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Studying human–nature relationships through a network lens: A systematic review

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Abstract

1. Understanding the complex interlinkages between humans and nature is crucial for developing strategies to effectively manage natural resources and to enhance resilience of social–ecological systems (SES). Network analysis bears great potential to advance such comprehension of SESs because it allows for identifying and analysing direct and indirect relationships and processes. As a result, the number of network studies in social–ecological research has rapidly grown over the last decade.
2. This work systematizes existing network approaches for analysing human–nature relationships based on the level of integration of both the social and ecological realms in the network conceptualization.
3. A structured inductive review of existing empirical network studies exploring a wide range of phenomena at the human–nature interface was conducted, resulting in 138 studies falling into three proposed categories. We examine their network conceptualization and means of analysis, and discuss challenges and potentials of each of the three categories in empirical research.
4. The study highlights the diversity and creativity with which distinct social and ecological entities are defined to enable the use of a variety of network analytical approaches in SES research.
5. Demonstrating the increasing recognition of network analysis to describe human–nature relationships since the early 2000s and providing an overview of the many useful conceptual and methodological approaches, this article contributes to systematizing the existing studies and provides practical guidance for network research to help disentangling complex SES.

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KEYWORDS

complexity, connectivity, natural resource management, network analysis, social–ecological modelling, social–ecological network, social–ecological system

1 | INTRODUCTION

Human activities and environmental change alter ecological systems (Halpern et al., 2008; Kappel, 2005), often with unpredictable consequences for delivering ecosystem services essential to societal well-being and development world-wide (MEA, 2005; Rockström et al., 2009). This is aggravated by cumulative impacts of anthropogenic stressors progressing with a continuously growing human population (Giakoumi et al., 2015; Halpern et al., 2015, 2019). Understanding and predicting the consequences of environmental change and/or of management intervention has increasingly received scientific interest in recent years. Modelling approaches to predict responses of ecosystems to anthropogenic influences include mechanistic models, statistical models and machine learning approaches (Schuwirth et al., 2019), although the underlying model assumptions and uncertainties are often enough not specified, impeding the effective use for decision-making (GREGG & Chan, 2015). In addition, ecological and social systems interact in complex and dynamic ways at different geographical and temporal scales forming interlinked social–ecological systems (SES; Berkes, Colding, & Folke, 2003; Folke et al., 2010; Hughes, Carpenter, Rockström, Scheffer, & Walker, 2013). The dynamic processes in the ecological and social (sub-)systems and their interlinkages produce outcomes at the larger SES level, which, in turn, influence and change the subsystems and their components (Brondizio, Ostrom, & Young, 2009; Ostrom, 2009). This is why understanding these complex interdependencies in SESs is critical to developing effective strategies for steering towards more sustainable and resilient human–nature relationships (Bodin, Robins, et al., 2016; Yletyinen, Hentati-Sundberg, Blenckner, & Bodin, 2018).

Network analysis (NA) is a powerful tool for investigating relational structures and processes (Janssen et al., 2006). The elements of interest are represented as nodes (also called vertices or actors) and the interaction(s) between them as links (also called edges, ties or arcs; see Figure 1). The analysis of relational structure has a long research tradition in various academic fields, including social sciences (i.e. social network analysis [SNA], cf. Burt, 1992; Emirbayer & Goodwin, 1994; Granovetter, 1973; Moreno, 1934—but consider Freeman, 1996, for an overview of even earlier steps towards SNA) and ecology (ecological network analysis [ENA], cf. Fath et al., 2019; Fath & Patten, 1999; Finn, 1976; Hannon, 1973; Ulanowicz, 1980, 1983). Social systems may be understood as networks in which nodes commonly represent individual persons or collective actors (Lusher, Koskinen, & Robins, 2013; Wasserman & Faust, 1994). Analyses may then, for example, focus on flows between these social entities, such as passing on non-material (e.g. information, advice; cf. Barnes, Lynham, Kalberg, & Leung, 2016; Crona, Gelcich, & Bodin, 2017; Weiss, Hamann, Kinney, & Marsh, 2012) or material

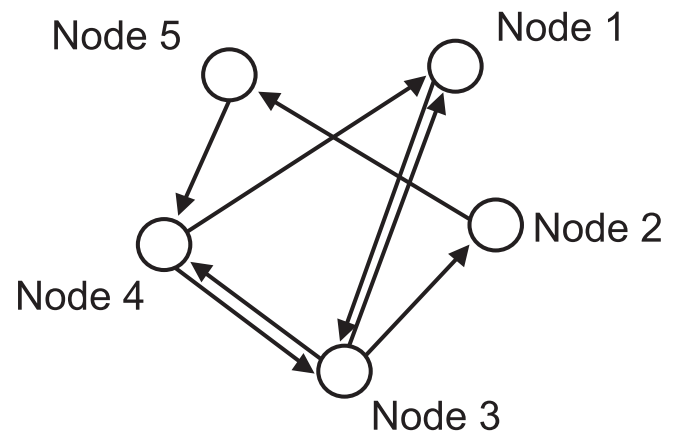


FIGURE 1 Example of the graphical representation of a directed network showing relationships (called links, edges, arcs or ties) between five hypothetical entities (called nodes, vertices or actors; figure first published in Kluger, Kochalski, Müller, Gorris, & Romagnoni, 2015)

goods or services (e.g. fishery products; cf. Baggio et al., 2016) to another social entity within the network boundaries. In the ecological realm, network analysis may be used to study interdependencies between parts of an ecosystem (Ulanowicz, 2004), considering networks of direct and indirect interactions between groups of organisms and abiotic components (e.g. nutrients, detritus) in a system of geographically defined areas of landscape (e.g. a lake, a forest patch). Their interactions (links) may depict trophic (i.e. feeding; cf. Allesina & Ulanowicz, 2004; Christensen & Pauly, 1992; Christensen & Walters, 2004; Fath & Patten, 1999; Wulff, Field, & Mann, 1989) or non-trophic interactions such as larvae dispersal (Keith, Herbert, Norton, Hawkins, & Newton, 2011), movement of organisms (Urban & Keitt, 2001), competition (Kéfi et al., 2012, 2015) or mutualism (Bascompte & Jordano, 2007; Rohr, Saavedra, & Bascompte, 2014).

In recent years, NA has increasingly been used for studying diverse phenomena at the human–nature interface, for example, to explore the impact of natural resource use (by humans) on a specific ecological system (e.g. Baird, Fath, Ulanowicz, Asmus, & Asmus, 2009; Bodin & Prell, 2011; Fath, Scharler, Ulanowicz, & Hannon, 2007; Heymans, Coll, Libralato, Morissette, & Christensen, 2014; Rocchi, Scotti, Micheli, & Bodini, 2017; Villasante et al., 2016). Drawing on graph theory, NA is a systematic approach to organizing, categorizing and quantifying the various components of a predefined system based on empirical data (Lusher et al., 2013; Wasserman & Faust, 1994), and is—in theory—well-suited to investigate relationships and system structures within complex SESs (Janssen et al., 2006). In the context of environmental governance, network analysis is often derived from the assumption that network structures help explaining the

effectiveness of governance output. For example, more centralized networks were discussed to facilitate effective and quick responses to high-risk environmental governance challenges such as invasive species eradication (Lubell, Jasny, & Hastings, 2016), however seem to be less robust to changing socio-political circumstances (Gorris & Glaser, in press). To give some examples, Marín, Gelcich, Castilla, and Berkes (2012) related co-management performance to social networks (reflecting social capital) of small-scale fishers involved in co-management regimes of benthic resources in Chile. Partelow and Nelson (2020) used NA to study the evolution of self-organized institutions for the governance of the dive tourism sector on an Indonesian island, analysing how the social collaborative networks of dive shop owners stipulated collective action for the emergence of adaptive environmental governance. A steadily growing number of studies uses the notion of social-ecological networks (SENs; cf. Sayles et al., 2019). However, the integrated analysis of social and ecological system components remains challenging (Bodin, Robins, et al., 2016; Cumming, Bodin, Ernstson, & Elmqvist, 2010), because of, for instance, the different conceptualizations of nodes and links in the social and ecological realm (Bodin et al., 2019) and differing terminology and scopes (Sayles et al., 2019).

In this research, we review studies carried out in the context of natural resource management that use network analysis of empirical data with the aim to (a) offer a systematic overview of existing approaches to conceptualize and analyse human-nature relationships and (b) to examine their potentials and challenges for practical use in natural resource management. We use a typology of network studies based on the degree to which both realms (human, nature; represented by ecological and/or human (societal, institutional) actors, as well as possible links between them) are integrated in the network conceptualization. Subsequently, we conduct a structured, purposive review of existing network studies, and systematize the studies based on the typology. The specific focus of this effort lies on synthesizing how networks are conceptualized, what means of analysis are applied and in what environmental setting (i.e. ecosystem type) the studies are embedded in. After presenting the results, we then discuss the comparative challenges and potentials of the different network analytical approaches in the context of the ongoing scientific discourses on networks and natural resource management.

The study complements recent efforts that push methodological and theoretical advancements in SEN analysis with the aim to allow for more integrated network research (see e.g. Barnes et al., 2019; Bodin, Robins, et al., 2016; Bodin & Tengö, 2012; Sayles et al., 2019). The discussion of the results of our study, however, emphasizes also the benefits of the diversity of *partially articulated* (sensu Sayles et al., 2019) network conceptualizations and approaches for tackling various possible challenges for natural resource management in the context of complex human-nature relationships. This diversity allows researchers to select an approach that is best suited for a particular case study or research context, and to address the specific questions at hand. Our article particularly aims

to assist researchers interested in studying human-nature relationships through a network lens who are new to the topic, by adding an even broader view to the perspective than presented by the abovementioned authors, as to be able to choose the most suitable approach for their study by discussing potentials and challenges of the different approaches and show-casing previous studies. Moreover, we take stock of the empirical network studies in the literature on natural resource management and discuss potentials and pathways for further research.

2 | TYPES OF NETWORK CONCEPTUALIZATIONS

Countless possibilities to conceptualize SES as networks exist and there are numerous ways to conceptualize links within and between social and ecological system components. For example, some may categorize a link as ecological if it entails the exchange of a natural resource (e.g. the selling of fish or sharing of wood; Baggio et al., 2016), or as social if it describes an anthropomorphized action (e.g. cohesion among dolphins, e.g. Wiszniewski, Lusseau, & Möller, 2010). However, general archetypes of network conceptualizations can be derived from the degree to which social and ecological components and relationships are included. Following Bodin and Tengö (2012), a SES can be thought of as consisting of both social and ecological entities (i.e. nodes) representing the social and ecological SES subsystems. These two units may be connected by three types of links: (a) those that connect social nodes (SS links), (b) those that connect ecological nodes (EE links) and (c) links that connect social and ecological nodes (SE links; for a schematic representation see Figure 2). Hence, we define the different types of links based on the nodes they interrelate, not on the nature of the link itself. Acknowledging that there are other concepts, based on our definition, social-ecological edges only describe those links crossing the human-nature interface.

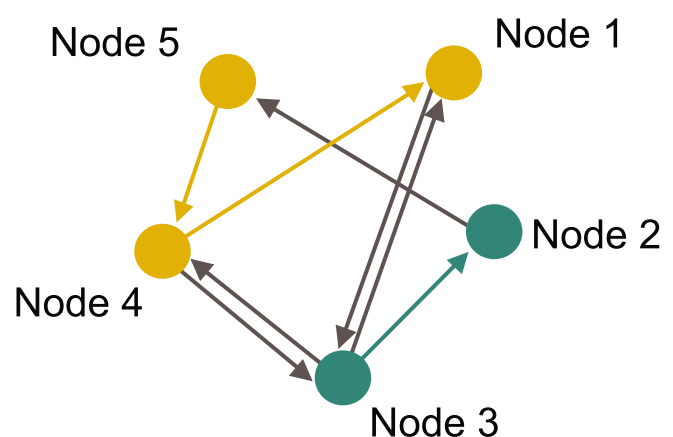


FIGURE 2 Theoretical conceptualization of a directed network consisting of social (in yellow) and ecological (in green) nodes connected by three types of links: social-to-social (SS, in yellow), ecological-to-ecological (EE, in green) and social-ecological (SE, in grey)

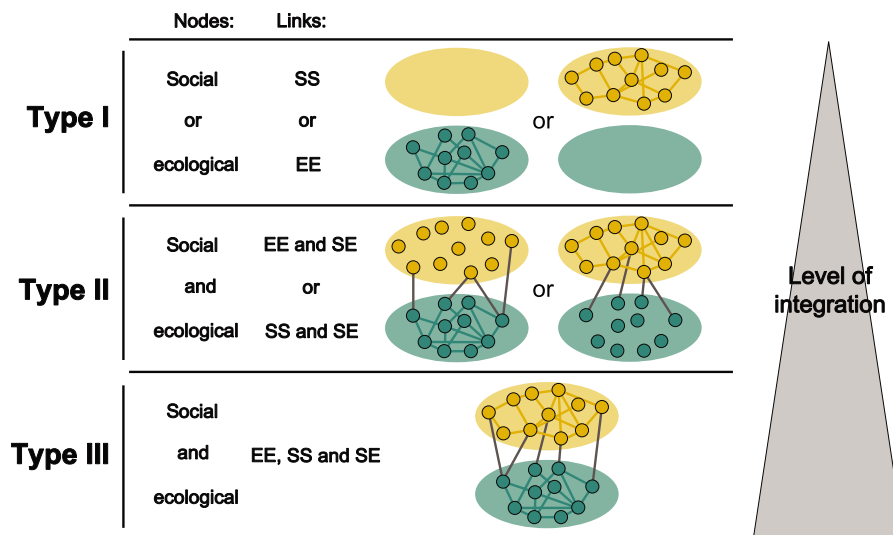


FIGURE 3 A typology of network studies analysing human–nature relationships in social–ecological systems based on different levels of integration of the social (yellow) and/or ecological (green) realm. EE, ecological-to-ecological links; SE, social–ecological links; SS, social-to-social links (for further conceptualization of links compare Section 2 and Figure 2)

Consequently, three different archetypes of network conceptualizations emerge (Figure 3):

- **Type I** considers one type of nodes (either from the social or from the ecological realm) and one type of link (either SS or EE interactions). Since only one realm (social or ecological) is represented, SE links are not incorporated.
- **Type II** integrates two types of nodes (from both the social and from the ecological realm) and two types of links (SS and SE, or EE and SE links). Although the interaction of one realm with certain actors from the respectively other dimension is conceptualized, no further links between the nodes of that other realm are considered.
- **Type III** comprises two types of nodes (from both the social and from the ecological realm) and three types of links (SS, EE and SE) between these actors.

While Type I integrates only entities and their interactions from one realm (either the ecological or social dimension), Type II and III integrate both dimensions—but to different degrees—into the network conceptualization (Figure 3). In Type II studies, two of three possible link types are included, while in Type III networks elements of both social and ecological realms and all types of interactions are considered. Studies falling into the Type II and III categories therefore represent *partially* and *fully articulated* (sensu Sayles et al., 2019) SENS, respectively.

3 | METHODS

Following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol (sensu Liberati et al., 2009), we applied a structured, purposive approach to systematic sampling, analysis and synthesis of research articles that investigate human–nature relationships in SES through a network analysis approach. Relevant studies were identified using the core collection of ISI Web of Knowledge (www.webofknowledge.com), conducting two searches in June 2019 (for records from 1900 to mid-2019) and in May 2020 (for all records

in 2019). Search strings consisting of keywords relevant to study human–nature relationships in SES research were identified through several rounds of discussion among all authors, and were then consistently used for both searches (for the exact terms included in the search string, see Table 1). Only peer-reviewed journal articles published in English until 31/12/2019 were considered, that is, excluding book chapters, editorial material, pure reviews and books. In total, the search retrieved 656 articles (Table 1). Full records of each search string were downloaded as individual BibTeX files that were joined in the R environment (R Core Team, 2019) using the BIBLIOMETRIX package (Aria & Cuccurullo, 2017). Graphics presenting results (i.e. Figures 5 and 6) were created using the R packages READXL (Wickham & Bryan, 2019) and GGLOT2 (Wickham, 2009), while for Figure 6, additionally the package DPLYR (Wickham, François, Henry, & Müller, 2019) was used.

All articles were reviewed and included in the analysis if they (a) applied a network approach to empirical data and (b) focused on human–nature relationships. For this, the notion of ‘human–nature relationship’ was defined in a broad sense, that is, studies were included if they explicitly aimed to improve management or governance of the natural environment (ecosystems, natural resources, SES, etc.), to understand human impacts on ecosystems, to analyse implications of ecosystem change on humans or offered explicit policy implications relevant for at least one of these three research areas. These criteria did not have to be explicitly stated within the study, but had to be identifiable for coders. Since this study focused on network approaches based on graph theoretical foundations, studies using other theoretical concepts for studying networks (e.g. neural networks, Bayesian networks) were excluded. Theoretical work was only considered if it contained tests of respective assumptions on empirical datasets. Following these criteria, 138 of the 656 studies initially encountered were classified as relevant (Figure 4).

The selected articles were then reviewed with regard to the type of nodes and links, and how these were conceptualized, based on the described typology (Section 2, Figure 3). Moreover, the study system (terrestrial, freshwater, marine) was recorded, as well as other characteristics related to the case studies (e.g. country and continent, year of publication). The coding was first tested in a pilot classification of

TABLE 1 Search strings identified through several rounds of discussion among co-authors and then applied for the retrieval of literature from the ISI Web of Knowledge database. Peer-reviewed journal articles published in English, that is, excluding book chapters, editorial material, pure reviews and books were considered, resulting in a total of 656 articles (Figure 4). Full records of each search string were downloaded as individual BibTex files that were joined in the R environment (R Core Team, 2019) using the BIBLIOMETRIX package (Aria & Cuccurullo, 2017). Two search events in June 2019 and May 2020 retrieved records for until 2019 and for 2019, respectively (cf. Section 3 for more details)

Search string	Number of hits (for until 2019)	Number of hits (for 2019)
'social-ecological network' OR 'socio-ecological network' OR 'eco-social network'	25	5
'ecological network' AND 'social'	96	23
'social network' AND 'ecological'	427	70
'social-ecological system' AND ('network approach' OR 'network analysis' OR 'network model')	15	4
'socio-ecological system' AND ('network approach' OR 'network analysis' OR 'network model')	6	2
'social-ecological' AND ('network approach' OR 'network analysis' OR 'network model')	113	21
'socio-ecological' AND ('network approach' OR 'network analysis' OR 'network model')	30	12
'eco-social' AND ('network approach' OR 'network analysis' OR 'network model')	1	0
'eco-social system' AND ('network approach' OR 'network analysis' OR 'network model')	0	0
Total	713	134
Total (after removing duplicated studies appearing in more than one search string)	587	100
Total (after removing duplicated studies appearing in both search events for the year 2019)		656

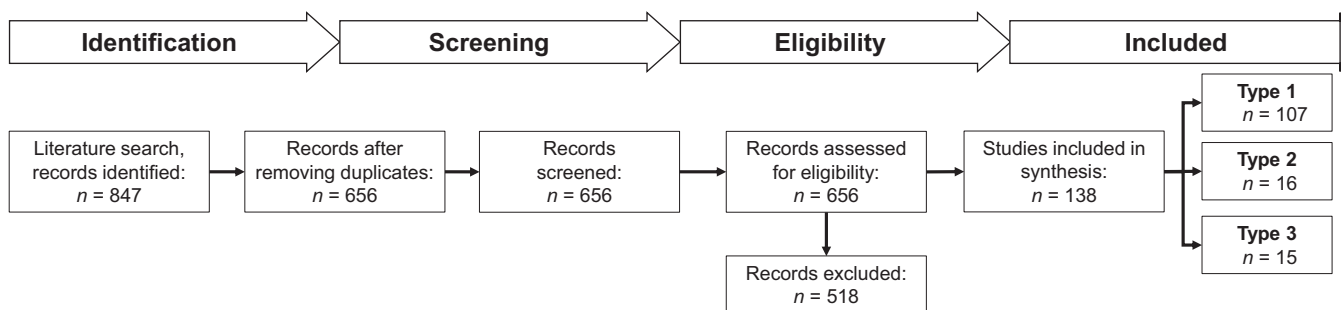


FIGURE 4 PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses, sensu Liberati et al., 2009) protocol demonstrating the different steps of the here presented literature review for identifying studies applying a network approach to investigate human-nature interactions

five articles done by all five authors, with codes per category emerging from the data itself. After having discussed the procedures and results of the pilot, all authors classified a comparable number of randomly assigned articles. Reliability and homogenization of coding between articles was achieved through cross-checking between authors and consensus-building discussions. The compiled data reviewed and analysed in this study have been made publicly available on the Zenodo Digital Repository (Kluger et al., 2020).

4 | RESULTS

4.1 | Quantitative overview

Network analysis in SES research showed to be a relatively young research field, with the first publication retrieved by our search string

dating back to 2006. Particularly since 2012, the annual number of relevant publications rose, reaching more than 16 published studies annually since 2014 and the highest value of 24 studies in 2017 (Figure 5). The first study falling into Type III was published in 2010, and the first Type II in 2013, after which the number of publications of these Types steadily rose (Figure 5). Overall, 78% ($n = 107$) of the studies fell into category Type I, 12% ($n = 16$) into Type II and 11% ($n = 15$) into Type III (Figure 6a). Regarding the type of nodes used in the studies, all studies falling into Types II and III (i.e. 23% of total) included both social and ecological nodes (Figure 6b), while 86% ($n = 92$) of the studies falling into Type I worked exclusively with social nodes and 13% ($n = 14$) focused on ecological nodes only. One Type I study (1% of all Type I) used two networks with ecological and social nodes, respectively, while analysis was conducted separately.

Since five studies used stylized networks for empirical analysis (i.e. they did not use a specific case study), 133 studies were classified

for the system type in which the data were collected (Figure 6c). The majority of studies focused on land-based systems (64%, $n = 85$ of these 133 studies), followed by marine (24%, $n = 32$) and freshwater

(9%, $n = 12$) ecosystems; only 3% ($n = 4$) of the studies included data from more than one system type (Figure 6c).

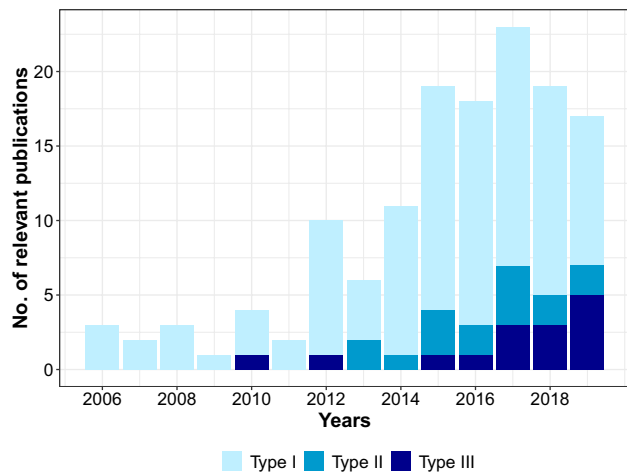


FIGURE 5 Number of studies using a network approach for studying human–nature interactions in social–ecological systems ($n = 138$) falling into the three proposed categories (Types I–III, compare Figure 3) over time (2006–2019)

4.2 | Type I network studies for SES research

Type I studies were defined to look at one node type, either from the social or from the ecological realm, and the links (either SS or EE) between them (compare Figures 2 and 3). The literature search identified 107 studies that corresponded to the Type I category (compare Figure 6a; Table 2). Most of these studies represented resource users or actors from the social realm involved in governing environmental problems as nodes. The idea of ‘social capital’ represented the most commonly used theoretical concept in the social setting and was applied, for instance, in the context of managing marine resources in a Kenyan fishing community (Bodin & Crona, 2008), or among fisher cooperatives in Chile to assess post-disaster trajectories (Marín, Bodin, Gelcich, & Crona, 2015). Especially the two aspects ‘collaboration’ and ‘information flows’ among individuals or groups have attracted considerable attention. One study, for example, showed how distinct patterns of collaboration between actors involved in ecosystem-based management in Sweden impact their ability to develop specific environmental policy

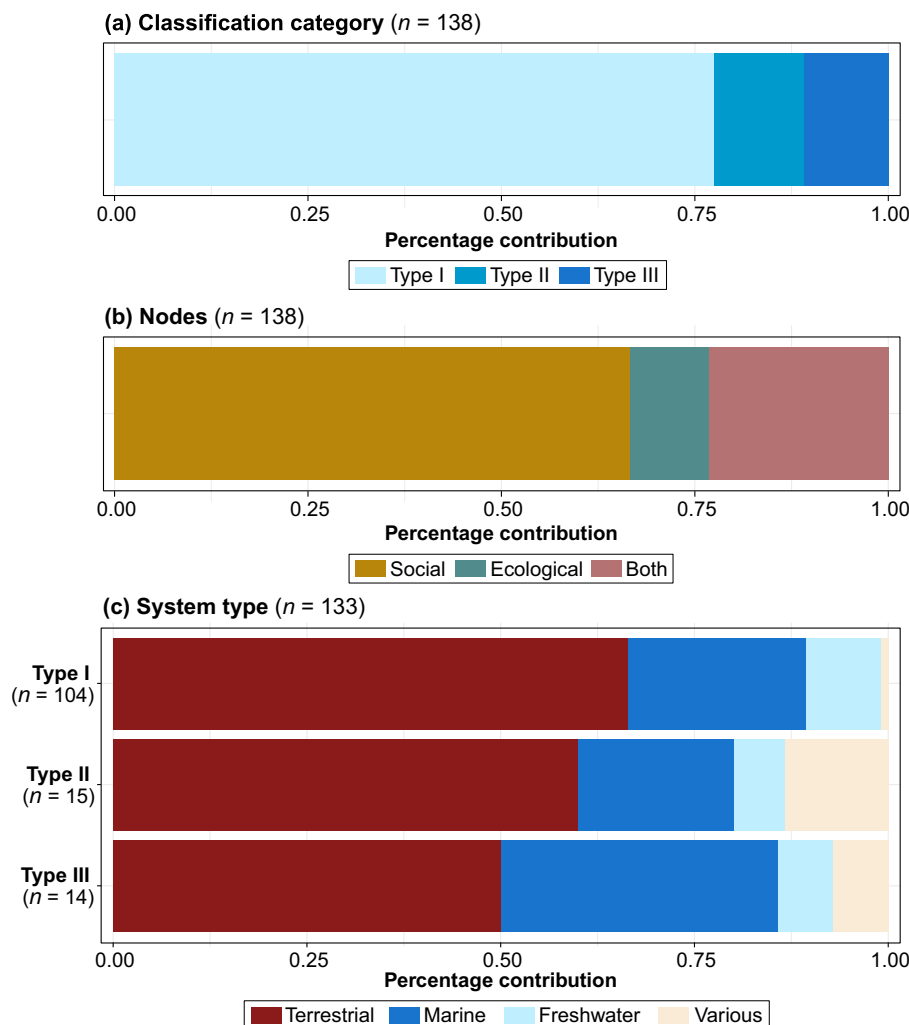


FIGURE 6 Percentage number of studies (a) falling into the different categories (Types I–III, compare Figure 3) of network approaches studying social–ecological system (SES; $n = 138$), (b) considering nodes from either the social, the ecological or from both realms of the SES ($n = 138$) and (c) representing the different ecosystem types (terrestrial, marine, freshwater, various) per network Type ($n = 133$)

TABLE 2 Exemplary means of analysis for different types of network studies. The table shows exemplary cases for the different types of network studies conducted to advance understanding of human–nature relationships in social–ecological systems. The purpose is to illustrate how authors used different types of analytical tools aiming to integrate social and ecological elements in network studies (i.e. studies in the categories Types II–III). For a complete list of the data reviewed and analysed in this study please see Kluger et al. (2020)

Type of network study	Type of data analysis applied					Principle findings	Reference
	Node type	Node definition	Edge type(s)	Edge definition	Data		
Type I	Social	Farmers	<u>SS</u>	Information flow among farmers	Collected from household surveys at two points of time (dynamic), stochastic actor-oriented modelling is applied to investigate evolution of learning network	<u>Output:</u> Identification of farmers' preferences for information exchange <u>Use:</u> Results allow to determine whether and how social networks can facilitate environmental interventions	Matous and Todo (2015)
	Social	Gardeners and home farmers	<u>SS</u>	The exchange of plant propagation material and of knowledge	Collected through participant observation, semi-structured interviews and a survey; the structure of the network and actor-specific centrality indices are analysed	<u>Output:</u> Identification of network characteristics that enhance or inhibit the flow of knowledge and plant material <u>Use:</u> Understanding of how social relations contribute to building local knowledge	Reyes-García et al. (2013)
Type II	Social, ecological	Variables of the SES as defined by the SES framework (Ostrom, 2009)	<u>SE, EE</u>	Influence and dependence relationships between variables	Analysed based on three measures of centrality and one of connectivity	<u>Output:</u> All three SES were considered to be highly connected and resilient but with different degrees of capacity or cumulative potential <u>Use:</u> Throughout understanding of the SES, basis for management	Delgado-Serrano et al. (2015)
	Social, ecological	Anglers (social) and water reservoirs (ecological)	<u>SE, EE</u>	Movement of anglers (SE), and trophic interactions in the food web (EE)	Collected through a survey and literature study, and analysed using a dynamic infectious disease model	<u>Output:</u> Identification of reservoirs highly prone to the introduction of invasive species <u>Use:</u> Identification of priority areas for management	Haak et al. (2017)
Type III	Social, ecological	Human actors (social) and vegetation clusters (ecological)	<u>SS, SE, EE</u>	Collaborative interactions between social actors (SS), species dispersal (EE) and actors' interest in different vegetation clusters for their conservation actions (SE)	Analysed for occurrence and frequency of motifs or building blocks and analysed through Exponential Random Graph Modelling	<u>Output:</u> Understanding of which governance forms can best address the problem of social–ecological fit <u>Use:</u> Evaluation of collaborative governance to improve preconditions for effectiveness of environmental programmes	Guerrero et al. (2015)
	Social, ecological	Local and regional managers (social) of units of small watersheds (ecological)	<u>SS, SE, EE</u>	Collaboration between managers (SS), spatial connectivity between areas (EE) and the responsibility of a manager for particular watershed unit (SE)	Analysed by calculating network properties such as centrality and density, and by comparing them between the different layers of the multi-level network	<u>Output:</u> Identification of problematic areas with scale mismatches <u>Use:</u> Assessment of social–ecological misalignment and identify focal areas for interventions aiming at strengthening environmental governance	Sayles and Baggio (2017)

output (Bodin, Sandström, & Crona, 2016). Another work described how segregation patterns in terms of information exchange emerging from ethnic clustering among fishers was correlated with environmental outcome related to shark bycatch rates (Barnes et al., 2016).

Studies from the ecological realm mainly analysed food webs (i.e. trophic links), for example focusing on the impact of fisheries on the marine food web (Rocchi et al., 2017), on the analysis of the role of keystone species, and/or the impact of invasive species on ecosystems (Ortiz, Rodríguez-Zaragoza, Hermosillo-Núñez, & Jordán, 2015; Vasas & Jordán, 2006). Another bulk of publications investigated spatial interdependencies between ecosystems (e.g. Banerjee, Banerjee, Mukherjee, Rakshit, & Ray, 2016) as represented by the movement of animals, for example, through ecological corridors and connectivity between places (Mokross, Ryder, Corrêa Côrtes, Wolfe, & Stouffer, 2014), in urban contexts (Aly & Amer, 2010; Calder, Cumming, Maciejewski, & Oschadleus, 2015) or between ecologically different areas subject to pastoralism (Easdale, Aguiar, & Paz, 2016).

Even though most publications discussed implications of their network results for the respectively other (i.e. not specifically incorporated) realm of the SES, only few studies presented a methodological approach for crossing the social-ecological interface. Examples include Ossola, Locke, Lin, and Minor (2019), who analysed tree canopy connectivity with node attributes being human use type, and Genc, Van Capelleveen, Erdis, Yildiz, and Yazan (2019), who applied both ENA and SNA metrics to a social network consisting of waste flows between companies. One study combined social network analysis with agent-based modelling to investigate human behaviour as to inform conservation interventions (Dobson, De Lange, Keane, Ibbett, & Milner-Gulland, 2019). Prager and Pfeifer (2015), as a third methodological example, constructed two separate networks comprising of social and ecological components, respectively, and then compared the findings of structural analysis with a spatial reference. The latter approach could be understood as what Sayles et al. (2019) conceptually term a *non-articulated SEN*.

4.3 | Type II network studies for SES research

Type II networks were defined to integrate two different types of nodes, that is, from both the social and the ecological realm. Links thus represent either SS and SE edges, or EE and SE interactions, while no direct links between the nodes from the respectively other realm are incorporated (compare Figures 2 and 3). In all, 16 studies fell into this category (compare Figure 6a; Table 2).

A diverse range of conceptualizations was used to construct the Type III networks. Social nodes either represented individual resource users (e.g. fishers) or collective actors (such as NGOs, state agencies) and were interacting with the biological realm of the SES as represented by natural resources (Leventon et al., 2017), compartments of a food web (Dimitriadis, Borthagaray, Vilela, Casadevall, & Carranza, 2016; Levine, Muthukrishna, Chan, & Satterfield, 2015), renewable resources in general (Barfuss, Donges, Wiedermann, & Lucht, 2017), ecosystem services (Alonso Roldán, Villasante, &

Outeiro, 2015) or ecological variables as defined by the SES framework of Ostrom (2009; e.g. Delgado-Serrano et al., 2015). Studies then looked at the interaction between resources and institutions in a resource management network, for example, through management actions (e.g. Alonso Roldán et al., 2015; Barfuss et al., 2017; Beilin, Reichelt, King, Long, & Cam, 2013; Leventon et al., 2017).

Other work studied the impact of fishing (i.e. with fishers representing social nodes) on food web dynamics (Dimitriadis et al., 2016; Levine et al., 2015). Haak, Fath, Forbes, Martin, and Pope (2017) investigated the transmission and contagion of aquatic species across ecosystems, operationalizing the nodes of the network as water reservoirs located in the United States connected by movement of anglers between the reservoirs. This was coupled with a trophic model for each reservoir implemented in Ecopath with Ecosim (EwE, Christensen & Walters, 2004), for which the impact of anglers' movement on trophic dynamics was estimated.

With only few exceptions, most studies classified as Type II used descriptive network statistics from classical social network analysis to study relational questions. For example, using network modularity for determining management units (Dimitriadis et al., 2016), or linking networks to 'qualities of resilience' (i.e. diversity, modularity, connectivity and feedback loops; Beilin et al., 2013). Only one study incorporated a temporal component into their analysis (Barfuss et al., 2017) while most other studies used network data to represent a status quo. Showing the diversity of applications, the studies' results related to a variety of purposes including the aim to solve questions on collaboration between institutions in resource management, describe effects of actor interactions in networks, identify the most critical variables in a SES and management units to be targeted and enhance understanding of processes and interactions in SESs (see also Table 2).

4.4 | Type III network studies for SES research

Type III network studies were defined to consider two node types, that is, entities from both the social and the ecological realm, as well as links between social actors (SS), between ecological units (EE) and bridging the human-nature interface (SE; cf. Figure 3). In all, 15 studies fell into this category (cf. Figure 6a; Table 2), with different analytical network approaches emerging.

Most studies falling into this category framed human-nature relations in the context of landscape management, with forest patches (Bodin, Robins, et al., 2016; Bodin & Tengö, 2012), vegetation clusters (Baggio & Hillis, 2018; Guerrero, Bodin, McAllister, & Wilson, 2015), local urban green spaces (Ernstson, Barthel, Andersson, & Borgström, 2010) or watershed units (Sayles & Baggio, 2017; Zhao, Wei, Wu, Lu, & Fu, 2018) representing ecological nodes managed by different human actors. A second major theme targeted fisheries, with fishers (as social nodes) engaging with their environment through the extraction of species from the ecosystem described as a food web (Barnes et al., 2019; Ortiz & Levins, 2017; Zador et al., 2017).

In terms of analysis, the majority of Type III studies investigated the occurrence of micro-structures (also called motifs, building blocks

or key configurations) in the network representing all possibilities how a total of four nodes (two social and two ecological entities) could be linked (Barnes et al., 2019; Bodin, Robins, et al., 2016; Bodin & Tengö, 2012; Guerrero et al., 2015; Hamilton, Fischer, & Ager, 2019). Theoretical assumptions were made as to which of all these possible motifs create favourable conditions for effectively dealing with environmental issues. Analysis then focused on the frequency with which each of these favourable building blocks occur (Bodin & Tengö, 2012; Guerrero et al., 2015; Bodin, Robins, et al., 2016; methods and limitations discussed in Bodin, Robins, et al., 2016). For the most part, this approach conceptualized SES as multi-layer networks in which the social and ecological nodes each constituted one layer. Social nodes were connected through collaboration or information between human actors (SS links) and ecological nodes through spatial proximity, dispersal of seeds or the movement of species (EE links), to then, as an example, explore the fit between social and ecological processes in environmental governance (with management of landscape patches conceptualized as SE links). Many examples combined motif analysis with exponential random graph modelling (ERGM; e.g. Barnes et al., 2019; Bodin, Robins, et al., 2016; Bodin & Tengö, 2012; Guerrero et al., 2015; Hamilton et al., 2019) and focused on topological questions of whole network metrics of each of the layers and the cross-layer links. Especially, the recent methodological advances in multi-level ERGM (see Lazega & Snijders, 2016) as used, for example, by Baggio et al. (2016), were discussed as powerful tools for analysing networks in future research. Indeed, also temporal ERGM (see e.g. Hanneke, Wenjie, & Xing, 2010) offer strong potential, since they allow for the analysis of network dynamics over time, an aspect that could often not be captured by more classical network approaches. TERGM, in contrast, allows to study time series of networks, assuming that interactions and interdependencies between actors (and hence broader network structures) arise sequentially, that is, conditional upon the rest of the network (Desmarais & Cranmer, 2012).

The second major approach applied qualitative network modelling (including the Loop Analysis approach, e.g. in Ortiz & Levins, 2017) for the analysis of links between fishers and respective markets (SS links), food web components (EE links) and between both realms through fisheries (SE links). With the aim of testing the stability of the SEN, the propagation of bottom-up and top-down perturbations was simulated through the elimination (Ortiz & Levins, 2017) or disturbance (Zador et al., 2017) of nodes to observe the effects on adjacent nodes and the entire network. The results provided insights on SES behaviour, for example, through the identification of the point at which a network breaks apart or the observation of (predicted) changes in strongly connected network components.

5 | DISCUSSION

5.1 | Understanding human–nature interaction

In an ever-interconnected world, with multiple anthropogenic pressures driving environmental and resource degradation

(Giakoumi et al., 2015; Halpern et al., 2008), it becomes imperative to study and understand these complex dynamics. Tackling these problems becomes an ever important endeavour if conceptualizing human–nature interactions in the context of complex SES (Berkes & Folke, 1998). While many different methodological approaches may exist to model SES, including mechanistic and statistical models (Schuwirth et al., 2019), modelling such complex systems requires to include non-linear feedbacks, adaptive processes, different time scales and spatial characteristics, as well as risks and uncertainties, while holding a clear knowledge of the key components of a specific problem (Levin et al., 2013). These aspects pose a challenge to most methodological approaches, but a basic first step should be the understanding of key elements and their interactions. This is why this study was based on two straightforward premises: (a) humans and nature are closely connected in SES (Ostrom, 2009) and (b) network analysis is exceptionally well-suited to understanding relational data (Wasserman & Faust, 1994). Our review indicated the increasing recognition of NA for describing human–nature relations since the mid-2000s, with both the annual number of studies and the level of integration continuously increasing ever since (Figure 5). Other studies exploring temporal patterns of research output related to a specific topic similarly reported increases in publication numbers in recent decades, which can indicate the progressing maturation of a scientific field (increased scientific and/or public interest leading to an intensification of research efforts) but also reflects general trends (acceleration of cooperation and publication processes). This exponential increase in publications makes systematic reviews and meta-analysis necessary tools to generate evidence-based practice and to resolve seemingly contradictory research outcomes in the respective fields (Gurevitch, Koricheva, Nakagawa, & Stewart, 2018), as well as to identify gaps in knowledge for the guidance of future research (Castellanos-Galindo et al., 2020). For example, systematic reviews have covered the topic of marine climate change research (Pedersen et al., 2016), sea grass ecology (Duarte, 1999), coral reef management (Comte & Pendleton, 2018), coastal planning (Sierra-Correa & Cantera Kintz, 2015), ecosystem service evaluation of 'blue forests' (i.e. salt marshes, sea grasses, mangroves; Himes-Cornell, Pendleton, & Atiyah, 2018) and mangrove research (Castellanos-Galindo et al., 2020). In our case, we believe the observed pattern is indicative of a field in its early stage of development with large potential for further applications. This is in particular apparent from the ever-increasing number of Type II and III studies (Figure 5). A broad range of methodological approaches were applied (see Sections 4.2–4.4) emphasizing the value of NA for studying SES. Categorizing existing network studies based on the level of incorporation of social and ecological realms provides the basis for a conscious decision as to design future research studying SES through a NA lens. As further discussed in the following sections, each of the three types of network approaches clearly has advantages and disadvantages, with the research question and case-specific reasoning ideally driving the choice of network

operationalization and analysis, and ultimately determining what insights can be drawn from the empirical studies.

5.2 | Potentials and challenges of the different network study approaches

Network analysis assumes, generally speaking, that there are properties and processes emerging from this global view that could not be seen if system components were studied individually, and separately. This consideration calls for the construction of networks as comprehensive as possible, that is, explicitly including in its analysis as many components of the network as possible. Type III network studies—representing social and ecological nodes and the articulated links between both node types (i.e. SS, SE, EE links)—offer therefore a viable pathway for research focusing on these emergent properties at the SES level that can only be explained through the interactions of its parts (Ostrom, 2009). It is, without doubt, methodologically and conceptually interesting to construct Type III networks to advance theory development based on the direct integration of social and ecological entities in the network conceptualization (Barnes et al., 2019; Bodin et al., 2019). The potential to include direct connections and feedback loops to capture the relationship within and across both realms is especially appealing. This allows to assess effects and repercussions for both realms simultaneously and theories from both the social and natural sciences can be integrated and tested using the same dataset and methodology (Bodin, Robins, et al., 2016; Guerrero et al., 2015). An in-depth discussion of the potential of the existing conceptualizations and analytical approaches of Type III networks is found in Sayles et al. (2019). However, it is important to emphasize that Type III network studies face also challenges, and a broad discussion of differently articulated SENs—as done in the present work—is of great value to compare the respective potential and limitations of different Types. For example, Type III networks require high amounts of data and high conceptual effort for constructing the network. The identification of relevant variables and network boundaries becomes even more challenging when one has to choose from a rich pool of possible social, ecological and socio-ecological variables (Bodin & Tengö, 2012). A complicated task for conceptualizing Type III networks also relates to the scale at which social and ecological units should be considered as network components, in particular if multiple link types cross the human–nature interface. Moreover, analysis in Type III network studies typically requires sophisticated mathematical and statistical approaches that may be unnecessary when aiming to resolve determinate questions that concern only parts of the SES. By this, Type III studies allow to enter new territories in terms of theory development (for a recent review and related hypotheses, see Bodin et al., 2019). For example, latest advances in exponential random graph modelling (ML-ERGM, see Wang, Robins, Pattison, & Lazega, 2013) offer an interesting mathematical approach to be used in Type III studies (cf. Section 4.4). However, we would argue

that the application of Type III studies is—due to the abovementioned aspects—still rather academic.

In contrast, Type I and Type II network conceptualizations present other advantages while facing challenges too. Clearly, both types are not as elegant since they do not include social and ecological variables as ‘equal’ partners in the conceptual and mathematical formulation of the network. Yet, Type I approaches have the strong advantage of building on long research traditions in ecological (ENA) and social (SNA) network analyses. Numerous theoretical assumptions have been developed in these lines of research that can be operationalized for the context of understanding human–nature relationships (see e.g. Bodin & Crona, 2008; Bodin & Prell, 2011; Fath et al., 2007; Ulanowicz, 2004). This provides for enhanced transferability of established assumptions between case studies and for comparative analysis to draw generalizable conclusions within the different disciplines. As for the social dimension, recent reviews have, for example, elaborated on structural properties (of social networks) that might be linked to sustainability outcomes (Henry & Vollan, 2014), the implications of network structure of and individual actor's positioning within collaborative networks for tackling environmental problems (Bodin, 2017), and how SNA is used in different management contexts (Groce, Farrelly, Jorgensen, & Cook, 2019). Although not operationalized as part of the network and included in the formal network analysis, qualitative or quantitative information on the respective other dimension (e.g. environmental change or ecological conditions in SNA studies) can be included in the study design and analysis to obtain meaningful insights on human–nature relationships; for instance, to obtain understanding of the relation between social structure and the ability of governance actors to successfully deal with environmental change (Bodin, Sandström, et al., 2016; Gorris, Glaser, Idrus, & Yusuf, 2019). The focus on either the social or the ecological dimension limits, however, the discussion of social–ecological feedbacks and outcomes on the SES level to indirect measures and the capability of capturing emergent properties of the system.

Type II studies analyse the direct relations between the nodes of one realm (either ecological or social) and how this network interacts with the respectively other dimension. This enables to assess the impact of certain actions or changes in one area (either the ecological or social realm) on the other. Based on our results, this type of network has much fewer empirical examples in the literature. Its potential is, for instance, evident in the study by Haak et al. (2017) who analyse the impact of fisheries (as social nodes) on the dynamics of food webs (the ecological network) for exploring different fisheries management regimes, focusing on the expected consequences for food web structure and/or the population dynamics of the main target species. Such Type II studies offer the possibility to directly integrate human–nature relationships in network analysis while facing less of the conceptual and methodological complexity and extensive data needs as Type III studies. At the same time, the studies may be able to better build on the strong theoretical and methodological foundations of the Type I studies than the Type III studies can. For example, when human interaction with a food web is conceptualized

as resource extraction (e.g. fishing), then social-to-ecological links are described in the same unit (biomass/energy flow) as ecological-to-ecological links among the biological actors, which facilitates quantitative analysis. Hence, as mentioned above, we argue that especially Type II network research offers an underexplored potential and ample scope for future studies.

In general, the specific research question should drive the decision of how much integration is actually necessary. Approaches that direct their attention to network complexity with, for example, multi-layer network coupling spatial patches, are well described; for example in Pilosof, Porter, Pascual, and Kéfi (2017), who describe multiple approaches for multi-layer networks. Nonetheless, their focus is chiefly on ecological aspects, which would classify all of the mentioned networks into our Type I, irrespective of their complexity. Other multi-layer networks (e.g. Friesen, Martone, Rubidge, Baggio, & Ban, 2019; Geier, Barfuss, Wiedermann, Kurths, & Donges, 2019) could, in contrast, be classified as Type II, emphasizing the need to let research questions drive the structure of the network, and not the other way around. These thoughts are particularly important when limited resources need to be invested in the most efficient way. Davis, Chadès, Rhodes, and Bode (2019) argue that neither ecological nor social information is necessarily most important for studying a SES, but that researchers should rather focus on understanding the 'primary effects of their management actions'. Bodin, Robins, et al. (2016) comment in this regard that when assessing the necessity (or lack thereof) of increased collaboration in resource management, an excessive complexity can be counterproductive. Since conceptualization and parametrization of nodes and edges are still difficult to standardize among social and ecological subsystems, data requirements and methodological possibilities for analysis are often still limited as to produce case-specific conclusions only. This links also to the work of Bodin et al. (2019) who emphasize the necessity to formulate clear assumptions of causality when constructing networks to study social-ecological interdependencies, which is an especially difficult task for Type III network studies. Given the existing barriers and challenges for the development of Type III studies, a detailed quantitative analysis of one realm using a Type I or II approach might, in comparison, be more suitable and/or relevant to questions related to the impact evaluation of (expected) changes.

5.3 | Conceptual and methodological challenges for integrating social and ecological realms

One basic assumption to systematically revise and categorize SENs relates to the definition of network compartments (nodes, links). For this work, we defined links as social, if connecting two social (i.e. human) entities. Similarly, edges were considered ecological, if linking two biological actors, while social-ecological links were conceptualized as to cross the human-nature interface, that is, connecting one social and one ecological node (cf. Section 2). Alternative approaches could engage, in contrast, with the nature of links. In this case, an ecological link might be anything that is

derived from nature—be it physically (e.g. the movement of organisms, flow or sharing of biological resources) or theoretically (e.g. ecosystem services). This would imply that two social nodes (e.g. two fishers, or a retailer and a customer) could be connected by an ecological link (e.g. biomass of fish sold). Accordingly, two ecological vertices (e.g. individuals or groups of mammals) could be interconnected by a social action (e.g. the transfer of knowledge). This intriguing approach, however, was not followed in our work due to the difficulty to standardize the intrinsically subjective definitions of social edges, relating to different perspectives on anthropomorphized, human-centred concepts, for example, on what a social action entails. Since the purpose of this review was to present a general conceptualization aimed to engage with an as broad audience as possible, the discussion of these concepts would go beyond the scope of the present work.

In our literature review, most studies that fell into Types I and II analysed primarily social nodes (Figure 6b). This can likely be explained with the different terminology authors of network studies with an ecological focus commonly use. Author's choices of terminology for both network components and the framing of the studies reflects how authors classify their research, that is, not necessarily as studying human-nature interaction and/or analysing SES, albeit they often could be understood as such, especially when social agents are integrated in the respective network analysis. This argument is supported by the relatively small number of identified studies using food-web models. For example, out of the several hundred models developed with the EwE modelling framework (Christensen & Pauly, 1992; Christensen & Walters, 2004; Colléter et al., 2015), only a few were encountered by our search that tried to capture empirical studies on human-nature relationships in SES, and none in the recent review by Sayles et al. (2019). In theory, the EwE framework is based on network analytic concepts and allows for building ecological networks of marine food webs (Type I), integrating the effects of fisheries on ecological networks (Type II, cf. Bacalso & Wolff, 2014; Kluger, Taylor, Mendo, Tam, & Wolff, 2016) and tracking the biomass flow from the ecosystem to the consumers of fishery resources (Type III, cf. Christensen, de la Puente, Sueiro, Steenbeek, & Majluf, 2014; Christensen, Steenbeek, & Failler, 2011). Thus, this tool harbours great potential to advance SEN analysis. The absence of these studies in the present work is likely related to our inductive method only capturing research that self-identified as a network study tackling human-nature interaction (compare Table 1). Hence, although the graph theoretic foundations of network research do offer common ground for a joint scientific terminology (Janssen et al., 2006), there is room for improvement in terms of building a common language that could better integrate ecological research in SEN research. This 'disciplinary fragmentation' (sensu Gregr & Chan, 2015) is also common to other scientific topics. As an example, Gregr and Chan (2015) found in their review only a 5% overlap of papers being captured by different search strings related to (marine) ecosystem modelling tools, as well as a lack of cross-referencing. We would similarly argue that while adding the disciplinary foci and methods to SES research might help

in deepening the understanding of behaviour and dynamics of single system components, true social–ecological approaches should, however, necessarily be of inter- and transdisciplinary nature. Hence, a common language—to which we hope to have contributed with the present work—is an indispensable first step to structuring a joint research agenda.

In terms of methodology, a certain degree of overlap was identified with respect to topics and methods covered by the different Types. For example, analysis of the network topology is widely applied in all three categories, for example, the analysis of node removal was used to assess network-wide impact in Type I (e.g. Rocchi et al., 2017) but also Type III (e.g. Ortiz & Levins, 2017; Zador et al., 2017) cases. Multi-layer network approaches were found for Type I (e.g. Prager & Pfeifer, 2015), Type II (e.g. Geier et al., 2019; Haak et al., 2017) and Type III (e.g. Sayles & Baggio, 2017) studies. Some authors even combine approaches, for example node removal on multi-layer networks (Baggio et al., 2016). In terms of topics addressed, the food-web effects of human action (represented as fishing or harvesting resources) were assessed using Type II (e.g. Dimitriadis et al., 2016) and Type III but also using Type I (Rocchi et al., 2017) network approaches; while issues of spatial misfits were addressed using Type I (Easdale et al., 2016), Type II (Bergsten, Galafassi, & Bodin, 2014) or Type III (Bodin, Robins, et al., 2016; Ernstson et al., 2010). This exemplifies that several topics can be successfully approached by a range of network parametrization possibilities representing different levels of social–ecological integration, and also by using different analytical techniques. However, a particular challenge lies in the varying conceptualizations of nodes and links used in different NA studies because this complicates the comparison across cases, even though this theoretically represents one of the strengths of network analysis (Bodin et al., 2019). Similarly, the scale at which the social and ecological units that are included as nodes are defined (e.g. local to global), further hampers useful cross-case comparisons.

Our results show that the majority of case studies, for which networks (of all Types I–III) were constructed, were from the terrestrial context (Figure 6c). An increasing focus on marine SESs, however, is especially important considering that 40% of the world's population lives within 100 km of the coast with ever-growing demands for marine biotic resources and increasing pressure on coastal marine ecosystems (UN, 2017). Studies addressing marine systems were proportionally more represented in Types II and III than in Type I, possibly hinting at that these systems hold high potential for implementation of Type III studies, maybe because of the data availability, or because of the different characteristics of human–nature interaction at sea compared to terrestrial human–nature interactions. However, a large number of marine food-web models (i.e. networks of Type I) already exists but has not been captured by our literature review, rendering this comparison difficult. Based on these food webs, the connection to the social realm can conceptually relatively easily be included using fishing or other types of resource use for representing the social dimension (i.e. for construction networks of Type II or III). An example for this is the recent study by Kluger, Scotti, Vivar, and Wolff (2019) presenting a multiplex, multi-layer

SEN for a SES in which small-scale fisheries and aquaculture represent important contributions to local livelihoods. For this, social science data collection to study the dynamics within the fisheries value chain were combined with existing food webs (based on Kluger et al., 2016). In addition to the importance of an increased focus on coastal marine SES, the comparison across a wide range of different system types (terrestrial, marine, freshwater) holds strong potential to identify common relational features, but has not been opted for in the reviewed studies.

6 | CONCLUSIONS AND OUTLOOK

In an increasingly interconnected world, the understanding of direct and indirect linkages at the human–nature interface in SES is crucial for designing long-term management strategies to maintain important system functioning. This study set out to systematically examine the state of play in the growing and diversifying literature on empirical network research dealing with human–nature relationships in SES. The typology of network studies to represent archetypes of possible operationalization in empirical research for addressing the manifold questions surrounding (sustainable) human–nature relationships has proven to be very useful in systematizing the existing body of literature. The findings highlight the diversity and creativity with which distinct social and ecological entities are defined to enable the use of a variety of network analytical approaches in SES research. This demonstrates the broad applicability of network approaches in this field and emphasizes the importance of the diversity of conceptualizations and analytical approaches. Studies from all three types of network approaches have significantly contributed to a better understanding of human–nature relationships and we argue that neither of the three archetypes should generally be considered 'better' suited for advancing the understanding of human–nature relationships. Rather, in the context of the many useful conceptual and methodological approaches to study human–nature relationship based on network research, this article contributes to systematizing the existing network research and assists researchers interested in developing networks for studying SESs to thoroughly think of a way to operationalize the empirical research depending on what questions are to be addressed.

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CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

AUTHORS' CONTRIBUTIONS

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DATA AVAILABILITY STATEMENT

The compiled data reviewed and analysed in this study have been made publicly available on the Zenodo Digital Repository through the <https://doi.org/10.5281/zenodo.3929436> (Kluger, Gorris, Kochalski, Müller, & Romagnoni, 2020).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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