looking at micro-level configurations, nor by aggregating the complexity of social-ecological systems into one social and one ecological network (Fig. 1a).

Defining appropriate nodes and links

Overall, to maximize the relative utility of a social-ecological network based study versus other approaches, both social and ecological nodes should be defined in a way that they are relevant to each other in terms of impacts, i.e. a social node (or a small group of nodes) should be able to influence the status of an ecological node in a significant way, and vice versa[6]. If that is not the case, the utility of applying a social-ecological network model would be of limited value. Generally, the more there is a 1-to-1 "influence relation" between a social and an ecological node, the more an integrated multi-level social-ecological network approach will be useful (and aiming for a balanced influence relation also gives clear guidance on how to choose the most appropriate levels of social- and ecological aggregations). Also, as elaborated in the main text, the ecological node could be a distinct biophysical entity such as a specific forest patch, but also a specific 'issue' (Fig. 1b). Further, in cases when either the social or the ecological network is bordering on trivial (e.g. only a very few number of nodes, and/or where individual nodes in one network are not strongly impacted by individual nodes in the other layer), an analyst can likely disregard that (social or ecological) network and perhaps instead focus on the other network.

Similarly, the social ties in a social-ecological network need to be defined based on the assumptions that the social ties influence social nodes (e.g. actors) in such a way that can or does affect how their social-ecological links are being utilized, and vice versa. Otherwise, what goes on in either the social or the ecological networks would not affect anything outside that network. Hence, defining appropriate social and ecological links is informed by which social-ecological interactions are in focus.

Further, the links connecting the ecological nodes could either represent a 'scientific' assessment of relevant ecological interdependencies, or represent actors' perceptions about how ecological nodes are interdependent. The overall guiding principle should be that if the focus is to primarily understand how actors behave and make decisions, the definition of ecological nodes and links should coincide with how actors perceive the issues that together constitute the environmental problem(s)(Fig. 1b). Conversely, if the focus is to understand how different decisions and resource uses affect environmental outcomes, the definition of ecological nodes and links should primarily derive from biophysical realities and not from actors' perceptions of such.

Table S1 – Design considerations in defining social-ecological networks

Component to define	**Considerations in defining the component**
Nodes	*Social nodes* The most straightforward conceptualization of social nodes would be the actors of relevance given the environmental problem. An actor could be an individual, household, or an organization of some sort. However, in other cases it makes more sense to define a social node as an institution, i.e. as a set of rules and norms to regulate certain behaviors; a policy document; or specific geographic areas or political entities. *Ecological nodes* This could be the ecological components of relevance given the environmental problem under consideration. A relevant node could be a well-defined ecological resource or a biophysical component, such as a forest patch or a targeted fish species. More complicated study objects might require a more abstract definition of an ecological node, e.g., based on the notion of "sub-problems" or "issue". An issue could be defined based on how different processes contribute to the overall environmental problem under consideration (e.g., if the main environmental problem under consideration is the loss of biodiversity, this problem is deriving from many different issues such as the loss of habitats, pollution, resource extraction, etc.). An issue could also be defined based on how a governing system has constructed different policy processes (i.e. issues); each with their own possible implications on the environmental problem under consideration.
Links	*Social-ecological links* Based on the social-ecological interdependencies that are assumed to be important in understanding and theorizing the environmental problem under consideration (e.g., property rights, occupancy, mandates/responsibilities, resource harvest/dependence, energy acquisition, ecosystem service utilization, etc.). *Ecological links* Defined through assumptions of how the ecological nodes can affect each other (e.g. species dispersal, flow of contaminants/invasive species, conflicting or synergistic uses of common resources, juridical overlap etc.). Further, these links should also be defined by taking the ecological consequences the chosen type of social-ecological interaction can give rise to into account. In other words, only ecological interdependencies that are related to the changes the chosen social-ecological interactions can induce on the ecological nodes should be considered. *Social links* Defined based on the social structures and processes at play that are assumed to be relevant to the chosen social-ecological links and the core governance challenge (typically, social interactions that represent different forms of working together, social learning etc., but other negative types of social interactions such as antagonistic behaviors or power imbalances could also be relevant).

Supplementary Results

Applying the heuristic

One study fits to the highest level of aggregation, and is based in the coastal Pacific Northwest of the USA[7]. The social nodes here represent "ocean-related state and federal laws and regulations that pertain to the west coast of the United States for the year 2006"[7], and the ecological nodes represent key components of a conceptual ecological model of the Pacific Northwest.

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 modeled as social nodes[8]. The network model does not include distinct ecological nodes, but it encompasses two types of links between the social nodes: the degree of ecological connectivity for a selected number of coral reef dwelling species, and the degree to which the states have signed on to joint agreements such as international arrangements and conventions. 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[9]. The social nodes represent key organizations and groups involved with some aspect of land-sea governance, and the ecological nodes represent key types of habitat, land cover, and land use that are found in each respective landscape and seascape. Thus, the ecological nodes were assessed as exhibiting a fairly high level of aggregation, whereas the social nodes were less aggregated in the sense that they represent individual organizations.

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[10,2]. In Madagascar, the social nodes represent clans, and the ecological nodes represent distinct forest patches in the agricultural landscape. The Kenyan case models groups of fishers using the same fishing gear type as social nodes, and targeted fish species as ecological nodes. The second study is based in Western Australia and analyzes a large-scale conservation program where individual organizations who undertake conservation and management activities in the study area were modeled as social nodes[11]. The ecological nodes represent vegetation clusters in the area targeted for conservation. The third study is based in and around metropolitan Stockholm in Sweden, and models the municipalities in the county as social nodes. Similar to the Indo West Pacific study[8], no distinct ecological nodes were defined; however, two types of links between municipalities were assessed. The first type represent engagement in joint planning activities, and the second represent ecological connectivity between wetlands residing in different municipalities.

Starting with the highest level of aggregation, the Pacific Northwest study neither tested (i) whether there is a propensity for social-ecological scale alignment (the "selection" type of causal assumption, Table 1); nor (ii) whether alignment led to certain social-ecological outcomes (the "Global network outcome" and "Global outcomes derived from and mediated by individual choices and behaviors in networks" types of causal assumption, Table 1). Rather, it was descriptive in the sense that it mapped out where in the social-ecological network alignment was present or not. Nonetheless, the study identified large differences in terms of misalignment. In particular, climate change stood out as not being well aligned from an institutional point of view with other interdependent key components of the social-ecological system. Furthermore, the study also noted important differences between states, e.g., only one state had taken steps implementing Ecosystem-Based Management (EBM)[12], and overall it had higher levels of social-ecological alignment. This shows, qualitatively, that alignment was likely not the result of a stochastic process, and thus deliberate efforts towards increasing social-ecological alignment can lead to structural changes that can be revealed using a social-ecological network approach.

The middle level study of the Indo West Pacific was similar to the Pacific Northwest study in that no causal assumption was tested. However, it showed a fairly high level of social-ecological alignment, while at the same time highlighting some significant gaps. The other middle level study in the Lesser Antilles, however, used a multilevel Exponential Random Graph Model (ERGM)[13] to explicitly test whether actors had a propensity to engage in configurations associated with social-ecological alignment (the "selection" type of causal assumption, Table 1). The results were a bit mixed in terms of whether there was any *general* tendency of actors to engage in, or avoid, closed four cycles where social and ecological links are aligned horizontally (Fig. 3b), yet there was a tendency for actors to engage in closed four cycles that crossed the land/sea interface (i.e., actors defined as mostly land- or sea-oriented, and having stakes in interdependent land and sea components, tended to be socially tied). In contrast, actors who were mostly land- or sea-oriented had a significant tendency overall not to be socially tied to each other (unless they, as stated, engaged in interdependent land and sea component). Hence, the results were a bit inconclusive in terms of actor propensities to form social ties in ways that reduce social-ecological mismatches.

The municipality study residing at the lowest level of aggregation showed similar results as the Lesser Antilles study in that it showed no statistically significant overall propensity to form closed four cycles[8]. The other two studies at this level also used multilevel ERGMs, and both showed a propensity not to engage in closed four cycles. In other words, there is a propensity for actors to be organized in a way that does not favor this type of social-ecological alignment. On the other hand, both the Western Australian case and the Madagascar case showed a clear tendency for actors to engage in closed triangles. In contrast, in the small-scale fishery case in Kenya actors did not show any tendencies to engage in closed triangles, i.e., when a social entity is linked to two interdependent ecological entities (Fig. 3c), albeit this analysis applied a more simplistic approach rather than fitting an ERGM.

The only study with 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" types of causal assumption, Table 1) compared the Kenyan and the Madagascar cases previously described[10]. The former was qualitatively assessed as less successful in terms of preservation of ecological resources than the latter. In light of this, the difference in terms of the actors' propensities to engage in closed triangles is very interesting. These results are indeed in line with theoretical expectations, i.e., that a better social-ecological match should lead to more desirable outcomes. Of course, this has to be an interim conclusion: (i) a range of other factors that could potentially explain these differences in outcomes needs to be investigated; (ii) the cases may have been confronted with other core challenges that also could have impacted outcomes; (iii) the comparison is based on just two single case studies; and (iv) most importantly, we are only observing associations, so a causal direction can only be hypothesized, not inferred.

References

1. Moreno, J. L. & Jennings, H. H. Statistics of social configurations. *Sociometry* **1**, 342–374 (1938).

2. Bodin, Ö. *et al.* Theorizing benefits and constraints in collaborative environmental governance: a transdisciplinary social-ecological network approach for empirical investigations. *Ecol. Soc.* **21**, 40 (2016).

3. Wasserman, S. & Faust, K. *Social Network Analysis - Methods and applications*. (Cambride University Press, 1994).

4. Kivela, M. *et al.* Multilayer networks. *J. Complex Networks* **2**, 203–271 (2014).

5. Baggio, J. A. *et al.* Multiplex social ecological network analysis reveals how social changes affect community robustness more than resource depletion. *Proc. Natl. Acad. Sci.* **113**, 13708–13713 (2016).

6. Bodin, Ö. & Tengö, M. Disentangling intangible social–ecological systems. *Glob. Environ. Chang.* **22**, 430–439 (2012).

7. Ekstrom, J. A. & Young, O. R. Evaluating Functional Fit between a Set of Institutions and an Ecosystem. *Ecol. Soc.* **14**, 16 (2009).

8. Treml, E., Fidelman, P. I. J., Kininmonth, S., Ekstrom, J. & Bodin, Ö. Analyzing the (mis)fit between the institutional and ecological networks of the Indo-West Pacific. *Glob. Environ. Chang.* **31**, 263–271 (2015).

9. Pittman, J. & Armitage, D. How does network governance affect social-ecological fit across the land-sea interface? An empirical assessment from the Lesser Antilles. *Ecol. Soc.* **22**, art5 (2017).

10. Bodin, Ö., Crona, B., Thyresson, M., Golz, A.-L. & Tengö, M. Conservation Success as a Function of Good Alignment of Social and Ecological Structures and Processes. *Conserv. Biol.* **28**, 1371–1379 (2014).

11. Guerrero, A. M., Bodin, Ö., McAllister, R. R. J. & Wilson, K. A. Achieving social-ecological fit through bottom-up collaborative governance: an empirical investigation. *Ecol. Soc.* **20**, 41 (2015).

12. Christensen, N. L. *et al.* The Report of the Ecological Society of America Committee on the Scientific Basis for Ecosystem Management. *Ecol. Appl.* **6**, 665–691 (1996).

13. Wang, P., Robins, G., Pattison, P. & Lazega, E. Exponential random graph models for multilevel networks. *Soc. Networks* **35**, 96–115 (2013).