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**Key considerations and challenges in the application of social-network research for environmental decision making**

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Article Impact Statement: Rigor of social-network research requires attention to dependency assumptions, theoretical grounding, and methods that respond to data needs.

## **Abstract**

Attempts to better understand the social context in which conservation and environmental decisions are made has led to increased interest in human social networks. To improve use of social-network analysis in conservation, we reviewed recent studies in the literature in which such methods were applied. In our review, we looked for problems in research design and analysis that limit the utility of network analysis. Nineteen of 55 articles published from January 2016 to June 2019 exhibited at least 1 of the following problems: application of analytical methods inadequate or sensitive to incomplete network data; application of statistical approaches that ignore dependency in the network; or lack of connection between the theoretical base, research question, and choice of analytical techniques. By drawing attention to these specific areas of concern and highlighting research frontiers and challenges,

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including causality, network dynamics, and new approaches, we responded to calls for increasing the rigorous application of social science in conservation.

## **Introduction**

The social environment in which environmental decisions are made is crucially important for preventing loss and degradation of the world's natural resources (Mascia et al. 2003; Ostrom 1990). There is growing concern about the methodological rigor and quality of social research in conservation (Bennett et al. 2017; Teel et al. 2018; Martin 2019). These concerns include ignoring the decision-making context (e.g., political, institutional, cultural factors), not recognizing multidirectional and reciprocal relationships and feedbacks between social and ecological components, inappropriate procedures, and lack of theoretical grounding (Guerrero et al. 2018; Rissman & Gillon 2016; Young et al. 2018). The design of effective environmental programs requires more than recognizing the importance of the human domain; it requires consistent and rigorous application of appropriate social science and interdisciplinary methods that overcome these problems.

Attempts to better understand the social component of conservation and environmental management has led to increased interest in human social networks (hereafter social networks) because the development and implementation of environmental and conservation interventions, policies, and practices naturally depend on social processes (Armitage et al. 2012) and sustaining effective conservation over time requires mobilization of resources, learning, and changes in human behavior (Mascia et al. 2003). These social processes can be

shaped by how diverse actors interact with one another in social networks (Bodin et al. 2006; Janssen 2015). Thus analyzing these interactions provides insights into how to design effective and sustainable environmental programs. Moreover, the boundary-spanning nature of many environmental problems makes it difficult for any single group to solve them because no single actor normally has the resources, jurisdictional competence, or knowledge to do so (e.g. Bodin 2017). Instead, achieving conservation goals often relies on the cooperation, coordination, participation, and compliance of different groups of people (Armitage et al. 2012; Ostrom 1990). Effective environmental decision making thus requires multiactor collaboration (Armitage et al. 2012; Bodin 2017; Guerrero et al. 2015b). One way to better understand these collaborations is by studying collaborations as social networks.

Social-network research has been applied to many environmental problems (e.g., biological resource use, climate-change adaptation, protected-area planning, large-scale conservation, and water management) (Bodin et al. 2006; Guerrero et al. 2015b; Lubell et al. 2017). and in different ways to support conservation (Groce et al. 2018). We highlighted 5 ways in which social-network research has demonstrated utility in achieving conservation or environmental objectives.

#### *Identifying stakeholders and stakeholder groups*

The effectiveness of conservation and resource management initiatives often depends on whether people participate in them, or at the very least, comply with the rules established (Arias 2015). Many conservation initiatives have failed due to inadequate understanding of

the range of stakeholders affected by conservation decisions and their unique knowledge, goals, and characteristics (Prell et al. 2009). Research on social networks can help prevent these failures by systematically identifying relevant stakeholders or stakeholder groups (Alexander et al. 2016; Barnes-Mauthe et al. 2013; Prell et al. 2009). It can also aid in the identification of key individuals, such as opinion leaders or brokers, who span different knowledge or interest groups, making them ideal candidates to involve in conservation planning and participatory resource management (Mbaru & Barnes 2017; Prell et al. 2009). Without social-network data, opinion leaders and brokers can be difficult to identify because they often lack formal leadership positions (Barnes-Mauthe et al. 2015). Similarly, stakeholder categories that make sense to policy makers and conservation practitioners (e.g., fishers, tourism operators, conservation groups) sometimes inadequately reflect social groups with different attitudes and interests that can have important impacts on conservation outcomes (Barnes-Mauthe et al. 2013; Barnes et al. 2016).

### *Cooperation, collaboration, and coordination*

Effective conservation almost always requires some level of cooperation or collaboration among multiple actors to coordinate activities and avoid conflicts over resources (Ostrom 1990). Research on social networks can improve understanding of the type and level of collaboration needed to meet objectives (Barnes et al. 2019; Bodin et al. 2017b; McAllister et al. 2015) and identify where governance capacity needs strengthening (Guerrero et al. 2015b; Sayles & Baggio 2017). For example, social-network analysis can help build strong comanagement systems (Alexander et al. 2015), identify bridging organizations (Rathwell & Peterson 2012), and improve understanding of complex governance arrangements that

operate across large spatial scales (Guerrero et al. 2015a; McAllister et al. 2015). The value of such research has been demonstrated when there is a need to match social institutions to the scale of ecological processes they are responsible for managing (Bodin & Tengo 2012; Guerrero et al. 2015a; Guerrero et al. 2013).

### *Mobilizing resources and support*

Formal and informal social networks can play a key role in the mobilization of resources and support across different sectors of society essential for addressing environmental problems (Bodin & Crona 2009). Research on social networks can provide critical insight into where necessary resources and support are or can be mobilized. This information can then be used along with ecological data to reveal areas of conservation priority that also represent areas of conservation opportunity (e.g., areas where stakeholder collaboration can be used to harness resources and support for the implementation of management actions [Guerrero & Wilson 2017; Mills et al. 2014]). Research on social networks can also uncover power dynamics that may pose barriers to or opportunities for effective governance (Bodin et al. 2006; Bodin & Crona 2009). For example, King (2000) showed that external, formal authorities who were linked to local resources users (but not involved in resource management) helped mobilize support to solve local-level resource-related problems. Such bridging or linking ties that facilitate the sharing of information and resources among diverse groups of actors have since played a crucial role in addressing a range of environmental issues, such as increasing the effectiveness of comanagement (Marin et al. 2012; Matous & Todo 2018), facilitating learning and stakeholder engagement (Jacobson & Robertson 2012), and increasing legitimacy of environmental programs (Sandström & Lundmark 2016). Social-network

research can provide a clear understanding of where these ties exist and where they should be built to facilitate conservation planning and identify potentially powerful actors in key positions that may impede conservation initiatives (intentionally or unintentionally).

### *Learning and innovation*

Data on information-sharing networks can greatly support conservation efforts because they can demonstrate how knowledge and information about environmental systems is generated, acquired, and diffused (Barnes-Mauthe et al. 2015; Crona & Bodin 2006), which can facilitate (or hinder) learning and innovation. For example, Crona and Bodin (2006) found that infrequent information exchange between fishers using different gear types in Kenya was likely a contributing factor behind the lack of a regulated use agreement—despite declining fish stocks. More recent research demonstrates how social-network research can be coupled with conservation interventions to facilitate learning (and eventually diffusion) (Matous & Todo 2018).

### *Participation and behavior*

Human behavior is the primary force driving environmental change and is therefore often the focus of many conservation initiatives (e.g., strategies to increase stakeholder participation or promote diffusion and adoption of sustainable practices [Pannell et al. 2006]). Social networks can have a profound influence on human behavior through processes of social influence and contagion (Christakis & Fowler 2007); therefore, social-network data can play a critical role in designing conservation initiatives (Mbaru & Barnes 2017). For example,



landholders are strongly influenced by their social networks when making decisions about participation in and ongoing support of environmental programs (Pannell & Vanclay 2011). Decision makers can use this information to find key individuals with high levels of influence to involve early in planning processes to achieve greater participation (Mbaru & Barnes 2017). If the goal is to change human behavior, many factors that influence decision making must be considered; failing to consider social networks can lead to incomplete conclusions or ineffective conservation interventions. For example, Barnes et al. (2016) demonstrated that differences in the bycatch of sharks in an industrial tuna fishery are strongly related to segregation in fisher's information-sharing networks, suggesting that social influence from fishers' peers affects their fishing behaviors and has direct consequences on ecological outcomes. Prior to this research, policy makers and even fishers themselves were unaware that some had learned how to reduce shark bycatch more effectively. Because these fishers were largely segregated along ethnic lines, without the social-network information, differences in fishing behaviors could have been incorrectly attributed to ethnic background, rather than whom fishers shared information with.

Despite the utility of social-network research for achieving the above objectives and supporting environmental problem solving, there are problems related to its application: analytical methods may be inadequate or sensitive to incomplete network data; statistical approaches may ignore dependency in the network; and connections among theory, research questions, and choice of analytical techniques may be lacking. These problems were identified by a group of 7 social and 4 natural science researchers during a meeting on social-network research and environmental decision making . There was agreement that these

problems are repeatedly found in environmental social-network research and that guidance for natural and other scientists new to this research is needed to ensure efficient use of the techniques. To confirm the prevalence of these problems we reviewed recent studies in which social-network analysis (SNA) was applied to conservation and environmental management research. We sought to highlight these problems to improve application of social-network research in conservation.

## **Methods**

In July 2019, we searched Web of Science biodiversity and conservation and environmental sciences and ecology areas for studies published from January 2016 to July 2019 (Supporting Information) in which SNA was applied. We also searched manually for social-network analysis articles in *Conservation Letters*, *Conservation Biology*, and *Biological Conservation*. Fifty-five articles were included in our analyses. We looked for studies in which the social-network methodological problems were not addressed or justified. In taking this approach we acknowledge that while some of these analyses may be defensible, the problem lies in the lack of justification or discussion of possible implications. We also acknowledge that our assessment is only based on published material; hence, it is possible that the authors could have adequately addressed the identified problems while conducting the studies or analyses but failed to report it. Details of the literature-review methods are in Supporting Information.

## Results

Of the 55 studies we examined, 19 (~35%) contained analytical, methodological, or theoretical problems. Eleven of these studies applied analytical methods that are inadequate or sensitive to incomplete network data without justification or discussion of possible implications. Nine studies applied statistical methods that do not account for network dependencies and these were not appropriately justified or addressed methodologically through complementary analysis. Five studies had a lack of connection between the theoretical base, research question, and choice of analytical techniques. This problem was difficult to evaluate due to the varying research traditions and practices in the different scientific disciplines and fields of research and the ambiguities in terms of what is a sound theoretical basis. Thus, we adopted a less strict approach and identified an issue only if deemed robust to all these differences. Hence, our estimate should be evaluated with this in mind—a stricter evaluation approach would likely generate a significantly higher number.

## Discussion

### *Partial network data and missing data*

Many network-analysis methods and concepts assume a complete network data set; thus missing data can produce incorrect estimates (Kossinets 2006). Missing data stem from difficulties in defining the study population. Social networks often lack a clear boundary; thus, the researcher must define relevant system boundaries (Fig. 1). Certain nodes can be deliberately excluded by design even when they are important. Nonresponding network nodes (i.e., those lacking outgoing ties) also present challenges.

Partial or missing data are particularly problematic in descriptive network analyses. Yet, gathering all network data is difficult because relationships are often fluid, which makes it challenging for respondents to correctly recall all their contacts (Marsden 1990). To address this issue one can rely on recognition (i.e., ask respondent to select from a predefined list of names). In practice this works only if the list is not so long as to induce respondent fatigue. Otherwise, the recall approach (participants recall contacts) has to suffice but could lead to unreported ties due to cognitive limitations (Marin & Hampton 2007).

Depending on research objectives and analyses used, criticality of gaps in the network data differ. Studying centrality is a good example. Basic centrality measures (e.g., degree centrality and indegree centrality) are robust to missing data (Costenbader and Valente 2003; Borgatti et al. 2006). Other measures are less robust to missing data (e.g., those that capture ideas of brokerage, such as betweenness centrality). Thus, if the objective is to investigate potential social ties in strongly coherent clusters (subgroups), a comparably high response rate is needed. Assume, for example, there is 1 actor linking 2 coherent clusters of nodes. In this case, the likelihood one would miss capturing that actor's ties (thereby falsely assuming clusters are disconnected) would be  $<5\%$  (statistically significant) only if the response rate was 95%, which is very high. Although this is an extreme example (one single actor connecting the clusters), it illustrates the problem with response rates when studying social networks, particularly concepts of brokerage. Analytical methods based on the assumption of stochasticity (e.g., exponential random graph models [ERGMs]) are typically more robust to missing data (Robins et al. 2004), but there are no universal standards on acceptable minimal

response rates that apply across all types of network studies. New methods to treat missing data in human social-network studies are being developed (Butts 2003; Koskinen et al. 2013).

### *Dependency*

Once a network perspective is adopted, some level of dependency among and between nodes and ties is implicitly assumed (Carrington et al. 2005) (Table 3). Such dependencies complicate statistical inference because they violate the assumption of independence central to standard statistical approaches. Thus, off-the-shelf standard regression methods are often inadequate, and statistical models that explicitly address data interdependencies are needed. Many such models exist. However, these are usually only presented in specialized network literature. For example, quadratic assignment procedure (QAP) regression and ERGMs are specifically designed to handle network dependence (Krackhardt 1988; Robins et al. 2007). In some cases random permutation or bootstrapping methods can be applied (e.g. Barnes et al. 2017b). In general, adopting a network approach inherently entails assumptions about network dependencies that cannot be ignored. Thus, researchers must consider carefully their data and context to decide what assumptions of independence are reasonable and defensible and what underlying theory is relevant and focus their research questions. The use of standard statistics in social-network studies should be appropriately justified.

### *Theoretical and empirical basis*

Many applications of social-network methods in environmental research are limited to descriptive accounts of systems and do not link to theoretical or empirical understanding that

connectivity, social processes, and social structures are relevant to explaining phenomena (Robins 2015; Groce et al. 2018) (Fig. 1). This wastes resources, does not provide useful explanations, and results in misperceptions of the utility of social-network research. Motivations behind social-network analysis should go beyond the appealing nature of the visualization techniques and quantitative measures. Researchers should consider whether a social-network study will inform management decisions, increase understanding of important social structures and processes, or help achieve a conservation objectives . Understanding social networks will not always help address conservation problems. Whether research on social networks can yield useful explanations depends on the nature of the research objective, time and resources available, and other factors that should be considered early in the process of research design (Fig. 1).

### *Designing and interpreting network analyses*

Researchers applying social-network research in environmental fields come from multiple disciplinary backgrounds and thus approach research and analysis differently. Social and ecological networks are similar in many ways, but understanding the dominant, persistent properties of social networks will help researchers better interpret and gain valuable insights from network analyses (Supporting information). For example, social networks are homophilic and transitive. Homophily implies similar actors are socially tied, and transitivity implies 2 actors tied to a common third actor are tied to each other. These properties are common in many social contexts. Homophily and transitivity result in higher levels of network clustering than occur in ecological networks (Newman & Park 2003) (Supporting Information). Humans in social networks also have intentionality; considerations humans take

into account when choosing who to interact with are many and interacting (Robins 2015).

These choices are often based on individual preferences; thus, intentionality drives the prevalence of attribute-based tie formation, which is not often seen in other types of networks, but choices are constrained by the social environment (Kossinets & Watts 2009). These properties of social networks—network clustering, homophily, transitivity, and intentionality (Supporting Information)—are key to understanding social phenomenon studied from a network perspective. Thus, important effects could be missed with social-network oversimplification. Not all network-analysis approaches account for these dominant properties of social networks.

### *Causality*

Work has begun to establish correlative relationships between environmental performance and the structure of social networks (Barnes et al. 2016; Barnes et al. 2019; Bodin et al. 2017b). Yet the practical utility of social-network research to inform conservation ultimately depends on the ability to understand the causal mechanisms of environmental outcomes (Groce et al. 2018). There are limitations to conducting replicable experiments to provide definitive empirical evidence of the relationships between social-network structures and environmental outcomes, holding other contextual and confounding factors constant (Emirbayer & Goodwin 1994; Robins 2015). Nonetheless, social networks can be analyzed through simulation experiments (Steglich et al. 2010) to determine the influence of the network structure on social processes, such as learning (Ohtsuki et al. 2006). Data on social networks and outcomes collected over time can also help overcome these limitations by isolating casual relationships (Bodin et al. 2019).

A social network can be treated as an independent or dependent variable, and the choice depends on the nature of the research objective and theoretical basis. If, for example, the objective is to understand what makes a particular system effective (e.g., an invasive species control system), the social network and other elements of the social-ecological system (e.g., enforcement) can all be considered candidate causes (independent variables) (Barnes et al. 2019). Network structures can emerge from the cycles of interaction between social processes (e.g., decision making) and outcomes. In these cycles, the outcomes of an intervention are fed back into the decision-making process, leading to the revision of goals and emergence of new social-network structures (Padgett & Powell 2012; Robins 2015). Thus, the social network can be viewed as an intermediate outcome (Ferraro & Hanauer 2014), where the network is an assumed precondition for a particular end outcome, making the network the focus of the examination (dependent variable).

### *Network dynamics*

Social networks are dynamic and evolving, and some change at a faster rate than others. Moreover, the rate at which social networks change (e.g., governance networks) often differs from the rate at which ecological networks change (e.g., invasive species spread). Thus, differences in social- or ecological-time dynamics will likely affect management outcomes (Bodin 2017), but these effects are often ignored. For instance, it is often assumed the effects of management occur faster than the rate of change in relevant network structures (social or ecological). Yet, this assumption of stability has not been tested empirically, and one would expect it to differ among systems. Thus, for management decisions to be relevant, evolution of networks cannot be ignored (Chades et al. 2011).



Statistical methods can be used on longitudinal data to study empirically coevolution of network structure and individual behavior (Snijders et al. 2006). Such studies use stochastic models to study the network structure and actor attributes (e.g., indicators of behavior) as joint dependent variables in a longitudinal modeling framework in which they influence one another over time (e.g., Steglich et al. 2010). In conservation, these methods allow analysis of joint dynamics of network structure (e.g., information sharing networks) and actor-level outcomes (e.g., conservation behavior) and can be used to understand the mechanisms of network formation by isolating different types of effects (e.g., effect of homophily) (Burk et al. 2007) (Table 2). Knowing which effect is strongest can lead to improved intervention outcomes.

#### *Designing optimal networks*

An open question in the use of social-network research in conservation is whether it is feasible to predict optimal network configurations. In theory, knowledge of what the optimal networks are for different conservation problems could facilitate design of better networks. However, networks of actors often have to address multiple types of problems, thus defining the optimal network involves balancing different, sometimes opposing network characteristics (Bodin 2017). Also, networks cannot be entirely designed; they evolve as actors engage with each other through different types of relationships. The factors behind actors' choice of network partners are, however, diverse and therefore often hard to control. Thus, the ability to design networks is limited, although there are ways to facilitate and potentially steer network evolution (Valente 2012) (e.g., through community-level training events). Even if interventions successfully facilitate new network structures, over time the

strength of influence of historical factors on patterns of relations may overcome ‘temporal’ patterns formed by the intervention.

#### *Value of information on social networks*

Many factors affect conservation problems in complex social-ecological systems; thus, the value of understanding social networks is context specific. Conducting social-network research can be costly and time consuming, so determining the value of collecting data on a particular social network is useful (Supporting Information). For instance, when the research objective is to inform management actions in a well-defined system, one may be able to determine a priori when understanding social networks can help maximize positive outcomes (Davis et al. 2019) (Supporting Information). Understanding the relative value of applying social-network research based on characteristics of a system remains a research gap.

Nonetheless, the value of having information on social networks goes beyond informing management decisions. Implementation of management actions often depends on coordination and cooperation among individuals and groups (Ostrom 1990). Thus, collecting and analyzing social-network data can inform management implementation and help forecast long-term success (e.g. Guerrero and Wilson 2016).

#### *Challenges and opportunities of social-ecological networks*

Social networks cover only one-half of an integrated social-ecological system. Because human and ecological systems can be described as networks, use of a network modeling approach to describe social-ecological systems as social-ecological networks is increasing

(Sayles et al. 2019), and approaches that enable empirical research have been developed and applied (e.g., Barnes et al. 2017a; Bodin et al. 2016; Bodin & Tengo 2012). These approaches are possible with new methods, such as exponential random graph modeling for multilevel network (ERGM; Wang et al. 2013), and recent contributions demonstrate how conceptual clarity, development of testable hypotheses, and statistical rigor can be accomplished (e.g., Guerrero et al. 2015a; Bodin et al. 2016; Barnes et al. 2019).

Social scientists are calling for increased rigour in the application of social science and interdisciplinary methods in conservation (Bennett et al. 2017; Teel et al. 2018; Martin 2019). Research on social networks can be incredibly valuable for conservation, yet there are common problems in its application that require attention. We hope future applications pay attention to the common issues we have highlighted here so that they can inform the design of more effective conservation and environmental programs.

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### **Supporting Information**

Details on the method used for the review of SNA studies (Appendix S1), key properties of social networks (Appendix S2), and an example of the value of information applied to social

networks (Appendix S3) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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**Table 1. Number of recent studies with analytical, methodological, and theoretical problems.**

Issues reviewed	Journal (alphabetical order)	Number of papers with problems	Issue examples*
Issue 1: application of analytical methods that are inadequate or sensitive to incomplete network data	<i>Biological Invasions; Coastal Management; Conservation Biology; Environmental Development; Impact Assessment and Project Appraisal; Journal of Environmental Management; Journal of Insect Conservation; Sustainability</i>	1 (20%)	<p>isolates are explicitly analyzed in a network that includes non-respondents. This is problematic because there is a chance that non-respondents could in fact have ties with nodes identified as isolates.</p> <p>An analysis on the density of ties capturing cross-group interactions is performed on a network that includes non-respondents. This is problematic because there is a chance that non-respondents could in fact have cross-group interactions.</p> <p>Whole-network measures are reported, yet the network has only a 13% response rate. The implications of using partial network data is not discussed.</p>
Issue 2: application of statistical approaches that ignore dependency in the network	<i>Conservation Biology; Ecology and Society; Environmental Management; Environment and Behaviour; Journal of Environmental Management; Regional Environmental Change; Society and Natural Resources; Sustainability</i>	9 (16%)	<p>A standard paired t-test is used on centrality measures.</p> <p>An Ordinary Least Squares (OLS) regression is used on centrality measures.</p> <p>A comparative study between different sites is performed, where several network measures are correlated against performance indicators.</p> <p>In all these examples the statistical approaches applied do not account for network dependencies. Issues of non-independence are not addressed methodologically or discussed in the text.</p>
Issue 3: lack of connection between the theoretical base, research question, and choice of analytical techniques	<i>Ecology and Society; Environmental Development and Sustainability; Environmental Management; Society and Natural Resources; Sustainability</i>	5 (9%)	<p>The network analyses performed are not described in relation to hypotheses or research questions, nor are they linked to existing theoretical or empirical evidence.</p> <p>A study presented as a network analysis limit their results to a fancy network graph without performing any actual analysis.</p> <p>Claiming causal effect between network interventions and observed increase density in network structure without performing any analysis to support this claim.</p> <p>Network analysis not supported by a defined research question.</p> <p>Network metrics are included in a regression to explain more variance but there is no theoretical support or link to research question.</p>

\* See Supporting information for a full list.

Figure 1. Guide to conducting research on social networks, including specific research objectives, key theories, design, and practical considerations (1, See Borgatti et al. (2009) for a full typology of ties studied in social network analysis; 2, Weighted ties and other types of relational data (e.g. information, friendship, trade) can also be captured as different sets of binary ties with multiplex networks and investigated using multiplex techniques such as QAP regression (quadratic assignment procedure) or ERGMs (exponential random graph models).

