Title: Structural dimensions of knowledge-action networks for sustainability

Tischa A. Muñoz-Erickson\textsuperscript{a}\textasteriskcentered
\textsuperscript{a}USDA Forest Service, International Institute of Tropical Forestry
1201 Jardín Botánico Sur
Río Piedras, Puerto Rico, 00926
tamunozerickson@fs.fed.us

Bethany Cutts\textsuperscript{b}
\textsuperscript{b}University of Illinois at Urbana-Champaign, Department of Natural Resources and
Environmental Sciences
1102 S. Goodwin Ave.,
Urbana Illinois, 61801

*Corresponding Author
Abstract
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: 1) defining boundaries; 2) characterizing power distributions; and, 3) 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.

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*–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 toward 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 (Leach et al. 2010), 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 knowledge systems). In other words, formal types of knowledge such as science, and informal types of knowledge such as 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: (1) 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; (2) 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 (3) 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 Fig. 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 social network analysis 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 Fig 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.

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*]). 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 system 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 depend 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 sup-optimal 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 [12,43–45**]. Together, these two indicators form degree centrality (Fig 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 the 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 (Fig 1.2.b; 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 critical knowledge that may be advantageous in creating new understandings and opportunities for natural resource management and sustainability that other actors do not recognize (Bodin et al. 2005). As such, high betweenness in a knowledge network can lead to efficient access to all information pathways (Fig 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 (Fig.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 that 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 (Fig 2.3.a). Generally, knowledge-action networks need to span knowledge types to be effective [28,53–56**]. 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. In 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 (Fig 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 2000’s, 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 analysis of stakeholders organizations to examine how the relationship 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 become 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. Based on 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 agencies, research institutions, non-governmental organizations, and conservation coalitions. The diversity and connectivity of this knowledge network was conducive for the knowledge-action systems necessary for sustainability. However, a closer look at the structural positions 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 dominate knowledge flow about land use are 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 is 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 system 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 allows 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 social network analysis 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.

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References
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.


This article presents the knowledge-action systems analysis (KASA) framework as a methodological approach that combines qualitative and quantitative social network analysis 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.


This paper is the most recent comprehensive literature review on the use of social network concepts to address key challenges of interest in 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 patterns of social interactions that support sustainability.


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


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


This paper offers a comprehensive review of social network analysis 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.


This paper discusses the value of social network analysis 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.


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.


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.


**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).

**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.

**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).
Figure 1

A. Scientist or Technical Expert → Water Manager

B. Knowledge-Action Network
   - Sustainability scientists
   - Infrastructure providers
   - Citizen groups
   - Water managers
   - City planners
   - Environmental NGO’s
   - Land managers
   - Businesses
2.1 Establish network boundaries that capture actors with relevant and diverse ways of knowing, regardless of whether they share information.

2.2 Identify whether a single way of knowing occupies a position of privilege and power over information.

2.3 Identify the probability that information sharing among multiple ways of knowing the whole network will encourage (or detract from) the effectiveness and efficiency of the knowledge network.