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SOCIAL NETWORK STRUCTURE AND DYNAMICS IN ADAPTIVE NATURAL RESOURCE GOVERNANCE: A CASE STUDY OF STREAM RESTORATION IN WEST VIRGINIA, USA

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ABSTRACT

Streams are globally important natural resources embedded in watersheds representing complex socio-ecological systems that provide environmental, economic, and social benefits. Streams, however, are highly vulnerable to anthropocentric impacts and are all too often in need of restoration. The primary objective of ecological restoration in general, and stream restoration in particular, is to bring back healthy and sustainable ecological functions. To achieve this end, recent studies suggest a growing global trend towards establishing collaborative and adaptive natural resource governance systems as opposed to traditional government and less effective top-down approaches. These governance systems are built on social networks underpinning cooperation, collective action, and co-management. However, there is a lack of empirical evidence on how these social networks emerge and evolve over time as well as how measurable network structure and character dynamics relate to adaptive governance system effectiveness. In the case of stream restoration in the Upper Shavers Fork of West Virginia, USA, social network analysis was used to investigate the emergence and evolution of collaborative and adaptive governance structures. Furthermore, in this case, research confirms that social network structure and character are linked to natural resource governance effectiveness, and perhaps more importantly, studying network structural dynamics yields greater insights than merely performing analysis at a single period in time. This research also exposes the persistence of core-periphery and polycentric network structures through time providing practical insights for future network development and ecological restoration efforts in West Virginia, and beyond.

INTRODUCTION

Many prominent earth scientists today suggest that we have entered the Anthropocene, a new geologic epoch of human making that began with the industrial revolution a mere two centuries ago (Syvitski 2012). Human endeavors in agriculture, mining, and urbanization, according to Syvitski (2012), have impacted the Earth surface at a magnitude commensurate with ice age changes but over a much shorter timeframe. These major landscape alterations have also caused impairment of complex social-ecological systems (Redman *et al*. 2004). However, as Syvitski (2012) points out, "the final chapter of the Anthropocene is yet to be written: the narrative will depend on our collective self- awareness and the capacity to correct our course…". The same human capacities for innovation and progress that fueled the industrial revolution, when combined with a spirit of responsibility and collaboration, may hold promise for a future course of incremental social-ecological systems restoration with globally significant results (Aronson *et al*. 2007). Egan *et al*. (2011) assert that humans are responsible for environmental and ecological degradation, and thus, must accept responsibility for restoration.

The ultimate goal of ecological restoration is to assist in nature's recovery processes of degraded or destroyed ecosystems (Aronson *et al*. 2006). While traditional ecological restoration research tends to be heavily weighted toward distinct measures of bio-physical response and/or direct socio-economic benefits (jobs, economic development, ecosystem services), modern social-ecological systems research suggests a more integrated perspective of ecological restoration whereby the value of social networks, in collective planning and action, are also considered (Pretty and Ward 2001; Aronson, *et al*. 2010; McClenachan *et al*. 2015). These social networks support collaboration in a variety of forms including partnerships, co-

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management arrangements, and adaptive governance systems that exhibit trust, reciprocity in exchanges, and common norms (Pretty and Ward 2001). In particular, adaptive natural resource governance systems (herein referred to as adaptive governance), as an alternative to top-down government control, rely on social networks that connect individuals, organizations, agencies, and enterprises for collaborative, flexible, and learning-based approaches to managing socio-ecological systems (Olsson *et al*. 2006; Sandström and Rova 2010; Hodge and Adams 2016). These social networks can also reduce risk in information and resource exchanges (Selin *et al*. 2007). Social networks have structure and character, such as density and centralization, that offer insight into the motivations for and performance of collaborative efforts and collective action (Barnes-Mauthe *et al*. 2015; Prell *et al*. 2009; Timur and Getz 2008). Research by Bodin and Crona (2009) suggests understanding social network structure "does make a difference, although the literature on how structural social network characteristics affect natural resource governance is still limited." Moreover, Sandstrom and Rova (2010) maintain that adaptive governance performance can be linked to social network structural dynamics; however, empirical evidence remains rare.

Recent studies indicate that adaptive governance is increasingly being deployed in the sustainable management of ever-changing complex social-ecological systems (Leong *et al*. 2011; Fliervoet *et al*. 2016). Increased effectiveness may explain this paradigm shift from top-down models to adaptive governance where "institutional arrangements and ecological knowledge are tested and revised in a dynamic, ongoing, self-organized process of trial and error" (Folke *et al*. 2005). As with ecological restoration in general, stream restoration is often viewed as an adaptive process whereby restoration measures allow for experimentation and learning in the enhancement of ecosystem structure and function (Petty and Meriam 2012; Lake *et al*. 2007). Spink *et al*. (2010) add that stream restoration is "as much a social undertaking as an environmental one", and is "not just the achievement of improved river condition or health, but also the initiation and strengthening of social networks." Social networks in stream restoration have the potential to increase collective action and success as well as a tendency to generate momentum or motivation for additional sustainable restoration and management (Prell *et al*. 2009; Philip and Beeckie 2013; McClenachan *et al*. 2015). Perhaps then, insights into the effectiveness of adaptive governance may be gained from better understanding the emergence and structural dynamics of the social networks on which they rely (Crona and Hubacek 2010).

Unfortunately, West Virginia (WV) offers compelling evidence of an Anthropocene, particularly in the negative impacts of mining, deforestation, acid precipitation, and transportation (road and railroad) development on watersheds and streams. WV streams and watersheds are critical social-ecological systems producing a host of ecosystems services including water supply, food, energy, tourism, and transportation. Many, if not all, are in need of some measure of ecological restoration and conservation (West Virginia Division of Environmental Protection 2012). Fortunately, for one particular stream, the Upper Shavers Fork, WV, USA (USF), a diversity of stakeholders recognized the need, accepted responsibility, and organized into an adaptive governance that successfully completed an ambitious stream and watershed restoration effort. The USF restoration effort was concerned with targeting benefits to brook trout populations while simultaneously enhancing overall watershed health. The brook trout is the only native trout to WV and represents a key ecological indicator of good water quality as well as overall stream and watershed ecosystem health (Eastern Brook Trout Joint Venture 2011).

The goal of this research was to investigate the emergence, evolution, and effectiveness of the USF adaptive governance by exploring relationships between underlying social network structural dynamics and stream restoration effort performance. While there exists theoretical as well as limited empirical evidence that social network structure and character are linked to adaptive governance performance, direct cause/effect relationships remain elusive (Sandström and Rova 2010). Moreover, temporal dynamics of network structures further complicate the matter; social networks are not static in nature, which perhaps renders one-time or cross-sectional analysis misleading (Angst and Hirschi 2016; Stein *et al*. 2011). This research utilizes a Social Network Analysis (SNA) approach to examine social network structural dynamics underlying the USF adaptive governance.

SNA is a well-proven quantitative methodology for the measurement, visualization, and analysis of social relationship structures and characteristics (Borgatti *et al*. 2009; Barnes-Mauthe *et al*. 2015). SNA employs graph theory and sociograms to illuminate network topologies which can provide insights into how individual actors or organizations behave as well as how collaborative efforts function and perform (Bodin and Crona 2009; Barnes-Mauthe *et al*. 2015). While direct SNA empirical stream restoration research appears to be quite limited, scholars analyzing natural resource management and governance issues, in general, have begun to adopt social network approaches (Barnes-Mauthe *et al*. 2015). Moreover, SNA is becoming more popular in social-ecological systems and adaptive governance research as in the case of rainwater management system development in context of stakeholder experience in Ethiopia (Prager and Pfeifer 2015). Furthermore, Fliervoet *et al*. (2016) used SNA in a case study of river management in the Netherlands to analyze conflicting uses of floodplains where stakeholder groups divided along the lines of "nature" and "flood protection" motivations. A Kenyan fishing community network was investigated by Bodin and Crona (2008) using SNA to explore deficiencies in social capital leading to over-exploitation of fisheries, and Stein *et al*. (2011) used SNA to "empirically map collaborative social networks between actors that either directly or indirectly influence water flows in the Mkindo catchment in Tanzania".

This research employs a retrospective survey methodology and SNA to evaluate the USF network evolution over time (before, during, and after restoration). The following research questions are addressed: (1) how did the USF network structure and character evolve or change over time, and how does this evolution compare to a static or time independent perspective? (2) How do these social network dynamics relate to USF adaptive governance performance as indicated by observed collaborative and positive outcomes? (3) What is the potential structure and character of a future stream restoration network with its beginnings in the USF restoration effort?

METHOD

Case Study: Upper Shavers Fork Stream Restoration

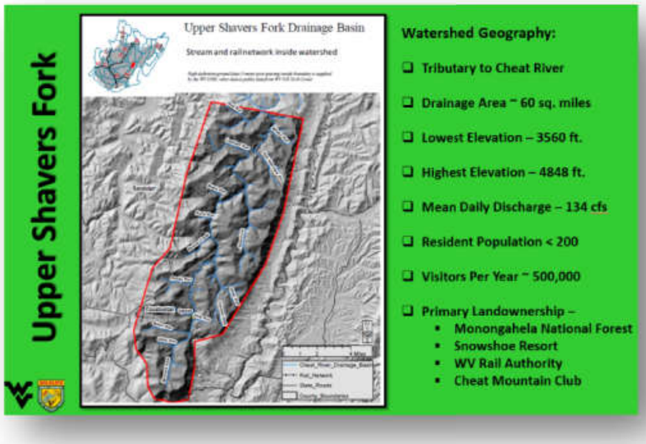

Fig 1 Study Area

The USF, a tributary of the Cheat River, is located in the West Virginia Allegheny Mountains and has an approximately 60 square mile watershed area (Figure 1). In the early 1990's, the West Virginia Division of Natural Resources (WVDNR), began successful mitigation of stream acidification in USF by introducing annual application of limestone sands. This achievement sparked momentum and interest in further and more holistic restoration of this watershed and once famous trout fishery among resource managers and academics, and thus, prompted WVDNR to fund a decade of USF research at West Virginia University (WVU). To address remaining limiting factors to the fishery, such as poor channel morphology, stream bank instability, insufficient forested riparia, excessive temperatures, severed tributaries, and poor habitat diversity, WVDNR and WVU forged a stream restoration partnership. In 2009, the WVDNR-WVU partnership added Canaan Valley Institute (CVI), a non-profit, local stakeholder driven organization with natural stream restoration experience, to the team. Through an aggressive outreach campaign, the WVDNR-WVU-CVI triad expanded the USF restoration network to ultimately include 104 stakeholders representing 38 organizations from academia, government, non-government, and the private sector.

With broad stakeholder agreement on restoration plans and funding secured, state-of-the-art natural stream restoration, watershed reforestation, and culvert replacements on USF began in 2010. Characteristics of natural, stable, and biologically functional stream reaches were used to design and implement restoration measures in selected impaired reaches and tributaries with aquatic passage barriers. By the end of 2013, three successful tributary fish passage barrier removal projects were completed, 4 miles of instream habitat enhancement were implemented, and hundreds forest acres were restored. The total cost for all restoration measures was approximately $9M and was secured from multiple sources within the USF network.

Data Collection and Analysis

To address research questions, a web-based survey instrument was developed and completed electronically from October 1, 2016 to November 1, 2016 by individuals (stakeholders) involved in USF stream and watershed restoration effort. The WVU Institutional Review Board approved this protocol on September 21, 2016. Phone and/or in-person interviews were conducted with those unable or unwilling to complete the survey electronically. Network survey questions were administered by roster to maximize recall (Borgatti *et al.* 2013). The initial roster was developed by reviewing USF partnership meeting notes, trip reports, and progress reports to funding agencies as well as personal communication. In a mixed method approach, snowball sampling, a well-established qualitative research methodology, was also used to identify stakeholders that may have been overlooked in the initial roster (Noy, 2008). Where possible, those left out were offered an opportunity to complete the electronic survey or participate in an in-person/phone interview.

Respondents were queried about their level of interaction with other stakeholders relating to the USF stream and watershed restoration effort over the past 10 years (before, during, after, and anticipated future restoration collaboration) as well as non-network questions relating to individual attributes and opinions. Network questions were categorical in nature (e.g. How often did you interact with each of the actors you listed during the USF restoration project? - once, daily, weekly, monthly, quarterly, yearly). 59 of the 95 targeted stakeholders completed the survey yielding a response rate of 62.1%. Nine additional stakeholders that were missed in the initial roster where identified, and only one of which completed the survey. Information about actor attributes and ties (i.e., relationships, interactions) were compiled as network data in SNA (Fischer *et al*. 2016). One-mode adjacency matrices where developed for the overall network independent of time as well as for before, during, after, and future time frames.

UCInet 6 for Windows was used to perform SNA on USF network data (Borgatti *et al*. 2002). The first step was to map, visualize, and analyze the USF network by individual actors and organizations before, during, and after restoration time frames as well as for an overall time independent network (combining before, during, and after). A potential future network was also mapped and analyzed. Embedded in the size, structure, and diversity of the USF network is the social capital that emerged and/or was enhanced by virtue of participation in the USF restoration effort. To address respondent recall challenges inherent to a retrospective survey approach, network data were simplified in the following manner: (1) all USF network analyses were conducted on undirected or symmetric ties (i.e., all ties were considered to be reciprocated between actors), and (2) all ties were dichotomized (i.e., made binary) where "regular" or "frequent" (quarterly or more frequent) communication/collaboration was coded as one and all others coded as zero (Borgatti and Halgin 2011; Fliervoet *et al*. 2016).

To complement USF network visualizations, the second step was to calculate key network metrics for this adaptive governance including size, relationships, number of organizations, cross-boundary exchange, organization type, network degree centralization, density, reachability, and network betweenness centrality (Table 1). These metrics relate network structure and character to behavior and performance in areas such as social memory, heterogeneity, redundancy, learning, adaptive capacity, and trust (Bodin *et al*. 2006; Sandström and Rova 2010). Angst and Hirschi (2016) also used similar network closure and centralization metrics, in a case study of Swiss landscape management, to verify an expected trend of more bonding social capital in maturing networks while also rejecting the notion that effective networks shift toward more decentralized structures over time. These metrics where then used to evaluate USF network structure and character changes before, during, and after the restoration effort as well as to compare this evolution to an overall time independent network.

USF Network Structure and Character Evolution

Table 2 presents the results of SNA performed on all time periods, including an overall time independent network (static view) that combined data from before, during, and after the restoration effort, and depicts network structural dynamics. Table 1 provides a definition and interpretation of nine key network metrics for adaptive governance that correspond with Table 2 results. Moreover, comparative visualizations of these networks by organization, including organization type, can be found in Figure 2.

Table 1 Network metrics used

Network Metric	Definition	Interpretation
Size	Number of actors or nodes	Size is critical for understanding overall network structure and character (Hanneman, & Riddle, 2005).
Relationships	Number of ties or links between actors.	Along with size, the number and types of relationships define social network structure and character (Hanneman, & Riddle, 2005). Relationships both enable and constrain; hence, depending on the issue at hand, network size and complexity may serve to increase or limit performance (Borgatti, *et al*., 2013).
Organizations	Number of distinct organizations in a network	Sandström and Rova (2010) suggest network heterogeneity is in part represented by diversity which is the number of distinct organizations comprising the network.
Cross-Boundary Exchange	Number of ties connecting actors of different organizations divided by the total number of connections in the network expressed as a percentage (Sandström, & Rova, 2010)	Along with network diversity, cross-boundary exchange is a measure of network heterogeneity (Sandström, & Rova, 2010). Networks exhibiting high degrees of heterogeneity are diverse in knowledge base and communication exchanges and have increased capacity for innovation (Bodin, *et al*., 2006)
Organization Type	Number of different organizations in the network	For the Upper Shavers Fork restoration, there were 9 different organization types including academia, county government, federal government, individual volunteers, media, non-governmental organizations (non-profits), private sector, regional government, and state government.
Network Degree Centralization	Freeman's approach - the degree of inequality or variance of a network compared to a perfectly centralized star network of the same size Hanneman and Riddle 2005)	Degree centralization is a measure of how tightly a network is organized around central point (i.e. how star-like is the network) (Fliervoet, *et al*., 2016). Networks with higher degrees of centralization may be more effective in problem solving, and coordination ability, but can stifle creativity andinnovation (Bodin, *et al*., 2006; Angst, & Hirschi, 2016)
Density	Number of ties (relationships) divided by maximum number of possible (number nodes in network) (Borgatti, *et al*., 2013)	Density is a measure of network connectedness and closure. Higher network densities promote collective action, development of trust in exchanges, and resiliency (redundancy in ties) (Fliervoet, *et al*., 2016; Bodin, *et al*., 2006). However, network densities that are too high over time may lead to knowledge homogenization and decreases in problem solving capacity (Fliervoet, *et al*., 2016)
Diameter	Network measure of reachability – the number of steps maximally necessary to reach from one network node to any other (Bodin, *et al*., 2006)	Lower diameter networks offer greater access to many actors or nodes whereby social memory and opportunities for social learning increase (Bodin, *et al*., 2006)
Network Betweenness Centrality	Network measure of how each node minimizes distances between other nodes in the network (Bodin *et al*., 2005)	Networks with higher betweenness centrality have more separation among subgroups which promotes heterogeneity and access to novel information; however, higher betweenness can undermine trust and represent vulnerabilities to fragmentation with a loss of bridging links (Bodin, *et al*., 2006)

The third step was to explore effectiveness by relating USF network structure and character dynamics to restoration effort performance over time. Indicators of effective USF adaptive governance were defined by observed and documented network positive outcomes including: (1) restoration plan developed; (2) $9 million funding secured; (3) adaptive capacity demonstrated; (4) successful implementation completed; (5) social learning occurred; (6) technological innovation materialized, and (7) resiliency and momentum realized (Provan and Kenis 2007). The last step was to visualize and investigate the size, structure, and diversity of a potential future restoration network that may continue work on Shavers Fork as well as other stream restoration projects throughout the Appalachia. Again, key network metrics (Table 1) were calculated for the network of anticipated future communication/collaboration.

RESULTS

This section presents SNA results and is organized by the three research questions previously introduced.

Table 2 illustrates a large USF network size increase from before the project to during restoration, nearly doubling from 55 to 93 actors representing 19 and 38 organizations, respectively. This before-to-during USF network size increase was accompanied by an increase in cross-boundary exchange (2.4%) and organizational diversity as well as a decrease in network centralization (2.1%) and density (3%). Network diameter remained unchanged for the before-to-during time step while network betweenness centrality dropped by 11.4%.

After the restoration project, Table 2 illustrates a drop in network size to 71 actors and 31 organizations; however, these numbers still remained higher than the before project values. Moreover, one organizational type was lost after the restoration project and network density fell slightly. Cross-boundary exchange, network degree centralization, and diameter all increased above the values before restoration. After restoration, network betweenness centrality increased over the during restoration level, but remained lower than before restoration.

Table 2 SNA Results

USF Networks	Size (No.)	Relation-ships (No.)	Organ-izations (No.)	Cross-Boundary Exchange	Organ-ization type (No.)	Network Degree Centralization	Density	Diameter (reachability)	Network Betweenness Centrality
TIME Independent	104	918	38	32.4%	9	45.7%	8.6%	5	27.0%
BEFORE Project	55	332	19	27.1%	7	40.3%	11.2%	5	37.5%
DURING Project	93	704	35	29.5%	9	38.2%	8.2%	5	26.1%
AFTER Project	71	370	31	40.5%	8	40.8%	7.4%	6	32.1%
FUTURE Collaboration	58	292	28	38.4%	8	39.9%	8.8%	4	39.7%

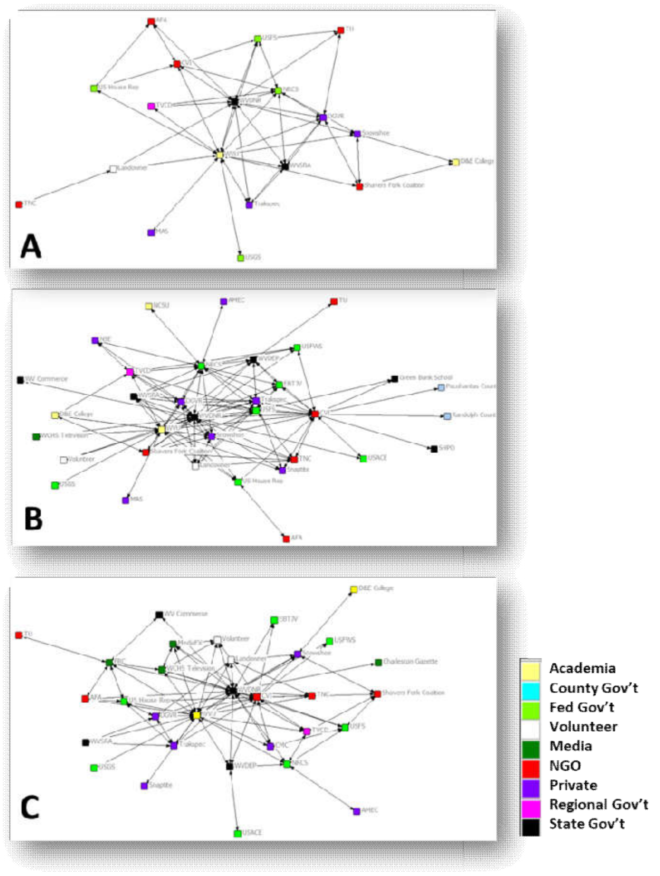

Fig 2 Map of USF Network by Organization (a) Before Restoration (before 2009), (b) During Restoration (2009-2013), and (c) After Restoration (after 2013)

The results for the USF time independent network are also presented in Table 2, and can be visualized in Figure 3. In comparing results of USF network dynamics to the time independent network, it is not surprising that the size, number of relationships, and number of organizations are greater in the time independent network given that this is a combination before, during, and after time periods. Cross-boundary exchange in the time independent network is higher than before and during networks, but lower than after restoration. All 9 organizational types are represented in the time independent network. This network is more centralized when compared to other time periods. The time independent network density is higher than during or after restoration, but lower than before restoration. The diameter of the time independent network is lower than after the restoration effort while its betweenness centrality is only greater than the during restoration time frame.

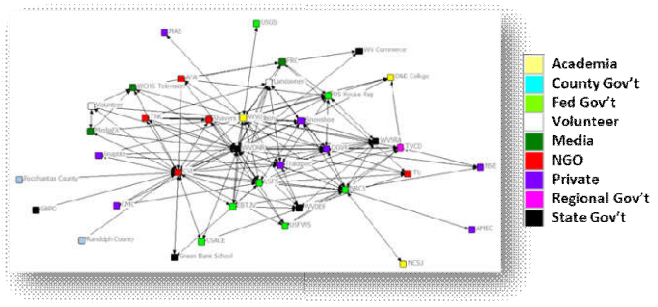

Fig 3 Map of USF Network by Organization Independent of Time

USF Network Dynamics and Performance

Table 3 presents relationships between USF network dynamics and restoration effort performance and was produced from a combination of USF partnership meeting notes, trip reports, progress reports to funding agencies, survey responses, and personal observation. These indicators or measures of network effectiveness are defined by documented positive outcomes that could not have been achieved by stakeholders acting independently (Provan and Kenis 2007). Agreement upon and development of a restoration plan for USF to address remaining limiting factors occurred within the context of the before project network. Funding for the USF restoration effort was largely secured in the before project timeframe; however, some additional funds were raised during the construction/ implementation phase to address some unforeseen circumstances. In all time periods, the USF network demonstrated adaptive capacity and flexibility in overcoming challenges. Successful implementation of restoration measures was completed in the during project timeframe on schedule and within budget. Social learning occurred throughout all restoration effort timeframes. However, survey responses seem to suggest that the greatest strides in social learning occurred before the project when actors worked together to grasp the transdisciplinary and complex nature of such a restoration effort. Technological innovation materialized during the construction/implementation phase as well as in bio-physical monitoring after the project. Lastly, the structure and character of a potential future collaboration network, in addition to survey responses (81% reported that they are extremely likely to encourage and/or participate in further stream restoration, and 79% reported that the USF effort fueled momentum in WV stream restoration), suggest network resiliency and momentum.

Table 3 USF Network Dynamics in Relation to Indicators of Effectiveness

USF Restoration Effort Outcomes	Before Project	During Project	After Project	Future Collaboration
1- Restoration Plan	X			
2- $9 Million Funding	X	X		
3- Adaptive Capacity	X	X	X	X
4- Effective Implementation		X		
5- Social Learning	X	X	X	X
6- Technology Innovation		X	X	
7- Resiliency and momentum				X

Potential Future Restoration Network

Table 2 describes and Figure 4 illustrates a potential future restoration network with 58 individuals representing 28 organizations of 8 different types. This network has a cross-boundary exchange of 38.4% which is higher than before or during project levels, and a network degree centralization and density of 39.9% and 8.8%, respectively. The future network diameter is the smallest of any timeframe. However, its network betweenness centrality is the highest at 39.7%. Survey responses, that queried subject matter of communication/ collaboration, suggest that a future network would largely busy itself with planning and education/outreach endeavors. WVDNR is the most central organization in the future network along with CVI in the second position and WVU in the third.

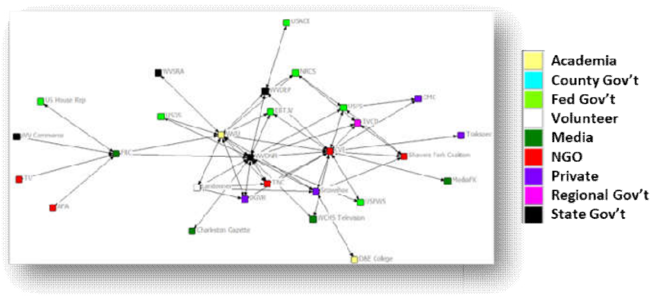

Fig 4 USF Network by Organization Potential Future Collaboration

DISCUSSION

The aim of this study was to investigate the effectiveness observed in USF adaptive governance with empirical evidence linking social network structural dynamics to restoration effort performance. Perhaps a better understanding of these linkages holds promise for informing and encouraging more social-ecological systems restoration throughout Appalachia. SNA was used to analyze USF network dynamics and results demonstrate that USF network structure and character indeed varied over time. Moreover, these analyses of network dynamics yielded different results than merely studying an overall time independent (static) composition of USF network data which supports the notion that more empirical studies of network dynamics are needed (Angst and Hirschi 2016; Bodin and Crona 2009; Stein *et al*. 2011). While direct cause/effect relationships between network structural dynamics and restoration effort effectiveness cannot be clearly drawn, results here strongly support theoretic and empirical evidence that network structure and character, as illustrated in the case of USF stream restoration, change over time and can provide insights into performance (Angst and Hirschi 2016; Bodin and Crona 2009; Stein *et al*. 2011).

An unexpected result was the size and diversity of the USF before project network. While 95 stakeholders were asked to complete the survey, meeting notes and records suggested that a smaller number of those actors were actively engaged in restoration effort initiation. However, network degree centrality and density signifies that this original group of stakeholders were tightly connected and well organized for coordination and collective action. While WVDNR, WVU, and CVI were the most central organizations before the project (and remained so through all time periods), the diversity of the initial network included 19 different organizations representing academia, federal government, volunteers, NGOs, the private sector, and state government. Hence, this suggests that in addition to being an adaptive governance system, the USF effort can also be characterized as polycentric governance.

The effectiveness of this adaptive and polycentric governance can be explained, in part, by relating underlying network structural dynamics to observed positive outcomes. The before project network was moderately centralized in both degree (40.3%) and betweenness (37.5%) as compared to other natural resource networks of similar size found in the literature (Stein *et al*.; Sandström and Rova 2010; Fliervoet *et al*. 2015). The before project network density was the highest of all time periods. From Table 1, this network structure and character indicates effectiveness in problem solving, coordination, and collective action along with trust in exchanges. Furthermore, the relatively high betweenness centrality for this before restoration network as compared to other time periods, may have offset some potential drawbacks of more closed networks (e.g. homogenization of ideas, stifling of creativity) by facilitating the brokering of novel information. This, at least in part, explains the before project network achievements in collaborative restoration planning and project fund raising (Table 3).

During the project, more indicators of effectiveness were revealed as the USF adaptive governance supported technological innovation (e.g. baffled culvert systems for fish passage) and completing restoration construction/ implementation on schedule and within budget (Table 3). In this phase, the network size nearly doubled and diversity increased dramatically. However, this during project network became less dense and centralized which contradicts Angst and Hirschi's (2016) results pertaining to nature resource governance maturation, but supports the theory that top-down centralized management is less effective for common pool resources (Bodin and Crona 2009). These decreases in network centralization and density when combined with an increase in cross-boundary exchange help explain the heterogeneity of ideas and innovation that was essential to complete this most intensive phase of the project.

After the project, the network decreased in size and diversity, but maintained levels above the network before restoration. This, along with a large increase in cross-boundary exchange, suggests a measure of network resiliency as stakeholders continued to communicate, collaborate, and learn from one another. Network density dropped substantially during this phase as stakeholders turned their attention to new projects and obligations. However, the core group of most central actors (WVDNR-WVU-CVI triad) maintained ties across the network and capitalized on project momentum by producing a PBS documentary "Stewards of Shavers Fork" detailing the UFS restoration effort. Moreover, an increase in the after project network centrality to a level higher than any other time period may explain the core-group transformation of lessons learned from USF into a formal WV statewide aquatic habitat restoration program.

In theory, optimal network structures for effective adaptive governance might entail a balance between network closure and network heterogeneity (Sandström and Rova 2010; Burt 2000). In practice, establishing or prescribing such optimal network structures with ubiquitous utility is likely impossible. Nevertheless, effectiveness in the USF case argues for network structures that are dynamic in closure and heterogeneity adapting to continuous social and ecological challenges of restoration. Moreover, the persistent core-periphery structure in the USF effort provided consistent leadership, social memory, and trust in the core while promoting innovation through new information exchanges with the periphery. The polycentric nature of the USF restoration network also enhanced adaptive capacity by offering a diversity of knowledge and experience to overcome problems and share risk.

Survey respondents were also asked with whom they might collaborate/communicate with regarding future Shavers Fork and/or other stream restoration. SNA of this future network, in addition to survey responses to non-network questions (e.g. How likely are you to encourage, support, and/or participate in more stream/watershed restoration work in West Virginia?), strongly suggest a resilient and sustainable future stream restoration network. Cross-boundary exchange and network betweenness centrality scores for the future network support the notion that USF restoration participants are planning to continue collaboration and learning from one another (Table 3). Moreover, the results of the most central organization analyses show the WVDNR- WVU-CVI (government, academia, and non-profit) triad as key contributors in facilitating this future network.

While this study serves to inform future stream restoration efforts by illuminating linkages between social network dynamics and effective adaptive governance, it is not without limitations. First, direct cause/effect relationships between social network structure and performance are not realized. Social capital (as expressed in social networks), along with other community capitals such as natural, financial, human, cultural, built and political, must be integrated for composite evaluation to fully understand direct cause/effect relationships in natural or common pool resource management (Emery and Flora 2006). A second limitation to this study is the retrospective design. It is difficult for respondents to recall, with a high level of accuracy, the nature and dynamics of relationships over a long period of time. In this case, respondents were asked to record relationships over a 10-year period. Nevertheless, retrospective surveys are less costly and time consuming to administer and can be augmented with meeting records and other project documentation. However, a true longitudinal study where respondents are queried yearly or more frequently during a restoration effort would likely yield better results by minimizing recall error. A third limitation is also in the realm of data collection. Possibly relating to the recall issue previously acknowledged, it appears that some respondents may tend to overstate their participation or perhaps "importance" when queried about previous relationships especially in light of positive outcomes and success. For instance, a few respondents indicated they had a high level of communication/collaboration with other stakeholders regarding the USF restoration before the project began. However, this participation could not be corroborated by project documentation (i.e., meeting records, reports, and personal observation).

Despite limitations, this study contributes empirical results to what has been deemed to be lacking in the natural resource governance literature: (1) network structural dynamics of natural or common pool resource management and (2) evaluation of social networks in stream/watershed restoration (Angst and Hirschi 2016; Bodin and Crona 2009). Anticipated future research includes exploring relationships between key actor attributes (e.g., professional background, gender, age, affiliations) and their network capital as well as dynamics in their network roles or positions over time (Barnes-Mauthe *et al*. 2015). Furthermore, the exploration of stakeholder homophily and heterophily in terms of attributes, opinions, and roles may provide further insights into network performance. Lastly, Geographic Information Systems integration with SNA may also hold promise for evaluating spatially explicit attributes such as actor residence in proximity to the restoration or actor recreational use of the watershed in relation to levels of effort or network centrality (Barnes-Mauthe *et al*. 2015).

CONCLUSIONS

Throughout much of the 20th century, the river engineering paradigm reigned and declared war on natural streams and their watersheds calling for them to be harnessed largely for economic gain (Everard and Powell 2002). Much like the recent shift from this river engineering paradigm to more holistic and integrated stream restoration approaches, top-down and centralized natural resource government is increasingly being abandoned for more decentralized and adaptive structures as in the case of the USF. Linking underlying social network structure and character dynamics to adaptive governance performance and effectiveness provides a roadmap and guidance for future restoration initiatives to follow. For instance, sustaining a core and polycentric leadership group representing transdisciplinary expertise appears to be important throughout all stages of restoration effort. This, however, could also represent a vulnerability should one or more of these core organizations leave the effort. Perhaps then, it would be prudent to densify the network with more leadership redundancy at the core while simultaneously maintaining bridges to expertise and knowledge on the periphery. Moreover, future restoration efforts should strive for inclusiveness, high diversity, and less centralization during the most intense implementation phases. After restoration, maintaining a high level of cross-boundary exchange (i.e. open lines of communication and collaboration between a diversity of organizations) supports the adaptive cycle and momentum for more restoration.

If USF stakeholders were queried about what they wanted to see happen as a result of their efforts, the answer would undoubtedly be "We want a thriving brook trout population back in the USF." Several years have passed since the restoration efforts were completed, and biolift is indeed happening, albeit slowly. Egan *et al*. (2011) submit that ecological restoration is an act of faith, hope, and love, but perhaps it is also an exercise in patience, persistence, and adaptability. While the USF stakeholders wait for the ecological fruits of their labor to mature, they are already reaping social benefits from their achievements. That is, a strong, diverse, and effective adaptive governance system which emerged and evolved to meet the challenges of restoring an important natural resource. Furthermore, this social capital persists today; new relationships have matured into sustainable partnerships that readily exchange ideas and resources moving beyond the USF toward further restoration of Appalachian streams and watersheds. Anthropocentric changes to rivers, landscapes, and ecological systems are nearly always described in negative terms. However, this need not be so. What began in the USF as a discrete stream restoration project has progressed into a more geographically diverse movement of incremental and positive change.

Ethical Approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. For this type study formal consent is not required.

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