Available online at www.sciencedirect.com

ScienceDirect

Current Opinion in Environmental Sustainability

Structural dimensions of knowledge-action networks for sustainability

Tischa A Muñoz-Erickson[1] and Bethany B Cutts[2]

Research on the influence of social network structure over flows of knowledge in support of sustainability governance and action has recently flourished. These studies highlight three challenges to evaluating knowledge-action networks: first, defining boundaries; second, characterizing power distributions; and third, identifying obstacles to knowledge sharing and connectivity. We present concepts from social network analysis (SNA) commonly found to influence knowledge flows. We examine applications of SNA from across the social sciences and use the case of land governance in San Juan, Puerto Rico, as an illustration of how all three challenges affect knowledge-action networks. SNA is a useful way to understand and overcome many challenges to knowledge flow and thus help improve informational governance strategies for sustainability.

Addresses
[1] USDA Forest Service, International Institute of Tropical Forestry, 1201 Jardín Botánico Sur, Río Piedras, PR 00926, United States
[2] University of Illinois at Urbana-Champaign, Department of Natural Resources and Environmental Sciences, 1102 S. Goodwin Avenue, Urbana, IL, 61801, United States

Corresponding author: Muñoz-Erickson, Tischa A (tamunozerickson@fs.fed.us)

Current Opinion in Environmental Sustainability 2016, **18**:56–64

This review comes from a themed issue on **Sustainability governance and transformation**

Edited by **Bertrum MacDonald**, **Katrien Termeer**, **Paul Opdam** and **Katrine Soma**

Received 12 April 2015; Accepted 25 August 2015

http://dx.doi.org/10.1016/j.cosust.2015.08.013

1877-3435/Published by Elsevier B.V.

Introduction

In this paper we aim to present the various ways in which social networks shape the production, dissemination, and use of knowledge in decision-making and action for sustainability. New institutional arrangements are emerging that recognize the complex, and sometimes networked, interactions between knowledge and decision-making for environmental sustainability [1•,2–4]. In the area of urban sustainability, for instance, cities and national entities are investing in efforts that facilitate knowledge production, dissemination, and use across multiple sectors by creating boundary organizations to manage water and other resources (e.g., [5]), long-term collaborative social-ecological research sites (e.g., [6]) and most recently, sustainability research networks by the National Science Foundation (e.g., [7]). The range of political actors and stakeholders who play important roles in defining what should be sustained (and how to do it) is diverse and include members of academia, government, business, and civic sectors [8•,9]. Investments in these arrangements recognize that the connections between knowledge and action are complex and outside of the direct control of individual organizations and agencies. Further, they are an attempt to resolve the limitations of unidirectional models of *information* flow and transfer (Figure 1a) which have failed to both recognize the full suite of useful knowledge and motivate successful actions [10,11]. By expanding the breadth of credible and legitimate knowledge types, scholars have started to view the interactions between actors that hold relevant knowledge for environmental sustainability and those capable of action as *networks* (Figure 1b; [12••,13–15]). Studies of these knowledge-action networks aim to analyze and understand how these efforts are working and how successful they are in advancing the production and implementation of knowledge in support of transitions towards sustainability (e.g., [8•,16–19]).

This paper reviews the most recent research on how social network structure affects the flow of knowledge in knowledge-action networks. Social networks are patterned social relations that link actors together through various connections, such as friendships, communication, information, and in this case, knowledge. As incentives to form knowledge-action networks grow, so too does the need to confront the different ways of knowing and visions of a desirable future. Because sustainability is a process, not an objective endpoint, in which the definition of which specific aspects of economic vitality, environmental health, and equity are to be sustained is deliberated among multiple sectors of society [66], it is important to understand the ideas about how to pursue sustainability that become embedded in these networks. Therefore, in these knowledge-action networks, opportunities for knowledge flow go beyond the flow of information in the form of facts, data, etc. Instead, what flows through the network is knowledge, here understood as including content (i.e., what people know) and the normative and political dimensions of that knowledge (i.e., beliefs and visions of the world), as well as the social practices associated with producing that knowledge by multiple formal and informal actors (i.e., how people know or their

Figure 1

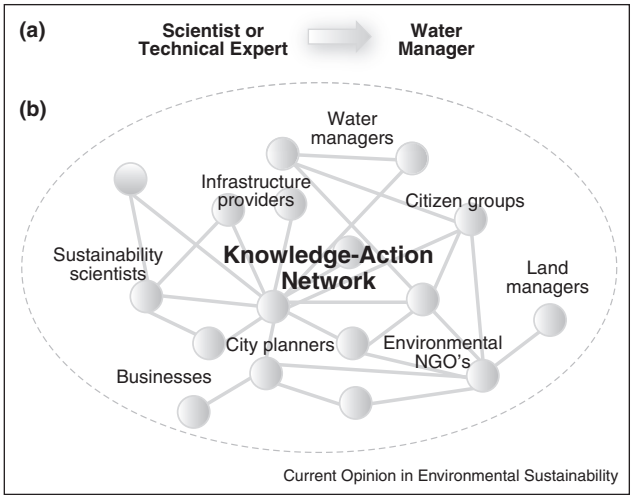


Illustration of the linkage between knowledge and action as a conventional unidirectional flow of information transfer between a scientist or expert and a decision-maker or manager **(a)**, and the emerging view of multiple actors and different types of knowledge interacting through a knowledge-action network **(b)**.

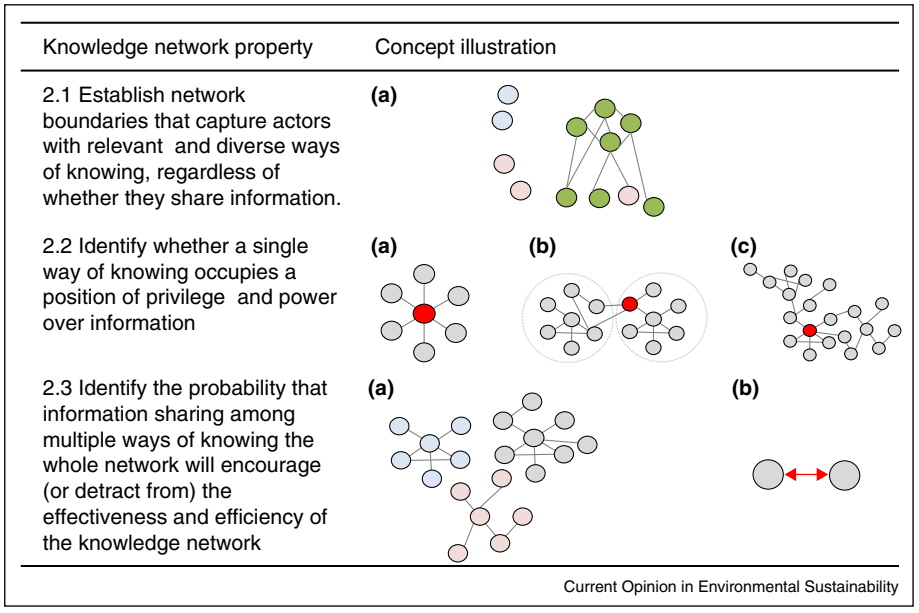
knowledge systems). In other words, formal types of knowledge such as science, and informal types of knowledge such us practical or experiential, are both valid ways of knowing and sources of expertise in these networks. The distinction is that scientific knowledge may be justified based on accepted standards and peer review while practical knowledge is justified based on personal experience and validation by the community [11].

Because the foundation of knowledge-action networks are social relations among actors (or organizations for the purposes of this review) involved in knowledge and decision-making, it is appropriate to use concepts and tools of social network analysis (SNA) to explicitly examine network structure and understand barriers and opportunities to knowledge flow. SNA is a technique that is increasingly used in natural resource management and sustainability to quantify emergent social structures and their connections through the construction of graphs of nodes/actors and links/ties [20–23]. We view SNA as a promising approach to understand and overcome structural challenges to knowledge flow and thus help improve the way that these networks are designed and constructed as informational governance strategies for sustainability. In the sections that follow we review three analytical challenges to evaluating structural dimensions of knowledge flow in knowledge-action networks: first, how to best define meaningful and inclusive boundaries to form a *diverse composition for the knowledge-action network*, especially when the connections among relevant knowledge holders may be sparse; second, how to characterize and diagnose *the distribution of power across the knowledge-action network*, or the ways that knowledge flows may privilege some types of knowledge over others and therefore lead to action outcomes that create undue tensions among sustainability goals; and third, how to identify probable challenges to efficient knowledge flow and sharing across the network, or its *connectivity*. While these do not represent an exhaustive list of SNA concepts that can capture structural influences on knowledge flow, they represent the most common approaches taken in the literature and offer a good starting point to examine knowledge-action networks. The concepts are illustrated in Figure 2. As an example of how the structure of a network can affect the capacity to build knowledge-action networks for sustainability, we present the case of land and green infrastructure governance in the city of San Juan, Puerto Rico.

Network boundaries and inclusion of diverse knowledge types

A fundamental question for both SNA and research on knowledge-action networks is how to define appropriate boundaries for the system under study [8•,23]. In a knowledge-action network, the goal is to broaden the composition of the network with a diversity of actors holding different types of knowledge [24]. Sustainability is facilitated by the integration among policy sectors, jurisdictional and spatial scales, or resource systems (e.g., land, water, energy) [25]. Thus, establishing appropriate limits to a sustainability knowledge network and deciding who is in and who is out can be especially challenging. Low connectivity (or high *fragmentation*) across different resource domains or systems may inhibit governance capacity because knowledge about different sectors/systems cannot circulate across the networks. For instance, although scholars suggest that land and water management should be coordinated to achieve more sustainable use of water resources, it is common for water and land managers to not interact with one another to obtain information, knowledge, or collaborate in implementing water management actions [26]. As illustrated in Figure 2.1.a, there may be important knowledge sources that are not connected, or underrepresented in a network. A growing body of work has found that networks in which one or more ways of knowing are peripheral (that is, are not part of the central component) are less likely to result in credible and feasible sustainability solutions (e.g., [24,27–35]). In another example, local governments in California were more likely to join regional sustainability planning networks when the ideology of the city's constituents was similar to those of municipalities already in the network [30]. This suggests that the regional planning network represents a narrowly defined set of knowledge types or expertise in comparison to the potential diversity of the region.

Figure 2



By synthesizing literature on sustainability knowledge production and social networks, we identify interactions between ways of knowing and information exchange that influence knowledge networks. Evaluating the barriers and opportunities to translating knowledge to action requires investigating (1) diversity and inclusion (2) position and power, and (3) connectivity.

Recent studies have borrowed from stakeholder elicitation methods designed to capture perspectives beyond those that are already engaged in the network (e.g., [8•,33,36,37•,38]). These methods typically focus on identifying sources of formal authorities or responsibility to generate and disperse knowledge, as well as institutions with informal authority derived from popularity as a representative of the public interest. Key informants and snowball sampling approaches are common approaches to identify who the relevant actors are when boundaries are not well defined [23]. With respect to knowledge-action networks, recent studies recognize that in the information society there is no distinct separation between knowledge producers and users [8•,33]. Because actors can be at the same time both sources and users of knowledge, researchers should cast a wide net of actors and not do *a priori* labeling of the role of actors with respect to knowledge in these networks. The full extent of the network is then defined by aggregating the range of connections elicited from each actor rather than by a frame defined by researchers ahead of time (e.g., [33]).

Distribution of power in knowledge-action networks

The way that power is distributed through the knowledge-action network can affect the level of access to knowledge and the extent to which there are asymmetries in how knowledge flows. The ability of an actor or organization to disseminate, restrict, or manipulate knowledge depends to some extent on how many other actors rely on them as a source of knowledge. Because the process of how knowledge flows can have enormous impacts on who is able to access and make use of it [39], it is crucial to understand how power asymmetries, or differences in the positions that different actors hold in the structure of the network, can affect the performance of the network [27]. For instance, a recent study of lobster fishery management showed that fisheries with the highest yields rates were most central to the information sharing network, but that this success was a result of disproportional sharing of information [34]. In other words, the fisheries with more powerful positions in the network achieved higher benefits by restricting access of other fishermen to alternative sources of information. Thus, a suboptimal network structure was affecting sustainable fishery outcomes because actors with the most information had low incentives to share information across the rest of the network. Such a scenario creates a management paradox if the goal is to better link knowledge to sustainability action. Other studies have shown a tendency for different types of knowledge to create barriers to information sharing and collaborative action (e.g., [28,29]). As Adger *et al.* posit more powerful actors can tilt the playing field to skew information and knowledge in their favor [40].

Different forms of power come from different measures of centrality in the network. Power can be manifested

through direct connections (degree centrality) and the balance between knowledge transfers that indicate levels of influence across different knowledge types [29,32,37•,41,42]. The number of links directed towards an actor, or incoming ties an actor receives, is a measure of in-degree centrality and is an indicator of the actor's popularity in the network. The number of links sent out from an actor, or outgoing ties an actor gives out, is a measure of out-degree centrality and it is an indication of knowledge dispersal or advice by an actor [12••,43,44,45••]. Together, these two indicators form *degree centrality* (Figure 1.2a) and the weighted calculation of the number and ratio of in-degree and out-degree centrality is an indicator of influence [27,29,32,37•,41,42,46]. When the same actors have high in-degree and high influence centrality, this indicates a network structure in which knowledge exchange is highly controlled and centralized. Correlations between either in-degree centrality or influence and a particular type of knowledge can be limiting for sustainability knowledge-action systems, as evidenced by examples in network applications beyond the sustainability literature [47]. In these cases, oversight is necessary to ensure accurate information and appropriate information and knowledge flow beyond the highly centralized actors.

Other studies find that filling a bridging role, or having high *betweenness centrality*, can influence the power of a particular organization over knowledge flows (Figure 1.2.b and 1.2.c). Betweenness centrality is another measure of network power and it consists of the number of times that an actor rests between two actors [20]. Actors with high betweenness can serve an important social role as knowledge brokers because they are connected to otherwise disconnected actors, therefore they have access to many unique pieces of information and can synthesize from this larger pool of knowledge. Thus, actors with high betweenness can possess crucial knowledge that may be advantageous in creating new understandings and opportunities for natural resource management and sustainability that other actors do not recognize [67]. As such, high betweenness in a knowledge network can lead to efficient access to all information pathways (Figure 1.2.b [29,37•,41,48,49•]). On the other hand, actors with high betweenness can also modify the amount and nature of knowledge that flows among members of the network, thus distorting proper flow and access to knowledge across the network (Figure 1.2.c [50,51•]). As with degree centrality, then, the distribution of power depends on both the evenness of betweenness centrality scores and whether betweenness centrality is concentrated in a single knowledge type [51•]. In a recent study of Costa Rican water management, the authors operationalized knowledge flows by tracing networks of collaboration, information sharing, and resource transfers. They uncovered that, while different types of knowledge were included in the network, local relationships were nevertheless mediated more by scientific knowledge generated at national level institutions than other ways of knowing [51•].

Connectivity across diverse knowledge types

Just as the positions of individual actors can sometimes privilege particular knowledge types, the configuration of ties across the whole network can encourage or detract from the effectiveness and efficiency of the network. The way those actors' ties cluster and the extent to which they exchange knowledge evenly can be used as tools to examine knowledge-action networks. Dense local and issue-specific knowledge flows with effective connections across actors are important, especially if the goal is to build social capital through trust and cohesion [52]. However, they can often be stymied by weak information sharing among alternative knowledge systems [28,53]. Network connectivity and divisions can serve as indicators of barriers in the connectivity of the network. *Homophily* for instance, is an indicator of the degree to which actors are tied to others with similar beliefs (Figure 2.3.a). Generally, knowledge-action networks need to span knowledge types to be effective [28,53–55,56••]. Interactions among actors with different geographic concerns can promote knowledge flow and initiate management actions at levels that are most appropriate and effective for the resource in question [53,56••], thus high homophily in the network can be a challenge to achieve outcomes of knowledge-action networks. For example, Berardo [31] found that low homophily supported knowledge integration in water resource management cost-sharing programs. By contrast, Wood *et al.* [57] found that farmers with dense but homophilous networks were more likely to incorporate only scientific knowledge in their actions than those with more integrated networks. Thus, while high homophily generally seems to undermine knowledge transfer, there is a need to understand other contextual factors that might complicate these results, as in the case of Wood *et al.* [57].

Other dimensions of connectivity, such as whether or not ties among different knowledge types are reciprocal, are also important for knowledge-action networks. *Reciprocal* ties are those in which knowledge exchange and transfer is happening in a two-way direction (Figure 2.3.b), such as when two actors are sharing direct knowledge. Scholars hypothesize that these reciprocated relationships are most essential when preventing defection is essential to achieving action [58,59]. Reciprocity is a common way that actors translate knowledge into cooperative action, when action cannot be achieved without buy-in from all partners and regular participation [60]. Mutually acknowledged two-directional knowledge flow indicates that working together is in the best interest of both parties. In a survey of national estuary programs, for example, Berardo *et al.* found that reciprocity was the best predictor of organizations' rating of other organization's trustworthiness [58].

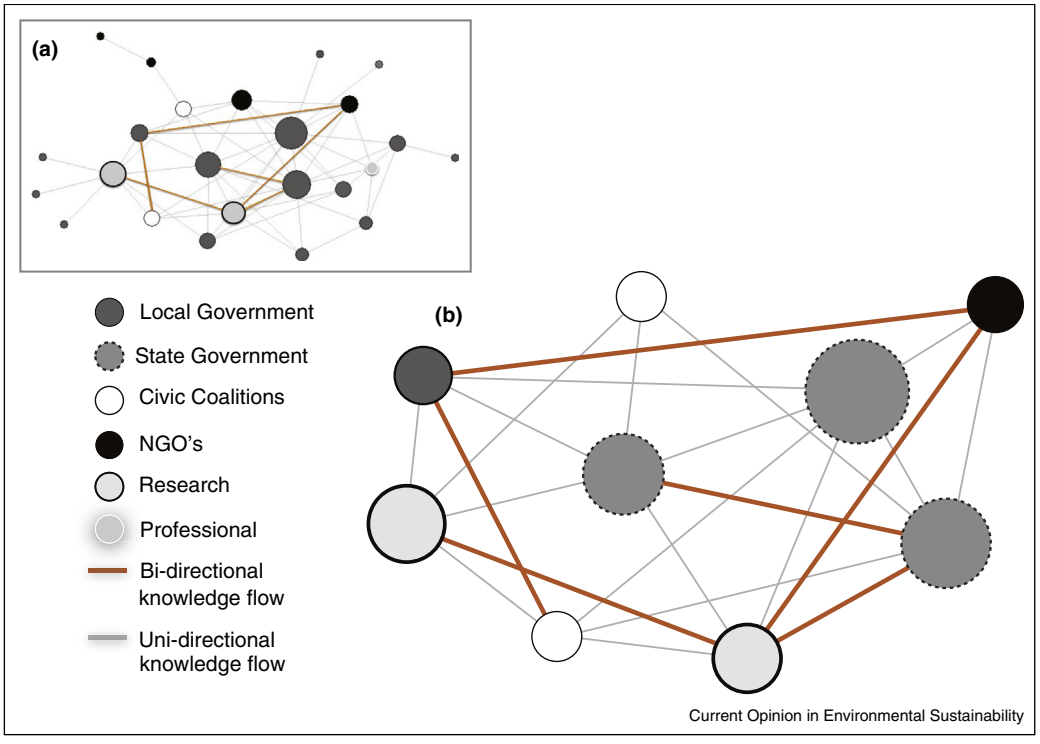
Analyzing structure in knowledge-action networks: an example

Beginning in the early 2000s, the Municipality of San Juan in northeastern Puerto Rico has been experiencing a shift towards more sustainable land use governance as it received autonomy from the state to develop its own system of information and planning for territorial ordinance. Parallel to this decentralization was the emergence of stewardship initiatives by non-profit organizations, community groups, private entities, and coalitions that also contributed different types of knowledge and created information networks to improve the urban environment. In 2009, Muñoz-Erickson [8•,61] conducted a social network analysis of stakeholder organizations to examine how the relationships among the different land governance sectors influenced the flow of knowledge regarding the management and governance of urban land and green infrastructure.

The study used a series of iterative steps to establish the boundaries of the knowledge network, identify the central actors in the network, and analyze the level of connectivity in the network. First, because there was no pre-defined boundary of the network, a wide net was cast on organizations involved in or affected by decisions over environmental and land use decision-making in the city. A total of 110 organizations were included in the study and no *a priori* decision was made as to which actors were knowledge producers or users. Instead, through a survey questionnaire administered to the 110 organizations, actors could self-identify whether they produced knowledge as well as identify the organizations that they go to frequently to obtain knowledge on land use and green infrastructure issues. The organizations that actors go to for knowledge became what are called in social network theory as their 'ego-network'. From this information the structure of the overall network of organizations, or 'whole network', was constructed for San Juan. On the basis of the number of times that an organization was mentioned by others as a source of knowledge (twice or more) in the survey, the boundary of the network was established and centrality measures (degree and betweenness) and reciprocity were calculated using SNA software UCINET.

The study found a network structure composed of 26 organizations (Figure 3a), of which 80% responded that they collected their own data and knowledge, thus engaging in knowledge generation not just use. The network was diverse including federal, state and local

Figure 3



Network of knowledge flow among stakeholder organizations involved in land and green area decision-making and governance in San Juan, Puerto Rico. The figure on the top left **(a)** shows all 26 organizations linked through knowledge flows. Different weights of the nodes means different levels of degree centrality, with greater nodes having greater degree centrality. The larger figure on the right **(b)** shows only the central actors in the network because they have higher degree centrality and betweenness (i.e., brokers) and the reciprocal ties among them (in orange).

agencies, research institutions, non-governmental organizations, and conservation coalitions. The diversity and connectivity of this network was conducive for the knowledge-action networks necessary for sustainability. However, a closer look at the structural position of the network's central actors — organizations with greater influence over the network — and the level of reciprocity among them revealed multiple barriers to knowledge flows and symmetries in knowledge systems (Figure 3b). First, the actors that dominated knowledge flow about land use were the same state agencies that used to have the jurisdiction over land use in the city, such as the Puerto Rico Planning Board. This suggests that much of what we know about land use patterns and dynamics is filtered (intentionally or unintentionally) by the values, beliefs, and ideologies, of the actors that used to control city resources, or that regulated them, even though the Municipality has now the power to make decisions over land use. Second, there was a lack of connectivity and reciprocity between these state agencies and the municipality, thus indicating a crucial breakdown in knowledge between these two key actors. Finally, knowledge asymmetries were also uncovered, with conventional knowledge systems associated with state administration (e.g., economic planning, technocratic approaches) dominating over other alternative types of knowledge (e.g., local, ecological, political, etc.) in the network.

This example illustrated how structural dimensions of the network, in particular the composition, position, and connectivity of central actors influenced what knowledge was more influential over others and how this knowledge circulated, or not, among network actors. The extent to which the structure of the network was conducive to building a knowledge-action network for sustainability is difficult to assert with only a snapshot in time. Implementation of the same methodology in the future will allow a longitudinal examination of how the structure changes and its influence on governance processes. In the short term, however, conflicting sustainability visions for the city among the network central actors have been observed [61], leading to hypothesize that the fragmentation in knowledge flow and ways of knowing could potentially be resulting in divergent values and expectations for the city. Uncovering these deficiencies in the knowledge network allowed for more in-depth mapping of the barriers and opportunities for knowledge flow and organizational cooperation to building knowledge-action systems for city sustainability planning [61].

Conclusions

We contend that knowledge-action networks can serve as an informational governance strategy to promote sustainability through increased connectivity among diverse types of knowledge that enable action. As research on informational governance advances our understanding of how information and knowledge can restructure sustainability decision-making and governance, it is crucial that we examine the underlying socio-political structural processes and trade-offs shaping successful knowledge-action networks. By success we mean that the network facilitates credible and legitimate processes of knowledge creation, dissemination, and utilization among multiple stakeholders in arenas where knowledge and visions can be deliberated, integrated, critiqued, and negotiated, ultimately leading to just and favorable social and ecological outcomes. Certainly, structure is not a sufficient condition for sound network operation. Other processes also come into play in how a network functions. Nevertheless, networks present structured social systems which can help illuminate whether failure to meet desired outcomes are due to identifiable network properties [62,63].

The studies we reviewed highlight some of the ways that the structure of knowledge flows can influence knowledge-action networks. We conclude that, first, informational governance is dependent on the structural dimensions of knowledge flows that connect knowledge and action through networks. The credibility of knowledge-action networks depends to a large extent on the degree to which they include diverse types of knowledge or knowledge systems, the opportunities for these multiple knowledges to interact, and on interactions that distribute power across these multiple knowledges. We expect that barriers on any one of these three domains can limit action. Second, social networks can exhibit complex effects. A particular structure may facilitate some action while constraining others [64]. Outcomes that rely on coordination are likely to require different network structures than those that require cooperation [12••,65]. There is a need for more studies that include multiple spheres of action, for example, linkages between knowledge systems for managing both invasive species and water quality. Relatively few studies have examined whether structural relations affect multiple outcomes, or whether the conditions that advance one sustainability goal come at the costs of others.

Better consideration of knowledge-action networks in studies of informational governance call for the use of social network analytical tools to examine the role of structure in these networks explicitly. Our review points to three key considerations in defining networks and analyzing the effect of structure. First, the process of establishing the boundary and composition of the networks is crucial. The simple act of visualizing connectivity can elucidate discrepancies between conventional wisdom about who is included and who is excluded in a network as well as about the level of participation, control, and kinds of responsibility leveraged by each actor. Researchers should cast a wide net as they define relevant actors and not do *a priori* labeling of the role of actors with respect to knowledge users or producer in

these networks. Second, through SNA it is evident that the distribution of power in the network, as well as who is linked to whom, can affect whether knowledge is evenly accessible to most network actors or if knowledge asymmetries are evident, as in the case of San Juan. Third, the way that network ties are configured can encourage the efficiency of knowledge flow through the network by encouraging reciprocal knowledge exchanges, or discourage it by linking actors with similar knowledge systems while excluding others.

To address sustainability, creating, managing, and disseminating different types of knowledge across a multiplicity of political actors is of crucial importance. Understanding the structure of knowledge-action networks can serve as an informational governance activity that is part of the tool-kit in working with multiple stakeholder organizations. Awareness of the different, and sometimes conflicting, ways of knowing that come to bear in complex decision-making settings is useful knowledge to design and build knowledge-action systems that can successfully address these challenges. The synthesis we present here offers a starting point to direct research towards better understanding of how knowledge-action networks work for informational governance of sustainability across a wide range of sectors and regions.

Acknowledgements

We are grateful to Katrine Soma and Paul Opdam for their useful comments on earlier versions of this manuscript. Support for this work was provided by the USDA Forest Service, International Institute of Tropical Forestry, the National Science Foundation under Grant number 0948507 (Urban Long-Term Research Area Exploratory) and the USDA under Grant number ILLU-875-919. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the view of the National Science Foundation (NSF) and the United States Department of Agriculture (USDA).

References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. • Cornell S, Berkhout F, Tuinstra W, Tàbara JD, Jäger J, Chabay I, de Wit B, Langlais R, Mills D, Moll P *et al.*: **Opening up knowledge systems for better responses to global environmental change**. *Environ Sci Policy* 2013, **28**:60-70 http://dx.doi.org/10.1016/j.envsci.2012.11.008.
In this conceptual article, authors argue for the transformation and 'opening up' of knowledge systems to address sustainability in which the interactions between scientists and actors in diverse knowledge systems is intensified and scientific practices are oriented more towards societal arenas where sustainability is being tackled. The authors provide a vision and roadmap for the coordination and organization of these knowledge systems.

2. Mauser W, Klepper G, Rice M, Schmalzbauer BS, Hackman H, Leemans R, Moore H: **Transdisciplinary global change research: the co-creation of knowledge for sustainability**. *Curr Opin Environ Sustain* 2013, **5**:420-431 http://dx.doi.org/10.1016/j.cosust.2013.07.001.

3. van Kerkhoff L, Szlezák AN: **The role of innovative global institutions in linking knowledge and action**. *Proc Natl Acad Sci U S A* 2010 http://dx.doi.org/10.1073/pnas.0900541107.

4. Clark WC, Tomich TP, van Noordwijk M, Guston D, Catacutan D, Dickson NM, McNie E: **Boundary work for sustainable development: natural resource management at the Consultative Group on International Agricultural Research (CGIAR)**. *Proc Natl Acad Sci U S A* 2011 http://dx.doi.org/10.1073/pnas.0900231108.

5. Larson KL, White DD, Gober P, Kirkwood CW, Smith VK, Nelson MC, Redman CL, Wittlinger SK: *Advancing Science in Support of Water Policy and Urban Climate Change Adaptation at Arizona State University's Decision Center for a Desert City: A Synthesis of Interdisciplinary Research on Climate, Water, and Decision Making Under Uncertainty*. 2013.

6. Grove JM, Pickett STA, Whitmer A, Cadenasso M: **Building an Urban LTSER: The case of Baltimore Ecosystem Study and the D.C./B.C. ULTRA-Ex Project. Long term socio-ecological research**. In *Long Term Socio-ecological Research.* Edited by Moran EF. Netherlands: Springer; 2013:369-408 http://dx.doi.org/10.1007/978-94-007-1177-8.

7. National Science Foundation: *Sustainability Research Networks Competition (SRN) 2014 Focus: Urban Sustainability*. 2015.

8. • Muñoz-Erickson TA: **Co-production of knowledge-action systems in urban sustainable governance: the KASA approach**. *Environ Sci Policy* 2014, **37**:182-191 http://dx.doi.org/10.1016/j.envsci.2013.09.014.
This article presents the knowledge-action systems analysis (KASA) framework as a methodological approach that combines qualitative and quantitative SNA to analyze the co-production of knowledge and decision-making in multi-stakeholder settings for sustainability. Using the case of land governance in the city of San Juan, Puerto Rico, the author demonstrate the utility of this integrated approach to understand knowledge-power dynamics in the governance of urban sustainability.

9. Muñoz-Erickson T: **Knowledge to serve the city: insights from an emerging knowledge-action network to address vulnerability and sustainability in San Juan, Puerto Rico**. *Cities Environ* 2014, **7**:5 http://digitalcommons.lmu.edu/cate/vol7/iss1/5/.

10. Wesselink A, Buchanan KS, Georgiadou Y, Turnhout E: **Technical knowledge, discursive spaces and politics at the science–policy interface**. *Environ Sci Policy* 2013, **30**:1-9 http://dx.doi.org/10.1016/j.envsci.2012.12.008.

11. van Kerkhoff L, Lebel L: **Linking knowledge and action for sustainable development**. *Annu Rev Environ Resour* 2006, **31**:445-477 http://dx.doi.org/10.1146/annurev.energy.31.102405.170850.

12. •• Henry AD, Vollan B: **Networks and the challenge of sustainable development**. *Annu Rev Environ Resour* 2014, **39**:583-610 http://dx.doi.org/10.1146/annurev-environ-101813-013246.
This paper is the most recent comprehensive literature review on the use of social network concepts to address key challenges of interest in the the sustainability science literature, including: linking knowledge to action, enhancing collective action, and promoting social learning. The authors argue that a better understanding of the structural properties of networks can inform strategies to promote patters of social interactions that support sustainability.

13. Cash DW: **Distributed assessment systems: an emerging paradigm of research, assessment and decision-making for environmental chang**. *Glob Environ Change* 2000, **10**:241-244 http://dx.doi.org/10.1016/S0959-3780(00)00031-5.

14. Vogel C, Moser SC, Kasperson RE, Dabelko GD: **Linking vulnerability, adaptation, and resilience science to practice: pathways, players, and partnerships**. *Glob Environ Change* 2007, **17**:349-364 http://dx.doi.org/10.1016/j.gloenvcha.2007.05.002.

15. Miller C, Muñoz-Erickson TA, Monfreda C: *Knowledge Systems Analysis: A Report for the Advancing Conservation in a Social Context Project*. 2010.

16. Offermans A, Glasbergen P: **Boundary work in sustainability partnerships: an exploration of the Round Table on Sustainable Palm Oil**. *Environ Sci Policy* 2015, **50**:34-45 http://dx.doi.org/10.1016/j.envsci.2015.01.016.

17. Hegger D, Lamers M, Van Zeijl-Rozema A, Dieperink C: **Conceptualising joint knowledge production in regional climate change adaptation projects: success conditions and**

levers for action. *Environ Sci Policy* 2012, **18**:52-65 http://dx.doi.org/10.1016/j.envsci.2012.01.002.

18. Lang DJ, Wiek A, Bergmann M, Stauffacher M, Martens P, Moll P, Swilling M, Thomas CJ: **Transdisciplinary research in sustainability science: practice, principles, and challenges**. *Sustain Sci* 2012, **7**:25-43 http://dx.doi.org/10.1007/s11625-011-0149-x.

19. Crona BI, Parker JN: **Learning in support of governance: theories, methods, and a framework to assess how bridging organizations contribute to adaptive resource governance**. *Ecol Soc* 2012, **17**:32 http://dx.doi.org/10.5751/ES-04534-170132.

20. Wasserman S, Faust K: *Social Network Analysis: Methods and Applications*. Cambridge University Press; 1994.

21. Borgatti SP, Mehra A, Brass DJ, Labianca G: **Network analysis in the social sciences**. *Science* 2009, **323**:892-896 http://dx.doi.org/10.1126/science.1165821.

22. Prell C: **Some basic structural characteristics of networks**. In *Social Networks and Natural Resource Management: Uncovering the Social Fabric of Environmental Governance.* Edited by Bodin Öul., Prell C. Cambridge University Press; 2011:29-43.

23. Bodin Ö, Prell C: **Social network analysis in natural resource governance — summary and outlook**. In *Social Networks and Natural Resource Management: Uncovering the Social Fabric of Environmental Governance.* Edited by Bodin Öul., Prell C. Cambridge University Press; 2011:347-373.

24. Moeliono M, Gallemore C: **Information networks and power: confronting the "wicked problem" of REDD+ in Indonesia**. *Ecol Soc* 2014, **19**:9 http://dx.doi.org/10.5751/ES-06300-190209.

25. Shiroyama H, Yarime M, Matsuo M, Schroeder H, Scholz R, Ulrich AE: **Governance for sustainability: knowledge integration and multi-actor dimensions in risk management**. *Sustain Sci* 2012, **7**:45-55 http://dx.doi.org/10.1007/s11625-011-0155-z.

26. Gober P, Larson KL, Quay R, Polsky C, Chang H, Shandas V: **Why land planners and water managers don't talk to one another and why they should!** *Soc Nat Resour* 2012, **26**:356-364 http://dx.doi.org/10.1080/08941920.2012.713448.

27. Crona B, Bodin O: **Power asymmetries in small-scale fisheries: a barrier to governance transformability**. *Ecol Soc* 2010, **15**:32 http://www.ecologyandsociety.org/vol15/iss4/art32/.

28. Muñoz-Erickson TA, Cutts BB, Larson EK, Darby KJ, Neff M, Wutich A, Bolin B: **Spanning boundaries in an Arizona watershed partnership: information networks as tools for entrenchment or ties for collaboration?** *Ecol Soc* 2010, **15**:22 http://www.ecologyandsociety.org/vol15/iss3/art22/.

29. Gallemore C, Prasti H, Moeliono M: **Discursive barriers and cross-scale forest governance in Central Kalimantan, Indonesia**. *Ecol Soc* 2014, **19**:18 http://dx.doi.org/10.5751/ES-06418-190218.

30. Gerber ER, Henry AD, Lubell M: **Political homophily and collaboration in regional planning networks**. *Am J Pol Sci* 2013, **57**:598-610 http://dx.doi.org/10.1111/ajps.12011.

31. Berardo R: **Bridging and bonding capital in two-mode collaboration networks**. *Policy Stud J* 2014, **42**:197-225 http://dx.doi.org/10.1111/psj.12056.

32. Romolini M, Grove JM, Locke DH: **Assessing and comparing relationships between urban environmental stewardship networks and land cover in Baltimore and Seattle**. *Landsc Urban Plan* 2013, **120**:190-207 http://dx.doi.org/10.1016/j.landurbplan.2013.08.008.

33. Schut M, Klerkx L, Rodenburg J: **RAAIS: Rapid Appraisal of Agricultural Innovation Systems (Part I). A diagnostic tool for integrated analysis of complex problems and innovation capacity**. *Agric Syst* 2014, **132**:1-11 http://dx.doi.org/10.1016/j.agsy.2014.08.009.

34. Turner R, Polunin N, Stead S: **Social networks and fishers' behavior: exploring the links between information flow and fishing success in the Northumberland lobster fishery**. *Ecol Soc* 2014, **19**:38 http://dx.doi.org/10.5751/ES-06456-190238.

35. Sandström A, Crona B, Bodin Ö: **Legitimacy in co-management: the impact of preexisting structures, social networks and governance strategies**. *Environ Policy Gov* 2014, **24**:60-76 http://dx.doi.org/10.1002/eet.1633.

36. Chan K, Liebowitz J: **The synergy of social network analysis and knowledge mapping: a case study**. *Int J Manag Decis Mak* 2006, **7**:19-35 http://dx.doi.org/10.1504/IJMDM.2006.008169.

37. • Lienert J, Schnetzer F, Ingold K: **Stakeholder analysis combined with social network analysis provides fine-grained insights into water infrastructure planning processes**. *J Environ Manage* 2013, **125**:134-148 http://dx.doi.org/10.1016/j.jenvman.2013.03.052.

This paper examines the added value of combining qualitative stakeholder analysis with quantitative approaches of SNA to analyze collaborative and multi-level governance settings. Using the case of infrastructure in the Swiss water sector, the authors demonstrate that SNA provides a rigorous approach that gain deeper insights into planning processes.

38. Prell C, Hubacek K, Reed M: **Stakeholder analysis and social network analysis in natural resource management**. *Soc Nat Resour* 2009, **22**:501-518 http://dx.doi.org/10.1080/08941920802199202.

39. Miller C: **Resisting empire: globalism, relocalization, and the politics of knowledge**. In *Earthly Politics: Local and Global in Environmental Governance.* Edited by Jasanoff S, Martello ML. MIT Press; 2004.

40. Adger WN, Arnell NW, Tompkins EL: **Successful adaptation to climate change across scales**. *Glob Environ Change* 2005, **15**:77-86 http://dx.doi.org/10.1016/j.gloenvcha.2004.12.005.

41. Ingold K: **How involved are they really? A comparative network analysis of the institutional drivers of local actor inclusion**. *Land Use Policy* 2014, **39**:376-387 http://dx.doi.org/10.1016/j.landusepol.2014.01.013.

42. McAllister RRJ, McCrea R, Lubell MN: **Policy networks, stakeholder interactions and climate adaptation in the region of South East Queensland, Australia**. *Reg Environ Change* 2013, **14**:527-539 http://dx.doi.org/10.1007/s10113-013-0489-4.

43. Ward MD, Stovel K, Sacks A: **Network analysis and political science**. *Annu Rev PolSci* 2011, **14**:245-264 http://dx.doi.org/10.1146/annurev.polisci.12.040907.115949.

44. Robins G: **A tutorial on methods for the modeling and analysis of social network data**. *J Math Psychol* 2013, **57**:261-274 http://dx.doi.org/10.1016/j.jmp.2013.02.001.

45. •• Kapucu N, Hu Q, Khosa S: **The state of network research in public administration**. *Admin Soc* 2014 http://dx.doi.org/10.1177/0095399714555752. (online ahead 1–34).

This paper offers a comprehensive review of SNA in the public administration literature, finding a need for more studies that examine the intersection of policy, governance, and collaboration networks. The authors conclude by calling for more mixed-methods research, research on network substructures, and multilevel networks.

46. Yun S-J, Ku D, Han J-Y: **Climate policy networks in South Korea: alliances and conflicts**. *Clim Policy* 2014, **14**:283-301 http://dx.doi.org/10.1080/14693062.2013.831240.

47. Huitsing G, van Duijn MA, Snijders JTA, Wang B, Sainio P, Salmivalli M, Veenstra CR: **Univariate and multivariate models of positive and negative networks: liking, disliking, and bully–victim relationships**. *Soc Netw* 2012, **34**:645-657 http://dx.doi.org/10.1016/j.socnet.2012.08.001.

48. Ingold K, Fischer M: **Drivers of collaboration to mitigate climate change: an illustration of Swiss climate policy over 15 years**. *Glob Environ Change* 2014, **24**:88-98 http://dx.doi.org/10.1016/j.gloenvcha.2013.11.021.

49. • Mills M, Álvarez-Romero J: **Linking regional planning and local action: towards using social network analysis in systematic conservation planning**. *Biol Conserv* 2014, **169**:6-13 http://dx.doi.org/10.1016/j.biocon.2013.10.015.

This paper discusses the value of SNA in systematic conservation planning. The article focuses on the importance of cross-scales social

networks to facilitate adaptive management of coral reefs in the Solomon Islands.

50. Carina E, Keskitalo H, Baird J, Laszlo Ambjörnsson E, Plummer R: **Social network analysis of multi-level linkages: a Swedish case study on northern forest-based sectors**. *Ambio* 2014 http://dx.doi.org/10.1007/s13280-014-0492-0.

51. • Vignola R, McDaniels TL, Scholz RW: **Governance structures for ecosystem-based adaptation: using policy-network analysis to identify key organizations for bridging information across scales and policy areas**. *Environ Sci Policy* 2013, **31**:71-84 http://dx.doi.org/10.1016/j.envsci.2013.03.004.
This article discusses that both organization scale and network position are important to its ability to facilitate knowledge flow and encourage action informed by knowledge. The paper introduces cross-scale and cross-policy network terms that are used to identify the information-bridging capacity of organizations in Costa Rica with a stake in soil erosion processes.

52. Crona B, Ernstson H, Prell C, Reed M, Hubacek K: **Combining social network approaches with social theories to improve understanding of natural resource governance**. *Social Networks and Natural Resource Management: Uncovering the Social Fabric of Environmental Governance*. Cambridge University Press; 2011:: 44-73.

53. Guerrero AM, McAllister RRJ, Corcoran J, Wilson KA: **Scale mismatches, conservation planning, and the value of social-network analyses**. *Conserv Biol* 2013, **27**:35-44 http://dx.doi.org/10.1111/j.1523-1739.2012.01964.x.

54. Weible CM: **Beliefs and perceived influence in a natural resource conflict: an Advocacy Coalition Approach to policy networks**. *Pol Res Q* 2005, **58**:461-475 http://dx.doi.org/10.1177/106591290505800308.

55. Lubell M, Scholz J, Berardo R, Robins G: **Testing policy theory with statistical models**. *Policy Stud J* 2012, **40**:351-374.

56. •• Guerrero A, Mcallister R, Wilson K: **Achieving cross-scale collaboration for large scale conservation initiatives**. *Conserv Lett* 2014 http://dx.doi.org/10.1111/conl.12112.
This paper discusses high level network structure influences on knowledge flow. They suggest that regional conservation is enhanced when relations at the subregional level are strong. This is one of an emerging set of studies that examines interactions across issues and scales using an advanced statistical technique called exponential random graph models. The paper examines collaboration related to invasive animal control, revegetation, and all conservation activities in the Fitz-Stirling region of Australia.

57. Wood BA, Blair HT, Gray DI, Kemp PD, Kenyon PR, Morris ST, Sewell AM: **Agricultural science in the wild: a social network analysis of farmer knowledge exchange**. *PLoS One* 2014, **9**:e105203 http://dx.doi.org/10.1371/journal.pone.0105203.

58. Berardo R, Scholz JT: **Self-organizing policy networks: risk, partner selection, and cooperation in estuaries**. *Am J Pol Sci* 2010, **54**:632-649 http://dx.doi.org/10.1111/j.1540-5907.2010.00451.x.

59. Lubell M: **Collaborative institutions in an ecology of games**. *Am J Pol Sci* 2010, **20**:207-271 http://dx.doi.org/10.1162/ARTL_a_00126.

60. Baird J, Plummer R, Haug C, Huitema D: **Learning effects of interactive decision-making processes for climate change adaptation**. *Glob Environ Change* 2014, **27**:51-63 http://dx.doi.org/10.1016/j.gloenvcha.2014.04.019.

61. Muñoz-Erickson T: **Multiple pathways to sustainability in the city: the case of San Juan, Puerto Rico**. *Ecol Soc* 2014, **19**:2 http://dx.doi.org/10.5751/ES-06457-190302.

62. Robins G, Bates L, Pattison P: **Network governance and environmental management: conflict and cooperation**. *Public Adm* 2011, **89**:1293-1313 http://dx.doi.org/10.1111/j.1467-9299.2010.01884.x.

63. Robins G, Lewis JM, Wang P: **Statistical network analysis for analyzing policy network**. *Policy Stud J* 2012, **40**:375-401 http://dx.doi.org/10.1111/j.1541-0072.2012.00458.x.

64. Bodin Ö, Ramírez-Sánchez S, Ernstson H, Prell C: **A social relational approach to natural resource governance**. In *Social Networks and Natural Resource Management: Uncovering the Social Fabric of Environmental Governance.* Edited by Bodin Öul., Prell C. Cambridge University Press; 2011:3-28.

65. Bodin Ö, Crona BI: **The role of social networks in natural resource governance: what relational patterns make a difference?** *Glob Environ Change* 2009, **19**:366-374 http://dx.doi.org/10.1016/j.gloenvcha.2009.05.002.

66. Leach M, Scoones I, Stirling A: *Dynamic sustainabilities: technology, environment, social justice*. London, UK: Earthscan; 2010.

67. Bodin Ö, Crona B, Ernstson H: **Social networks in natural resource management: What is there to learn from a structural perspective**. *Ecol Soc* 2006, **11**:r2 http://www.ecologyandsociety.org/vol11/iss2/resp2/.