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Reframing urban governance for resilience implementation: The role of network closure and other insights from a network approach

R. Patrick Bixler[a,*], Katherine Lieberknecht[b], Samer Atshan[a], Clare P. Zutz[b], Steven M. Richter[b], J. Amy Belaire[c]

[a] LBJ School of Public Affairs, The University of Texas at Austin, United States of America
[b] School of Architecture, The University of Texas at Austin, United States of America
[c] The Nature Conservancy, Austin, TX, United States of America

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ABSTRACT

The concept of urban resilience, particularly through a systems framework, has advanced tremendously over the past decade. Relatedly, collaborative and network governance is increasingly considered essential for the sustainability of urban social-ecological-technical systems. However, empirical evidence explicitly linking metropolitan networks to resilience planning and implementation is sparse. We address this gap by researching a network of organizations pursuing resilience strategies within and across two major metropolitan areas in Texas – Austin and San Antonio. Utilizing a mixed-methods approach that includes qualitative and social network analysis (descriptive and exponential random graph modeling), we examine the factors that drive network formation around blue-green infrastructure in the study area. The planning and implementation of general resilience strategies across metropolitan jurisdictional boundaries is dependent upon the social infrastructure available for governance (i.e., the relationships among organizations engaged in resilience building activities). Our findings demonstrate the tendency for network closure as a key governance feature for resilience implementation. Providing urban policy-makers and planners with information about why networks form can facilitate implementation of blue-green infrastructure in this rapidly growing, climate change impacted region and beyond. Applying a network paradigm provides insights to build general resilience for adaptation and transformation in metropolitan systems.

1. Introduction

Resilience has risen rapidly over the last decade as an urban policy framework to address a range of interrelated issues such as ecological and global environmental change (including climate change), social vulnerability, socio-technological accidents, and socio-natural disasters. Despite, or perhaps because of, the popularity of the current resilience discourse, many resilient city policies aim to reduce specific risks and vulnerabilities at the expense of fostering an integrated and inclusive approach to designing and governing urban resilience. Cities are complex adaptive systems, composed of social, ecological, and technological subsystems subject to chronic stresses and acute shocks (Bixler et al., 2019). Understanding the social and governance infrastructure that maintain and increase the capacity to respond, adapt, and transform is key to building resilient urban systems. Collaborative governance across jurisdictional and sectoral boundaries is necessary for "an urban system – and all of its constituent socio-ecological and socio-technical networks across temporal and spatial scales – to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity" (definition of urban resilience by Meerow, Newell, & Stults, 2016, pg. 39). Effective urban resilience must cultivate resilience to known risks while also building general resilience (Walker & Salt, 2012) by addressing cross-scale trade-offs and balancing sustainability considerations across different resilience approaches of recovery, adaptation, and transformation (Chelleri, Waters, Olazabal, & Minucci, 2015). Of particular interest in this study is describing and modeling the network interdependencies that underpin the social infrastructure for governing general resilience planning and implementation in metropolitan systems.

Throughout the article, we argue that *metropolitan systems* are an important site for urban resilience. As McPhearson et al. (2016) argue, an urban ecological science of and for cities must "consider the relationships and feedbacks among social, ecological, and technical

* Corresponding author.
E-mail address: rpbixler@utexas.edu (R.P. Bixler).

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infrastructure components and subsystems of a specified urban system" (2016: 203). Moreover, a systems approach highlights the multiple spatial and temporal scales as well as the cross-scale interactions (Bai et al., 2016; McPhearson et al., 2016) where the assessment of resilience and sustainability trade-offs occur (Chelleri et al., 2015). Urban systems are open systems and have multiple scales from household, to neighborhood, to city and region (Bai et al., 2016; Elmqvist et al., 2019). Resilience strategies employed in a particular neighborhood, such as building a flood wall, may have consequences for other neighborhoods. The cross-scale nature of metropolitan systems implies a web of jurisdictional, administrative, and sectoral boundaries that do not match the functional ecological or hydrological scales needed for sustainability and resilience in metropolitan systems (Enqvist, Tengö, & Bodin, 2020). The design, planning, and implementation of urban resilience strategies is dependent upon the social infrastructure for governance (i.e., the relationships among organizations engaged in resilience-related activities) that can work across jurisdictional boundaries and converge knowledge of different system components.

For at least the past decade, the public administration literature has emphasized the important management changes required to address implementation of resilience policy (Bourgon, 2009; Normandin, Therrien, Pelling, & Paterson, 2019). Bureaucratic Weberian principles effective for managing predictable and routine situations must give way to flexible and reflexive network management and collaborative governance (Revi et al., 2014; Therrien, Jutras, & Usher, 2019; Therrien, Tanguay, & Beauregard-Guérin, 2015; Emerson, Nabatchi, & Balogh, 2012; Provan & Kenis, 2007; Bodin, 2017). This shift has been reflected in governance research in cities, where questions abound regarding structures of polycentrism, cross-sectoral collaboration, smart cities and data integration, and the role of active citizens and nonprofits shaping strategies for sustainable and equitable urban systems (Pierre, 2011). This stream of urban governance research relies on an institutional theoretic perspective that shifts analytical focus from "government" to focus on the process through which public and non-governmental resources are coordinated in the pursuit of collective interests. Governance is now a prominent research framework for understanding environment-society (Lemos & Agrawal, 2006), as well as urban politics and management (Pierre, 1999). The political and administrative implications of this shift from government to governance are significant for public service delivery writ large, and importantly provide a unique framework for thinking about resilience implementation in metropolitan areas. Yet, empirical evidence explicitly linking metropolitan governance – and governance networks – and resilience planning and implementation is sparse.

The literature on urban resilience includes various conceptual frameworks and perspectives that include different pathways to achieve urban resilience (Chelleri et al., 2015; Coaffee et al., 2018; Meerow et al., 2016). Despite some difference, most scholarship agrees urban resilience is dependent on the quantity, quality, and diversity of urban ecosystem services (Bai et al., 2017, 2016; McPhearson, Andersson, Elmqvist, & Frantzeskaki, 2015) and that vulnerability to climate change and socio-natural disasters is related to preservation or restoration of ecosystem services (Munang, Thiaw, Alverson, Liu, & Han, 2013). Evidence suggests that nature-based solutions that aim to restore or protect natural hydrological and ecological processes while also delivering co-benefits such as enhancing livability, public health, safety, and civic life are an important component of urban resilience (Keeler et al., 2019). The increased attention to nature-based solutions comes as a response to the coupled challenges of climate change and urbanization, such as increased impervious surface area, increased urban runoff, more intense storm events, catastrophic flooding and combined sewer overflow events. Furthermore, blue and green infrastructure (hereafter blue-green infrastructure) is receiving increased attention in many places where existing grey infrastructure is reaching the end of its design life and must be repaired or replaced with traditional "grey" solutions or "green" alternatives that accomplish multiple goals (or a hybrid of the two). Moreover, blue-green infrastructure enhances opportunities for climate adaptation and transformation in metropolitan systems (Kabisch, Korn, Stadler, & Bonn, 2017).

This research seeks to reframe urban resilience and its implementation by advancing a network-analytic perspective as a fundamental characteristic for metropolitan systems to recover, adapt, and transform. We utilize a mixed-methods approach that includes qualitative and social network analysis (descriptive and exponential random graph modeling) to examine the factors that drive network formation around blue-green infrastructure in the Austin-San Antonio metropolitan region and surrounding Hill Country landscape. The article will proceed as follows. First, the background and literature for nature-based solutions, e.g. blue-green infrastructure, as urban resilience strategies are provided. This is followed by background on networks in urban resilience and a brief overview of what predicts the likelihood of a network connection between any two organizations working together. We then set the demographic and ecological context for the research by describing the central Texas region of Austin-San Antonio. The next section discusses research methodology, including both qualitative and network methods employed (descriptive and predictive techniques). The network analysis results are presented, followed by key qualitative themes. Findings demonstrate the tendency for network closure to act as an important driver of collaborative tie formation with implications for how we think about and design multi-level, polycentric and network-based structures that can collaboratively implement nature-based solutions to build urban resilience (Frantzeskaki et al., 2019). Understanding why urban resilience networks form and how to cultivate them is of the utmost importance.

2. Background

2.1. Nature-based solutions as resilience strategies

Nature-based solutions (NbS) directly address and contribute to increased urban resilience through the delivery of a range of ecosystem services (Bush & Doyon, 2019) that include water purification, heat mitigation, amelioration of coastal and surface flooding, fostering human health and well-being, connection of people with nature and neighbors to each other (Frantzeskaki et al., 2019; Kabisch et al., 2017; Keeler et al., 2019; Lafortezza, Chen, van den Bosch, & Randrup, 2018; McPhearson et al., 2015). Implementation of nature-based solutions encompass a broad range of actions that address problems at multiple scales, including: tree-planting campaigns, new or improved parks or open spaces, implementing stormwater controls such as bioswales or retention ponds, restoration of urban rivers or streams, installation of green roofs or rain gardens, urban agriculture, and living shorelines (Keeler et al., 2019). Because multifunctionality is a key dimension of nature-based solutions, the planning and implementation process usually includes multiple stakeholders who seek to derive multiple (and synergistic) ecological, social, and economic benefits. Nature-based solutions, as an overarching framework and set of solutions, can occur at scales ranging from household or individual site-scale, such as distributed stormwater control measures, to neighborhood-scale canopy cover or pocket parks, to citywide, regional, or even national green space networks.

Blue-green infrastructure as a category of nature-based solutions combines the green infrastructure dialogue utilized by planners since the early 2000s (Benedict & McMahon, 2006) and incorporates bodies of waters, including: ponds, wetlands, rivers, streams, lakes, as well as estuaries, seas and oceans. Blue-green infrastructure is an interconnected network of natural and designed landscape elements, including water bodies and green and open spaces, which supply a wide range of ecosystem services to urban areas (Barbosa et al., 2019; Ghofrani, Sposito, & Faggian, 2017). Blue-green infrastructure is a relevant lens for this work because it provides a framework to consider how water flows through a landscape, highlighting the subsequent interconnections between aquatic and terrestrial systems (i.e., linkages between upstream-downstream, surface-subsurface, lake-stream, river-flood-plain, marine-freshwater). Blue-green infrastructure produces ecological, social, and economic benefits that scholars have documented, including: improving residents' health and wellbeing, providing food, lowering wind speeds, reducing storm-water run-off, lowering ambient temperatures, and sequestering carbon, among other 'ecosystem service benefits' (Keeler et al., 2019). Many of these ecosystem benefits directly support general resilience, in addition to general human health and well-being.

Protecting, restoring, and enhancing blue-green infrastructure across spatial and temporal scales in metropolitan areas enhances resilience to acute shocks and chronic stressors that cites are exposed to by enhancing the ability for urban systems to recover, adapt, and transform. For example, forested buffers adjacent to urban waterways provide flood protection and reduce the occurrence of extreme urban heat events—two key urban socio-natural disasters requiring preparation, recovery, and resilience (Rosenzweig et al., 2018; Vargo, Dana Habeeb, Liu, & Russell, 2016).

However, current governance systems rarely match the functional and jurisdictional scales necessary to implement blue-green infrastructure resilience strategies – a challenge known as institutional fit (Bergsten, Galafassi, & Bodin, 2014). Urban waterways provide a useful example the institutional and spatial mismatch of ecological/hydrological and governance processes. In Texas, as in many other jurisdictions, a municipality can regulate impervious cover within a city boundary for the purpose of building the general resilience of an urban waterway and surrounding neighborhoods. However, most urban watersheds begin prior to and continue beyond municipal boundaries, where different approaches to impervious cover regulation and enforcement may marginalize the benefits of a municipality's efforts. Because of the spatial and institutional mismatch, or "area versus power" problem (Page & Susskind, 2007), urban waterways, as well as many other forms of urban blue-green infrastructure, require collaborative or polycentric governance approaches. As a result, a growing emphasis on blue-green infrastructure as a significant contributor to urban resilience necessitates a more thorough understanding of the institutional fit between the social infrastructure for governance, such as metropolitan networks, and the function and implementation of blue-green infrastructure in metropolitan systems. Network management and collaborative governance is necessary to mobilize different types of knowledge, navigate the politics of planning (Meerow, 2020), promote alternative opportunities to learn about the system, and transform trajectories toward resilient systems (Elmqvist et al., 2019).

2.2. The role of networks in urban resilience and drivers of network formation

Theoretical and empirical work relating networks to resilience come from two mostly separate bodies of literature. One thread of scholarship focuses on the resilience of social-ecological systems (Barnes, Lynham, Kalberg, & Leung, 2016; Bixler et al., 2016; Bodin, 2017; Bodin & Prell, 2011; Crona & Hubacek, 2010). Here, networks are associated with the adaptability and transformability aspects of resilience and research sites typically include large terrestrial landscapes or marine protected areas (rather than urban areas). However, a related body of urban civic environmental organization research exists (Jasny, Johnson, Campbell, Svendsen, & Redmond, 2019; Johnson et al., 2019; Romolini, Grove, Ventriss, Koliba, & Krymkowski, 2016) and there is a strong acknowledgment that a more sustainable and resilient urban social-ecological-technical system will require active engagement from diverse public agencies, non-profit organizations, businesses, natural resource managers, scientists, and other actors (Romolini, Bixler, & Grove, 2016). A growing appreciation that metropolitan areas are open and complex systems (Bai et al., 2016) and that "it takes a network" to improve ecology *in*, *of*, and *for* cities is becoming widespread (Pickett, Cadenasso, Childers, McDonnell, & Zhou, 2016). Networks that span spatial and temporal scales provide the necessary lens to understand the cycles of resilience (panarchy) in urban areas (Ernstson et al., 2010) and are important to link the different social-ecological-and technical dimensions of urban resilience together (Bixler et al., 2019).

Additionally, research related to networks has been important in understanding response to socio-natural disasters (Nowell, Steelman, Velez, & Yang, 2018). As resilience research evolves to include examinations of community-scaled resilience, in addition to the more traditional focus on individual-level resilience, collective activities have been critical to improved resilience (Pfefferbaum et al., 2013) and "networks of adaptive capacities." Specifically, the literature on community resilience after socio-natural disasters (Doerfel, 2015; Houston, 2018; Norris, Stevens, Pfefferbaum, Wyche, & Pfefferbaum, 2008; Pfefferbaum et al., 2016, 2013) has found that resilience depends on community networks and relationships, in addition to other factors that strengthen these networks, such as local knowledge, communication, governance and leadership, resources, and preparedness (Patel, Brooke Rogers, Amlôt, & James Rubin, 2017).

Both strands of research build upon what is now a robust body of neo-institutionalism scholarship that argues for the inclusion of structural and normative dimensions of networks (North, 1991; Ostrom, 2000). This suggests there are two key drivers of network tie formation – 1) structures and 2) systems of norms, beliefs, practices, and routines; these drivers each reinforce the other and play key roles in shaping governance (Peters, 2011). Network theory and research suggests similar dynamics as to how ties form and sustain (Rivera, Soderstrom, & Uzzi, 2010), including: structural effects, spatial effects, organizational characteristics, and neighborhood context (Jasny et al., 2019). This includes: "friends of a friend will be a friend" (Granovetter, 1973), or structurally driven tie formation; "birds of a feather flock together" (McPherson, Smith-Lovin, & Cook, 2001), where common attributes drive tie formation; finally, that spatial, contextual or other exogenous factors, such as geographic proximity, drive tie formation (Belaire, Dribin, Johnston, Lynch, & Minor, 2011; Gieryn, 2000).

For example, attribute-based network tie formation is most commonly associated with homophily, or that birds of a feather will flock together (McPherson et al., 2001). Homophily – the tendency to disproportionately form social ties with others most similar – is one of the primary drivers of network tie formation and has been demonstrated to shape environmental outcomes (Barnes et al., 2016). Some scholars have argued when organizations share attributes it facilitates trust (Kleinbaum, Stuart, & Tushman, 2013), which is important because homophilic network structures affect the flow of information to non-similar organization types. Organizations may choose to work with others who have similar missions, resources, capabilities or those of similar age, status or because they share a funding partner (Atouba & Shumate, 2015; Gulati & Gargiulo, 1999). Those preferences and resulting network relationships shape network governance strategies (Provan & Kenis, 2007). We hypothesize that organization type (i.e., city or county agency, community-based organization, statewide non-profit, etc.) is an important driver of tie formation in urban resilience networks.

Structural tie formation, or more specifically network closure, can be explained by two related but separate network effects: triadic closure and preferential attachment (Barabási & Albert, 1999). Triadic closure is the idea that organizations tend to introduce their collaborators to each other, thus actors separated by one intermediary are the most likely to become connected in subsequent time periods (Rivera et al., 2010). These transitive structures occur when actor Z is connected to actors Y and X, such that actors Y and X are more likely to be connected to one another as well. This clustering forms dense interconnections made up of organizations who all work together. The other structural effect – preferential attachment – is the tendency for edges to accrue among a small number of popular nodes. If one or a few nodes are highly connected the overall network becomes highly centralized (think a hub and spoke figure), a process known as network centralization, which has been a demonstrated effect in environmental policy networks (Berardo & Scholz, 2010). These concepts more broadly are related to network closure and reflect bonding social capital, frequently considered an important dimension of urban resilience (Aldrich, 2012). We hypothesize triadic closure is an important driver of tie formation in urban resilience networks.

Finally, other work on urban environmental networks has found that geographic proximity may play a role in network tie formation (Belaire et al., 2011; Jasny et al., 2019). Those working in closer geographic proximity are more likely to interact and will require less energy to maintain a collaborative relationship.

2.3. The study context: the Austin and San Antonio Metropolitan Areas in central Texas

Austin, Texas is located in central Texas and is the fourth-largest city in Texas, the 11th-largest city in the United States, with a population of 950,715 residents as of 2017. The Austin Metropolitan Statistical Area (MSA), as defined by the U.S. Office of Management and Budget, includes five counties (Bastrop, Caldwell, Hays, Travis, and Williamson) and over 2 million people, making it the 35th largest metropolitan area in the United States. Situated 128 km south on U.S. Interstate 35 is San Antonio, the second most populous city in Texas, seventh most populous city in the United States, and the 24th largest MSA in the United States with over 2.5 million people (see Table 1). The San Antonio MSA includes the counties of Atascosa, Bandera, Bexar, Comal, Guadalupe, Kendall, Medina, and Wilson (Fig. 1).

Between 2018 and 2050, the Austin and San Antonio metropolitan statistical areas are projected to add >2.7 million new residents (Table 1), significantly altering the social-ecological-technological systems (SETs) present today. Such growth presents opportunities – continued economic competitiveness and robust tax bases – matched by challenges like housing unaffordability, inequitable access to services and infrastructure driven by neighborhood displacement, and increasing consumption of water and land. The expected metropolitan expansion in terms of population and development footprint will have negative consequences to regional ecosystem services putting extreme stress on water supply (quantity) and quality. This is compounded by climate forecasts that point to a higher intensity flood-drought regime in the region.

The Austin and San Antonio metro regions lie on the border between the arid southwest and humid southeast, with significant annual fluctuations in precipitation. Both metros have historically relied heavily on a single source of water supply, the Lower Colorado River and the Edwards Aquifer, respectively. In addition, both water sources flow toward the metro areas from the Hill Country landscapes to the west. These water sources provide substantial quantities of fresh water, but both have a history of volatility in response to drought. Combined reservoir storage along the Colorado has dropped dangerously low on several occasions, including dropping to 30% during the recent 2011 to 2015 drought. Similarly, the Edwards Aquifer, a confined karst limestone aquifer, is highly sensitive to drops in precipitation. Since aquifer levels in San Antonio were tracked, 60% of years have seen groundwater levels currently deemed critical.

Over the last few decades, both metros have implemented conservation and drought management measures. The 2017 State Water Plan (TWDB, 2017) shows that both cities will not only continue to expand conservation, but also the reuse of treated water (often called “reclaimed” water). Nearly half of Austin metro's municipal water strategies through 2050 call for either conservation (28%) or reuse (20%). San Antonio's plans for conservation (33%) and reuse (26%) are even greater. Despite these figures, overall municipal water use is predicted to increase by 41% in Austin and 12% in San Antonio.

Precipitation volatility not only threatens water supply, but also presents severe risks for water quality, as the Fall 2018 City of Austin water-boil notice demonstrates (Lieberknecht, 2018). During intense rains, the landscape provides important ecological services of rainfall interception and infiltration that mitigate some of the flood risk associated with intense rainfall and keep water quality high; however, the physical land use patterns that accompany rapid population growth threaten the landscape that provides these services (Table 2). Across the two metros development expanded by >160,000 acres from 2001 to 2016, an increase of 21% of developed land. In 2016, the Austin MSA was approximately 14% denser overall than the San Antonio MSA, though still much less dense than cities in the Northeast US or California. Expansion per capita across both MSAs was 113.9 acres developed per 1000 new residents, which is low for Texas (average of 135.4 acres per 000s) but is much higher than cities that more strictly manage growth (Richter, 2020). For example, Portland, OR, expansion per capita was 34.2 acres per 000s.

Such substantial increases in the physical footprint of cities present risks to water quality and flooding (among other issues such as urban heat island, etc.). Technological solutions can mitigate some of the flood and water quality impacts of new development (Keeler et al., 2019), but these require strong development regulations and enforcement. The City of Austin exerts strong municipal control over land development, with strict limits on impervious cover for new development. Nevertheless, the Austin MSA increased its average percentage imperviousness of the developed landscape from 25.6% to 31.1%, the largest such increase for any Texas metro region and for any US metro over 200,000 people. Moreover, three of the top four MSAs in terms of increased imperviousness are found along the I-35 corridor, with Killeen-Temple MSA (22.4% to 26.8%) and San Antonio MSA (27.0% to 30.9%) just behind Austin MSA (Richter, 2020). Such increases are not surprising given the rapid population growth across the region – larger cities tend to have higher levels of imperviousness – but the risks presented by such changes in the built landscape require close monitoring and mitigation. Much of this intense development is occurring outside the jurisdiction of the City of Austin, but within watersheds that flow through the City of Austin. Such social-ecological risk requires multi-relational networks to fill the gaps left by formal municipal governance and the relative absence of regional governance.

Both Austin and San Antonio have been proactive in investing in blue-green infrastructure resilience strategies. For the past several decades, Austin has strategically acquired undeveloped open spaces to maintain a network of green infrastructure (primarily parklands and preserves) and to protect environmentally sensitive resources. Open space acquisition has been largely supported through municipal bond funds supported by Austin residents since 1998. In the most recent bond election in 2018, Austin residents demonstrated overwhelming support for two municipal bond propositions to (1) acquire open space to

Table 1
Austin MSA and San Antonio MSA population in 2000, 2018, and 2050 (projected).
Source: [i]U.S. Census Bureau 2000; [ii]U.S. Census Bureau 2018; [iii]Texas Water Development Board: 2017 State Water Plan.

MSA	2000 population[i]	2018 population[ii]	2050 population projection[iii]	% growth: '00–'18	% growth: '18–'50
Austin-Round Rock	1,249,763	2,168,316	3,863,795	73%	78%
San Antonio-New Braunfels	1,711,703	2,518,036	3,608,137	47%	43%
Combined	2,961,466	4,686,352	7,471,932	58%	59%

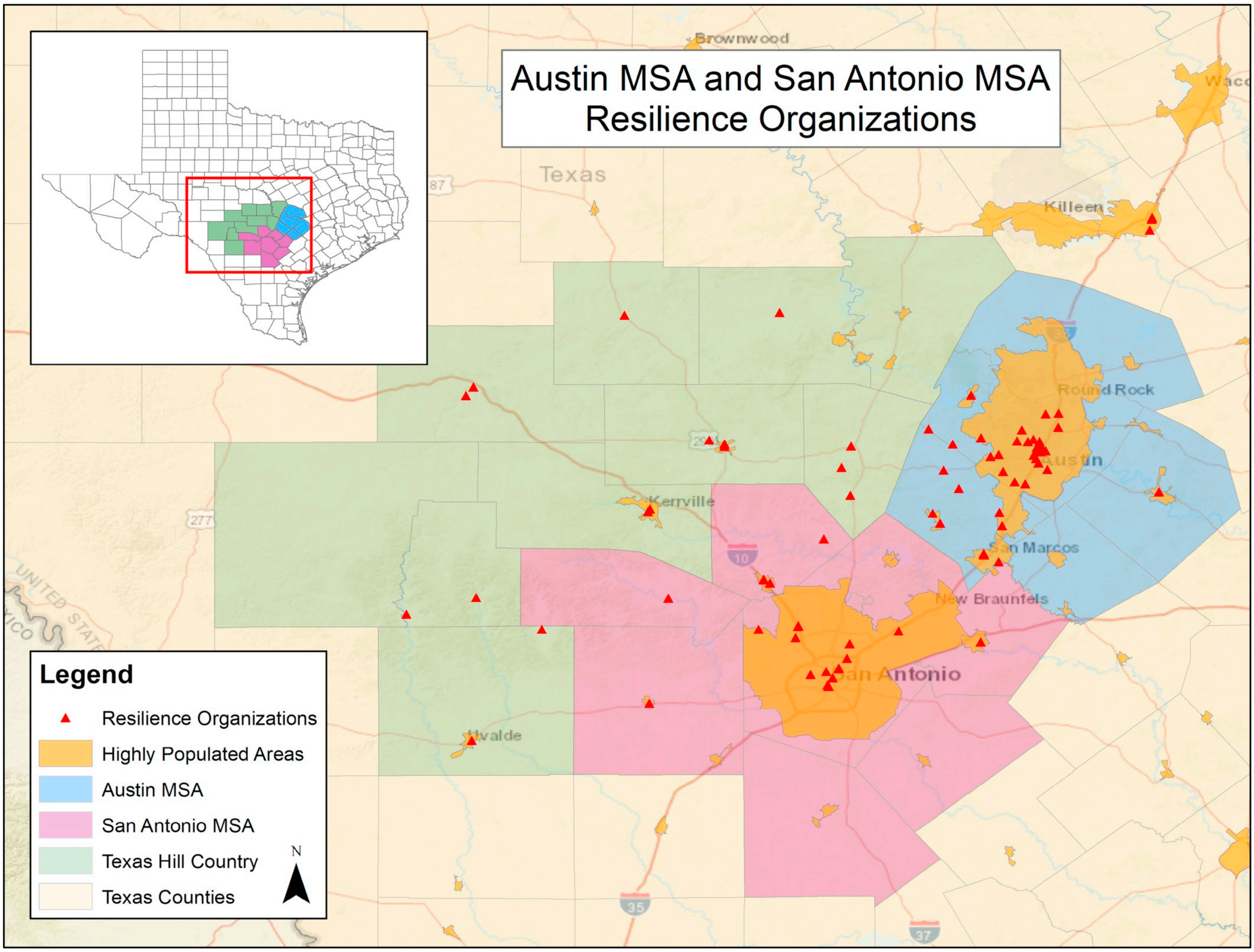

Fig. 1. Austin-San Antonio Metropolitan Areas (with "resilience organizations" identified in this study).

Table 2
Developed acres, density, and Avg imperviousness for 2001 and 2016.
Source: National Land Cover Database.

MSA	Developed acres			Density (ppl/acre)			Avg imperviousness (%)		
	2001	2016	% Change	2001	2016	% Change	2001	2016	% Change
Austin-Round Rock	316,001	397,715	25.9%	4.18	5.19	26.2%	25.6%	31.1%	21.5%
San Antonio-New Braunfels	453,402	533,473	17.7%	3.86	4.55	17.6%	27.0%	30.9%	14.3%
Combined	769,403	931,189	21.0%	3.97	4.82	21.5%	26.4%	31.0%	17.2%

dedicate as parkland in the form of destination parks, infill parks, and greenbelts and (2) for flood mitigation, open space, and water quality protection. Austin's stated priority for acquisition of water quality protection lands is to limit development to 10% impervious cover in the Edwards Aquifer recharge and contributing zones, which equates to the protection of approximately 100,000 acres of undeveloped land. This goal is currently 28% complete, with 28,000 acres protected primarily south and west of the city. The 2018 bond package allocation of $72 million will support protection of an additional 4300 acres.

In addition to municipal bonds discussed above, Austin is also leading efforts to integrate green infrastructure within the fabric of development – through new developments and retrofitting existing developments. Additionally, the City of Austin has developed innovative strategies for integrating green infrastructure into existing development through retrofits. For example, Austin's Watershed Protection Department (WPD) is implementing a five-year Rain Catcher Pilot Program (RCPP) in an effort to "fix a broken watershed" with distributed small-scale stormwater management solutions. The pilot project, running from 2019 to 2023, aims to reverse the effects of urbanization by providing incentives and assistance to homeowners for the installation of sponge-like rain gardens and cisterns in up to 1250 residential yards in the upper portion of an urban watershed.

In San Antonio, investments in blue-green infrastructure over the past two decades have also led the way in building resilience, especially in terms of securing clean, plentiful drinking water supplies. In 2000, voters approved a one-eighth-cent sales tax to fund protection of the Edwards Aquifer, which is the primary source of drinking water for the city. Rainfall replenishes groundwater in the Edwards Aquifer by "recharging" through caves, sinkholes, and other features in the landscape; however, urban development can negatively impact the quality and quantity of water entering the aquifer. The sales tax approved by San Antonio's voters enables the City to protect land over the aquifer's sensitive recharge and contributing zones, thereby ensuring long-term protection of the city's drinking water. Since the program's inception in 2000, San Antonio voters have repeatedly approved the one-eighth-cent sales tax, resulting in over $250 million dedicated toward purchasing and protecting land over the Edwards Aquifer. In total, over 160,000 acres of land has been protected through this program. In addition, since 2015, a portion of these funds have been used to support water quality projects within already-urbanized portions of the recharge and contributing zones, such as green infrastructure features adjacent to roadways that clean and infiltrate stormwater runoff while reducing urban heat island effects.

2.4. *Drivers of urban resilience tie formation in Austin and San Antonio Metropolitan Areas*

Three processes and associated hypotheses examined here are theoretically informed from the background on (1) governance, (2) urban resilience, and (3) the specific context of this case. The starting points – structure, partner attributes, and geographic proximity – are relatively common endogenous and exogenous assumptions within network studies (Lusher, Koskinen, & Robins, 2013; Rivera et al., 2010), which are then informed by empirical examples of urban resilience governance and implementation. This is not an exhaustive list of relevant hypotheses, but a list that can provide insight into some of the dynamics under consideration.

Hypothesis 1. Network tie formation is driven by “type of” organization. Given the rapid pace of population growth combined with the lack of planning authority outside of municipal boundaries, we suggest “city and county agencies” are an important organization type in this broader network of green and blue infrastructure planning and implementation. Organizations will be likely to form network ties with these entities because of the formal authority and access to funding (including municipal and county bonds).

Hypothesis 2. Geographic proximity, here captured as being located in the same county or metropolitan area, contributes to the formation of network ties. Exogenous variables such as geographic proximity is common across several settings, but seem particularly relevant in population dense metropolitan areas.

Hypothesis 3. Triadic closure contributes to the formation of network ties. Given the regulatory environment and political context in Texas more broadly, dense structures and bonding social capital will be important for coalition building, legislative maneuvering and implementing blue and green infrastructure projects in spite of lax environmental regulation.

Hypothesis 4. Preferential attachment will drive tie formation. Generally speaking, the population of civic environmental organizations is relatively small in Texas as compared to similarly populated states. Network tie formation is driven by central organizations establishing new ties with other organizations.

3. Research methodology

This study employed a mixed methods approach that included both interviews and an online social network survey. Research has demonstrated the benefit of combining social network analysis with interviews, ethnography and historical research (Cross, Dickmann, Newman-Gonchar, & Fagan, 2009). Integrating social network data with other methods adds the context to help interpret network data and provide insights into structural relations, why they occur and what their consequences might be.

3.1. *Qualitative data and analysis*

The first stage of the research included qualitative interviews with 27 key informants working on green and blue infrastructure in the Austin and San Antonio MSAs. The interviews were accompanied with participant observation – frequent visits at meetings and field sites – establishing trust between researchers and participants and providing an in-depth knowledge of people, their activities and a place (Creswell, 2007). We built a population sample for the interviews using a purposive snowball technique in which we asked participants to provide names of other stakeholders with valuable perspectives (Bryman, 2004). We designed a quota framework for interviews to ensure we had representative perspectives by geography (Austin MSA/San Antonio MSA) and by topic (Green/Blue Infrastructure). Through this process we identified and interviewed key decision-makers, community leaders, executive directors of environmental non-governmental organizations (NGOs), city and county agency leadership.

A semi-structured interview guide was used to ensure consistency across participants; however, participants were also encouraged to talk about related topics of interest to them. The interviews, which ranged from approximately 40 min to 1.5 h in length, were digitally recorded and transcribed to permit detailed coding (Strauss & Corbin, 1998). Analysis of the emerging concepts was done through an initial coding and recoding of the data, followed by a second set of codes that emphasized the emerging relationships between previously coded themes (Charmaz, 2006). Key themes emerged around the motivations and mechanisms to build networks that promote urban sustainability and resilience.

3.2. *Social network data and analysis*

The interview protocol included structured questions aimed at identifying additional organizations (agencies or NGOs) working on green or blue infrastructure in the Austin and San Antonio metropolitan areas. This process generated a list of 105 organizations that included community-based organizations, regional NGOs, River Authorities and groundwater conservation districts, city and county agencies, state and federal agencies, universities, and land trusts. The organizations identified were invited to participate in an online survey. Sixty-six of 105 organizations responded to the survey, a response rate of approximately 63%.

In this study, organizations were chosen as the node unit of analysis (sensu Jasny et al., 2019, Daher, Hannibal, Portney, & Mohtar, 2019; Jedd & Bixler, 2015). The survey consisted of an introduction that stated the objective of the survey, questions on the organizational characteristics, scale of activities, and involvement or interest in both green infrastructure and blue infrastructure. Respondents were asked to select from a list of 40 organizations for which they have “talked with, met in person with, or collaborated on a project with” on “land conservation or land use planning issues” (green infrastructure) and to “water planning, policy, and conservation issues” (blue infrastructure). By selecting an organization, the respondent was indicating a network tie between the two organizations, indicative of information sharing. In some cases, ties were both “green” and “blue”. All incoming and outgoing information ties were treated as binary (i.e., no directionality or strength). The list of 40 entities was established and vetted through the interview process and a study steering team of key organizations and/or agencies working in the Austin and San Antonio areas. The respondents were also provided space to fill in additional organizations or agencies that they work with that were not on the list of 40.

Analysis of the network data employs methods that are *structurally descriptive* and *structurally explicit* (Scott & Ulibarri, 2019). Structurally descriptive network studies seek to characterize an entity (such as an organization or individual) or network in terms of aggregate structural features (e.g., what actor or organization is most central in a network, or whether one network is denser than another). In contrast,

Table 3
Structurally descriptive network statistics.

Network composition		
		# of orgs (percentage of network)
Total "resilience orgs"		156 (100%)
Austin MSA		82 (53%)
San Antonio MSA		27 (17%)
Other Hill Country Regional County		47 (30%)
Sector	Organization type	
Civil society (61%)	Land trusts	8 (5%)
	Community-based	35 (22%)
	Regional	20 (13%)
	State	22 (14%)
	National	11 (7%)
Public (23%)	City and county	10 (6%)
	State & federal	11 (7%)
	River authorities + groundwater conservation districts	16 (10%)
Private (8%)	Business	13 (8%)
University (6%)	University	10 (6%)

Edge composition			
Blue edges	Green edges	Both (black)	Total edges
225 (22%)	476 (47%)	322 (31%)	1023 (100%)

Network statistics		
Density	Centralization	Transitivity
0.064	0.535	0.423

structurally explicit network studies seek to draw inferences about what gives rise to specific ties or tie arrangements. For the former, we summarize actor and network level statistics (see Table 3) and provide network visualizations. For the latter, we employ a class of stochastic network models known as exponential random graph models (ERGMs). ERGMs are empirically informed models that compare observed, empirical networks with a null, random network (Lusher et al., 2013). ERGMs are tie-based models that account for the presence (and absence) of network ties by inferring the processes and drivers that give rise to the formation and maintenance of network ties. The way each parameter in an ERGM can be interpreted is similar to that of a logistic regression, where each coefficient has an additive effect on the log odds of a tie being equal to 1 instead of 0 (Koskinen & Daraganova, 2013). We utilize the R package statnet for network analysis of our data (Handcock, Hunter, Butts, Goodreau, & Morris, 2008; Morris, Handcock, & Hunter, 2008). Our ERGM analysis utilized a Robbins-Monro stochastic approximation for obtaining maximum likelihood estimations (Snijders, Pattison, Robins, & Handcock, 2006).

4. Results

4.1. Structurally descriptive network analysis

The online survey resulted in a list of 156 entities (local, regional, statewide, and national non-governmental organizations; city, county, state, and federal agencies) and relationship data between those entities. For analysis and descriptive purposes, we refer to all network entities as organizations (referring to the organizations engaged in blue-green infrastructure to build general resilience, or resilience organizations). The network is composed of diverse organization types: community-based NGOs (22%), followed by State NGOs (14%), Regional NGO (13%), River Authority and Groundwater Conservation Districts (10%), businesses (8%), state and federal agencies (7%), and land trusts (5%) of the network. See Fig. 2 and Table 3.

Fig. 2 visualizes the Austin MSA (53% of reported network), San Antonio MSA (17% of reported network), along with additional counties that were nominated outside of the metropolitan statistical areas (30% of reported network) but were part of the central Texas Hill Country region that connects the MSAs to water resources in the west.

In total, 1023 edge ties between organizations were reported. Of those, 225 were specifically focused on blue infrastructure (22%), 476 on green infrastructure (47%), and 322 (31%) reported blue & green infrastructure related network connections.

In structurally descriptive empirical network studies, frequently used metrics of network closure include: density, centralization, and transitivity. The number of ties in the network divided by the maximum ties possible is known as network density (Wasserman & Faust, 1995). The network under study has a density of 0.064, a relatively low density

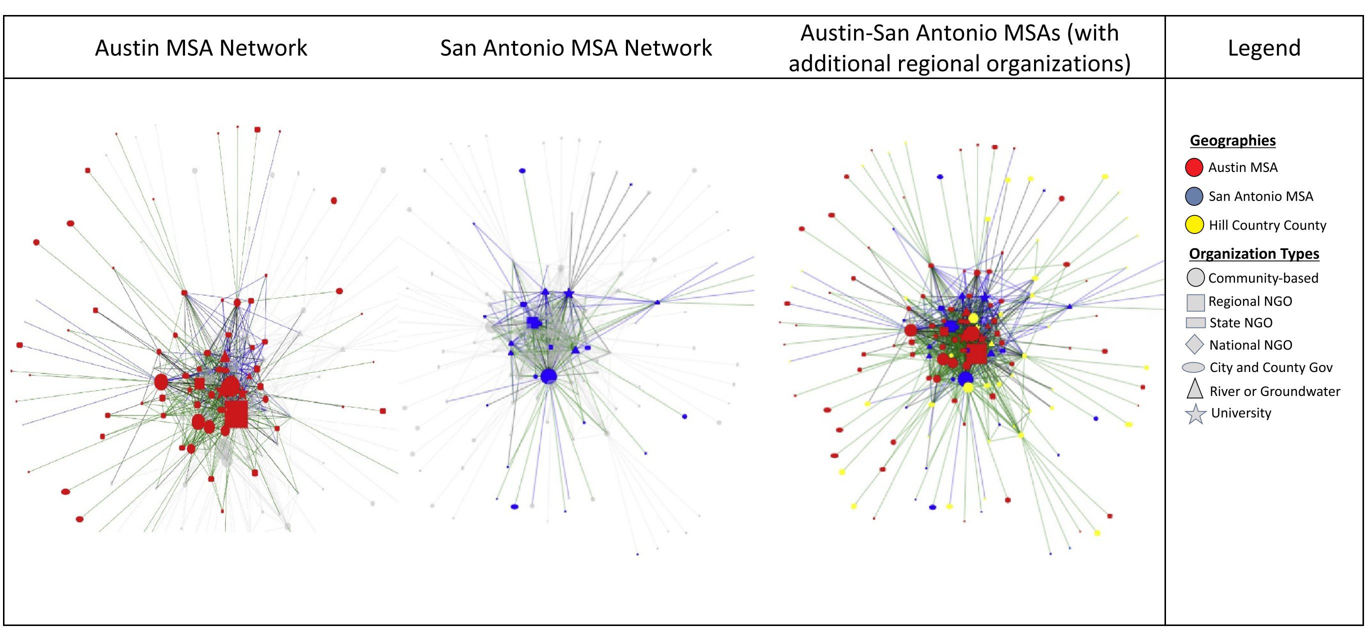

Fig. 2. Network(s) of "resilience organizations" identified in this study.

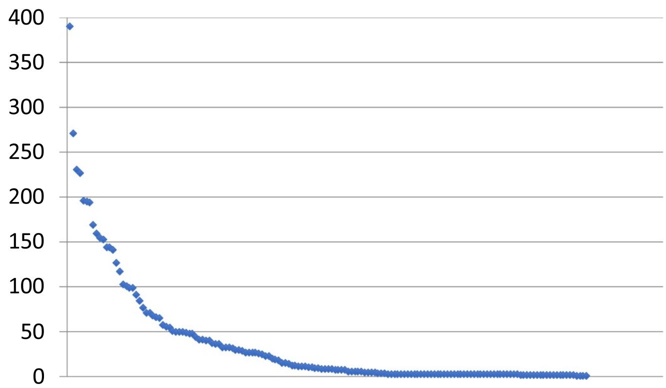

Fig. 3. Degree distribution for Austin MSA + San Antonio MSA + Additional Regional Organizations.

but not unsurprising given the number of nodes in the reported network. Generally, the density metric analyzes the connectedness of the network and the higher level of density translates to the potential for more collective action. However, a very high network density may decrease group's effectiveness because of homogenization of knowledge/information, which decreases capacity for solving problems. Density metrics are extremely sensitive to total number of nodes. Centralization is the extent to which network ties are channeled through a single actor, thus reflecting hierarchy in a network (Wasserman & Faust, 1995). Highly centralized network structures are highly connected structures, since many nodes are connected through one or few actors. The centralization score for this network is 0.535. This is a relatively high score, indicating a relatively large difference in the number of edges between central nodes and other. The weighted degree centrality distribution graph in Fig. 3 demonstrates this distribution.

Related, transitivity is measured as the percentage of time that actor Z is connected to actors Y and X, such that actors Y also names X. It compares the proportion of triads that are closed to the network density and is frequently thought of as a measure of bonding capital since partners of partners work together (Henry, Lubell, & McCoy, 2011). The transitivity score for this network is 0.423.

4.2. Structurally explicit network analysis - ERGMs

Model 1 (Edge) is the null model. This is the simplest ERGM model with only one parameter, the single edge, which acts as the intercept. ERMG parameters can be interpreted similar to that of logistic regression, therefore the edge term can be interpreted as a baseline odd of an edge tie existing in this network, $\exp(-2.68) = 0.064$. See Table 4 for model parameters. The Bernoulli model using the edge parameter tests the assumption that the observed configuration of network ties is different from what would be expected at random (Snijders et al., 2006).

Model 2 (attribute model, endogenous effects) includes two parameters that were selected based on preliminary analysis that found no significant homophily effects between organization types. We found that organizations were not more likely to have a network tie with similar organization types than non-similar organization types. The preliminary models did show, however, a statistically significant effect of the covariate "organizational type" on probability of tie formation. Some organizational-types are more likely to form network ties than others (higher edge probabilities). Parameters in a preliminary model suggested that two org-types: *city and county agencies* and *state NGOs* had higher edge probabilities than other types. We developed a dummy variable to account for the effect of those two organizational types and include those in model 2.

Model 3 (geographic proximity model, exogenous effects) includes the effects for geographic proximity either being based in the same county

Table 4
Results of exponential random graph modeling.

	Austin-San Antonio Resilience Network			
	Model 1	Model 2	Model 3	Model 4
	(Edge, Bernoulli Null)	(Edge + Node Attribute)	(Edge + Node Attribute + Geographic Proximity)	(Edge + Node Attribute + Geographic Proximity + Triad Closure + GWD)
Edges	-2.680^{***} (0.035)*	-2.987^{***} (0.047)	-1.525^{***} (0.186)	2.388^{***} (0.574)
Org type-local agency		0.640^{***} (0.092)	0.558^{***} (0.093)	-5.285^{***} (0.292)
Org type-state NGO		0.643^{***} (0.062)	0.630^{***} (0.063)	0.403^{**} (0.166)
Geography-county			-0.122^{***} (0.016)	-0.436^{***} (0.045)
Geography-MSA			-0.094^{***} (0.030)	-0.699^{***} (0.071)
Triad				0.343^{***} (0.023)
Geometrically-weighed Degree (GWD)				1.594^{***} (0.111)
Akaike Inf. Crit.	6605.421	6482.033	6421.586	54,460.940
Bayesian Inf. Crit.	6612.958	6504.643	6459.270	54,513.700

* $p < 0.10$.
** $p < 0.05$.
*** $p < 0.01$.

(Geography-County) or same metropolitan statistical area (Geography-MSA). The geographic proximity estimates are significant but negative: the formation of network ties between organizations in our sample does not seem to respond to geographic proximity by county or MSA.

Model 4 (Edge + Node Attribute + Geography Proximity + Triad Closure + GWD). In model four we add the structural parameters: triadic closure and the geometrically-weighted degree (GWD) statistic. Both of these parameters are structural and relate to Hypotheses 3 and 4. The GWD statistic reflects the overall tendency for network centralization and/or dispersion, with a positive coefficient indicating greater dispersion (Koskinen & Daraganova, 2013). The GWD term models the degree distribution in a network and may be thought of as a measure of antipreferential attachment; a positive coefficient indicates a relatively homogeneous degree distribution, while a negative coefficient indicates a more skewed distribution where a few actors have a disproportionately high number of ties (Hunter, 2007). The GWD term in model four is significant and positive, suggesting a tendency toward antipreferential attachment (or dispersion) not supporting Hypothesis 4.

Finally, the triad parameter reflects the tendency for network closure by modeling triangle configurations, where a positive triad parameter indicates network closure or clustering (Karlberg, 1997). The triadic closure is positive and significant. This confirms Hypothesis 3, which states that triadic closure, or ties that form clusters of three, is an important predictor of network tie formation.

4.3. Qualitative

The qualitative interview analysis revealed key themes that support the interpretation of the network analysis data. Specifically, through coding of the qualitative data we identified key themes are around the (1) perceived motivations to network with organizations and the (2) perceived barriers to network.

4.3.1. Motivations to engage in network governance

The interview data highlighted three motivations of network governance in these metropolitan areas. First, interview respondents overwhelmingly indicated that the biggest driver was working on *legislative proposals* that can potentially lead to policy change. This theme was also represented by acknowledgement that many organizations frequently pool their resources to support lobbying for a particular issue.

Second, interviewees acknowledged that *sharing capacity and expertise* was a motivation for networking. Many of the organizations and agencies we talked to recognized the shared goals across the organizational landscape, and that working together to leverage expertise and resources in order to reap shared gains was important. Subthemes identified include reducing redundancy and that a "better process also leads to better products."

The final theme that emerged as motivating network governance was the ability to *rapidly respond to threats*. This feature of network governance related to responding to socio-natural disaster and disaster risk threats, as well as threats to land and water resources due to population growth pressures. This motivation to network can be summarized as issue-based collaboration because there is a particular catalyst – a disaster, threat, or opportunity – that activates a collaborative effort for a defined purpose.

4.3.2. Barriers to engage in network governance

Through qualitative analysis, we also identified three barriers to networking. One interviewee summed up the barriers by saying: "The environmental community is so small, we don't collaborate as much as we should. We're all fighting our own battles." This is perhaps best articulated by the first barrier theme: *lack of capacity and resources*. Many interviewees reported a lack of staff, funding, and time as inhibiting their ability to collaborate. This was articulated by one respondent, "Any relationship takes work. You always have to be cognizant coming from the conservation arena about your time, money and resources and how you spend them. Unfortunately, I think the relationship end gets short shifted because we are all too short on time or capacity." While this sentiment is applicable across different organization types, community-based organizations are particularly sensitive to capacity given small budgets and few, if any, paid staff. Community-based organizations comprised the largest overall percentage of the resilience network at approximately 22%. Some additional subthemes supporting this barrier include being overworked and that often deliverables and deadlines for collaboration don't match the timelines for individual organizations.

A second barrier identified was *navigating organizational boundaries*. This includes sharing authority for setting strategy or decision-making, which can be a challenge for NGOs when competing for limited philanthropic and government funding. The boundaries that form barriers to collaboration also include having different organizational cultures, different priorities or tactics, and sharing power in the setting of objectives and strategies. This is characterized by one interviewee saying, "People like to do their own thing. When you're working in a network, you have to be ok with giving up something, letting somebody else do it, but that can be hard."

The third barrier to network governance is the state-wide *political landscape*. One interviewee summed this up by saying: "The political landscape is very difficult. There is a fine line for people that support conservation for certain reasons and not for others." There are different degrees of environmentalism and for many actors a litigious and/or regulatory strategy is at odds with broader consensus building advocacy. Although organizations may agree on the alignment of broader goals, it ultimately hinders the individual organization's goals by being "aligned" in a formalized partnership or alliance if strategies are at odds.

5. Discussion and conclusion

Understanding the conditions for effective and legitimate governance, and the mechanisms that create those conditions, is critical to bridge the gap between urban resilience planning and implementation (Coaffee et al., 2018; Davidson, Nguyen, Beilin, & Briggs, 2019). Given the nature of the threats to resilience – complex and nonlinear social, ecological, and technical challenges – we argue that understanding the drivers of network formation will be key to building general resilience in metropolitan systems. Specifically, we focus on the role of network closure and how that links to polycentrism and network governance in metropolitan systems.

5.1. Network closure

Our results highlight the significant role of network closure, or bonding social capital, in the resilience network under study (triad parameter, model 4; sharing capacity and expertise qualitative theme). The propensity for network ties to form between collaborators who share a collaborator (Lusher et al., 2013) were significant in driving the existing, observed network. The benefit of bonding capital is that dense and overlapping relationships create trust, which helps sustain cooperation over time. Bonding social capital can decrease transactions costs and be instrumental in solving collective action issues (Bodin, 2017). This is the tendency of a "friend of a friend is my friend" and is important for resource sharing and was characterized by the following quote in our qualitative data: "If you're not talking amongst your peers, you could all be doing the exact same thing and help each other out, but you wouldn't know it." The tendency for network closure may be driven, in part, by face-to-face meetings or participation in collaborative policy forums (Berardo & Lubell, 2016).

Interestingly, we hypothesized that geographic proximity would be important for tie formation, but the geographic covariates were negative coefficients. Generally speaking, negative coefficients serve to reduce the expected value of a tie (the log-odds that a tie is present). While some threats to resilience are local, many are regional if not global. We interpret these two coefficients together (triad + geographic proximity) as a suggestion that network ties are likely to be both bonding and cross-scale. Such network ties may be critical for effectively responding to threats – either socio-natural disasters or disaster-related risk, or to threats to land and water resources due to population growth. This seems especially important for water issues where the spatial distance between upper and water lower watersheds can be significant.

When asked if and how they network with their peers, many of the interviewees immediately went into stories about responding to disasters, most notably floods. The interviews for this research took place within a year of the Blanco River Flood in the Wimberley Valley on May 24th, 2015 that crested 27 ft above flood stage and caused immense structural damage on private property. Interviewees also referred to "responding the threats" in terms of residential or water infrastructure development. Relatedly, when referencing a water development project, one participant noted, "We often see collaboration spring up around an imminent opportunity or threat. We realize we can either lose this asset or we can protect it." The specific example noted here referenced a project that would pump and transport water from east of the Austin MSA to San Antonio. In these examples, trusting network ties that are cross-scale are not only functional for collective action but seem instrumental in effectively responding to threats.

5.2. Metropolitan network governance and polycentrism

Recently, there has been a resurgent interest in the role of polycentricity in urban systems (Scott & Greer, 2019; Berardo & Lubell, 2016; but see early work by Ostrom, Tiebout, & Warren, 1961). Polycentricity is characterized by multiple and overlapping centers of decision-making authority (Ostrom, 1990) and is considered a source of connectivity in fragmented systems (Scott & Greer, 2019). Berardo and Lubell (2016) suggest polycentricity is partly a function of the strength of formal institutions, finding more network dispersion in weakly institutionalized systems. Our empirical network exhibits a tendency for dispersion (GWD parameter, model 4), a finding that is supported by the qualitative themes of *legislative proposals* (driver) and *political context* (barrier). Legal and regulatory frameworks in Texas make addressing challenges to land use, water, and population growth challenging. Private property rights are the primary authority for utilization of groundwater and for land-use outside of municipal boundaries. For these reasons, we hypothesized that the organization-type of city agencies, who do possess formal authority, would drive tie formation. Models two and three demonstrated this effect; however, when structural attributes were included in model 4, the propensity for this organization type to drive network tie formation reversed. We interpret this in the context of the broader challenges to resilience: the levers of authority controlled by cities are contained within municipal boundaries, whereas the forces that threaten the ecological, social, and technological resilience extend beyond those boundaries. This further emphasizes the notion that governance structure matters, and in order for local governments to tackle these issues, it will require leveraging the capacities and resources of a diverse set of actors – including statewide NGOs.

State NGOs are particularly interesting in this network, and we do see positive likelihood of tie formation with State NGOs across all models (two, three, and four) as they have the legitimacy and capacity to effectively engage in multiple policy forums (lobbying in the state legislature while also engaging in collaborative planning to advance blue-green strategies). In many cases, these organizations have both scientific expertise and advocacy capacity and are plugged into local and regional issues (most have central offices in Austin as it is the capital city of Texas). As a result, their professional ties likely extend statewide but their personal ties are likely stronger in the region of study (San Antonio and Austin), since this is where they live, work and play.

5.3. Limitations and concluding thoughts

If, as we and others suggest, urban resilience will be determined by the ability for social, ecological, and technical systems to not only persist in response to threats but also build capacity for adaptation and transformation, then understanding how an organizational network engages in collaborative governance across jurisdictions and sectors is critical. The network and qualitative aspects of our research have demonstrated that understanding what drives the governance system in a metropolitan region can provide insight into the most appropriate forms of local designs and implementation strategies to positively transform social-ecological conditions. The design, planning, and implementation of blue-green infrastructure for the purposes of building and enhancing urban resilience is dependent upon the governance infrastructure (i.e., the relationships among resilience organizations), especially in this particular context (little state support and limited municipal power). Utilizing network analysis provides an analytical lens to make explicit the parameters, strengths, and weaknesses of this governance infrastructure, which has real and important implications for the implementation of blue-green infrastructure in this rapidly growing, climate change impacted region.

While we believe that the findings from this research, and especially the reframing of urban governance for resilience implementation through a network paradigm, to be relevant beyond our study area, there are some important limitations to address. First, the empirical research focuses primarily on organizational actors engaged in advancing blue-green infrastructure within and across two major metropolitan areas in Central Texas. Our focus was primarily the “system of governance” of a metropolitan system with little empirical work given to the actual social, ecological, and technical components of the metropolitan system(s). The network of organizations under study were engaged in advancing blue-green infrastructure (ecological components), but our data does not link to specific sites of blue-green infrastructure implementation across space or time. Modeling the social-ecological network to better understand how governance and ecological components are interwoven offers a promising direction of research (conceptual and empirical examples include Enqvist, Tengö, & Bodin, 2019; Bodin et al., 2019).

Relatedly, notably absent from our analysis is the connection to technical components of these systems (infrastructure, buildings, information and communications technology, etc.). Additional research (here and elsewhere) is necessary to gather empirical data that can be used to determine the drivers of tie formation for governance networks inclusive of organizations addressing resilience from the technical perspective. Finally, our analysis is lacking attention to the role of local people as actors in designing and implementing resilience strategies. Organizational analysis offers an important lens to study network connections across space and time, but masks the importance of individuals, households, and non-formal neighborhood and community groups in addressing social vulnerability and building resilience in metropolitan areas. In our study sites in Texas, as well as urban areas across the world, individuals are critical actors for implementation and for structuring broader governance configurations.

Future research that can address these limitations will move a step closer to understanding the complexity inherent in metropolitan systems and the ingredients necessary for more broad-scale urban resilience implementation. As this study suggests, we believe there is great benefit in embracing a network governance perspective to address the gaps between theory and practice in urban resilience. Understanding the motivations and drivers that build robust, diverse, and cross-scale networks will be critical for effective urban resilience implementation in Texas and beyond. Urban resilience planning (and navigating the politics of planning) should explicitly address the structural considerations – such as the tendency for network closure – that will influence the capacity to implement. This and related research provide the conceptual and methodological tools to analyze the social infrastructure for metropolitan governance, which in turn allows us to anticipate changes, challenges, and needed transformation for urban resilience.

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CRediT authorship contribution statement

R. Patrick Bixler: Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft, Writing - review & editing, Project administration, Funding acquisition. **Katherine Lieberknecht:** Conceptualization, Writing - review & editing, Funding acquisition. **Samer Atshan:** Formal analysis, Data curation, Visualization. **Clare Zutz:** Writing - original draft, Writing - review & editing, Visualization. **Steven Richter:** Formal analysis, Data curation, Writing - original draft, Writing - review & editing. **Amy Belaire:**Conceptualization, Writing-original draft, Writing-review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Aldrich, D. P. (2012). *Building resilience: Social capital in post-disaster recovery.* University of Chicago Press.

Atouba, Y. C., & Shumate, M. (2015). International nonprofit collaboration: Examining the role of homophily. *Nonprofit and Voluntary Sector Quarterly, 44*(3), 587–608. https://doi.org/10.1177/0899764014524991.

Bai, X., McPhearson, T., Cleugh, H., Nagendra, H., Tong, X., Zhu, T., & Zhu, Y.-G. (2017). Linking urbanization and the environment: Conceptual and empirical advances. *Annual Review of Environment and Resources, 42*(1), 215–240. https://doi.org/10.1146/annurev-environ-102016-061128.

Bai, X., Surveyer, A., Elmqvist, T., Gatzweiler, F. W., Güneralp, B., Parnell, S., Prieur-Richard, A.-H., et al. (2016). Defining and advancing a systems approach for sustainable cities. *Current Opinion in Environmental Sustainability, 23*(part I), 69–78. https://doi.org/10.1016/j.cosust.2016.11.010 Open Issue. December.

Barabási, A.-L., & Albert, R. (1999). Emergence of scaling in random networks. *Science, 286*(5439), 509–512.

Barbosa, A., Martín, B., Hermoso, V., Arévalo-Torres, J., Barbière, J., Martínez-López, J., Domisch, S., et al. (2019). Cost-effective restoration and conservation planning in green and blue infrastructure designs. A case study on the intercontinental biosphere reserve of the Mediterranean: Andalusia (Spain) – Morocco. *Science of the Total Environment, 652*(February), 1463–1473. https://doi.org/10.1016/j.scitotenv.2018.10.416.

Barnes, M. L., Lynham, J., Kalberg, K., & Leung, P. S. (2016). Social networks and environmental outcomes. *Proceedings of the National Academy of Sciences, 113*(23), 6466–6471. https://doi.org/10.1073/pnas.1523245113.

Belaire, J. A., Dribin, A. K., Johnston, D. P., Lynch, D. J., & Minor, E. S. (2011). Mapping stewardship networks in urban ecosystems. *Conservation Letters, 4*(6), 464–473. https://doi.org/10.1111/j.1755-263X.2011.00200.x.

Benedict, M. A., & McMahon, E. (2006). *Green infrastructure: Linking landscapes and communities.* Washington, DC: Island Press.

Berardo, R., & Lubell, M. (2016). Understanding what shapes a polycentric governance system. *Public Administration Review, 76*(5), 738–751. https://doi.org/10.1111/puar.12532.

Berardo, R., & Scholz, J. T. (2010). Self-organizing policy networks: Risk, partner selection, and cooperation in estuaries. *American Journal of Political Science, 54*(3), 632–649. https://doi.org/10.1111/j.1540-5907.2010.00451.x.

Bergsten, A., Galafassi, D., & Bodin, Ö. (2014). The problem of spatial fit in social-ecological systems: Detecting mismatches between ecological connectivity and land management in an urban region. *Ecology and Society, 19*(4), https://doi.org/10.5751/ES-06931-190406.

Bixler, R. P., Johnson, S., Emerson, K., Nabatchi, T., Reuling, M., Curtin, C., ... Grove, J. M. (2016). Networks and landscapes: A framework for setting goals and evaluating performance at the large landscape scale. *Frontiers in Ecology and the Environment, 14*(3), 145–153. https://doi.org/10.1002/fee.1250.

Bixler, R. P., Lieberknecht, K., Leite, F., Felkner, J., Oden, M., Richter, S. M., ... Thomas, R. (2019). An observatory framework for metropolitan change: Understanding urban social–ecological–technical systems in Texas and beyond. *Sustainability, 11*(13), 3611. https://doi.org/10.3390/su11133611.

Bodin, Ö., Alexander, S. M., Baggio, J., Barnes, M. L., Berardo, R., Cumming, G. S., Dee, L. E., et al. (2019). Improving network approaches to the study of complex social–ecological interdependencies. *Nature Sustainability,* 1. https://doi.org/10.1038/s41893-019-0308-0 June.

Bodin, Ö. (2017). Collaborative environmental governance: Achieving collective action in social-ecological systems. *Science, 357*(6352), eaan1114. https://doi.org/10.1126/science.aan1114.

Bodin, Ö., & Prell, C. (2011). *Social networks and natural resource management: Uncovering the social fabric of environmental governance.* Cambridge University Press.

Bourgon, J. (2009). New directions in public administration: Serving beyond the predictable. *Public Policy and Administration, 24*(3), 309–330. https://doi.org/10.1177/0952076709103813.

Bryman, A. (2004). *Social Research Methods.* Oxford University Press.

Bush, J., & Doyon, A. (2019). Building urban resilience with nature-based solutions: How can urban planning contribute? *Cities, 95*(December), 102483. https://doi.org/10.1016/j.cities.2019.102483.

Charmaz, K. (2006). *Constructing grounded theory: A practical guide through qualitative analysis.* SAGE.

Chelleri, L., Waters, J. J., Olazabal, M., & Minucci, G. (2015). Resilience trade-offs: Addressing multiple scales and temporal aspects of urban resilience. *Environment and Urbanization, 27*(1), 181–198. https://doi.org/10.1177/0956247814550780.

Coaffee, J., Therrien, M.-C., Chelleri, L., Henstra, D., Aldrich, D. P., Mitchell, C. L., ... Rigaud, É., et al. (2018). Urban resilience implementation: A policy challenge and research agenda for the 21st century. *Journal of Contingencies & Crisis Management, 26*(3), 403–410. https://doi.org/10.1111/1468-5973.12233.

Creswell, J. W. (2007). *Qualitative inquiry & research design: Choosing among five approaches* (2nd ed.). Thousand Oaks: Sage Publications.

Crona, B., & Hubacek, K. (2010). The right connections: How do social networks lubricate the machinery of natural resource governance? *Ecology and Society, 15*(4), 1–5.

Cross, J. E., Dickmann, E., Newman-Gonchar, R., & Fagan, J. M. (2009). Using mixed-method design and network analysis to measure development of interagency collaboration. *American Journal of Evaluation, 30*(3), 310–329. https://doi.org/10.1177/1098214009340044.

Daher, B., Hannibal, B., Portney, K. E., & Mohtar, R. H. (2019). Toward creating an environment of cooperation between water, energy, and food stakeholders in San Antonio. *Science of the Total Environment, 651*(February), 2913–2926. https://doi.org/10.1016/j.scitotenv.2018.09.395.

Davidson, K., Nguyen, T. M. P., Beilin, R., & Briggs, J. (2019). The emerging addition of resilience as a component of sustainability in urban policy. *Cities, 92*(September), 1–9. https://doi.org/10.1016/j.cities.2019.03.012.

Doerfel, M. L. (2015). Networked forms of organizing, disaster-related disruptions, and public health. *Organizations, communication, and health*https://doi.org/10.4324/9781315723020-22 October 23, 2015.

Elmqvist, T., Andersson, E., Frantzeskaki, N., McPhearson, T., Olsson, P., Gaffney, O., ... Folke, C. (2019). Sustainability and resilience for transformation in the urban century. *Nature Sustainability, 2*(4), 267–273. https://doi.org/10.1038/s41893-019-0250-1.

Emerson, K., Nabatchi, T., & Balogh, S. (2012). An integrative framework for collaborative governance. *Journal of Public Administration Research and Theory, 22*(1), 1–29. https://doi.org/10.1093/jopart/mur011.

Enqvist, J. P., Tengö, M., & Bodin, Ö. (2019). Are bottom-up approaches good for promoting social–ecological fit in urban landscapes? *Ambio, March.* https://doi.org/10.1007/s13280-019-01163-4.

Enqvist, J. P., Tengö, M., & Bodin, Ö. (2020). Are bottom-up approaches good for promoting social–ecological fit in urban landscapes? *Ambio, 49*(1), 49–61. https://doi.org/10.1007/s13280-019-01163-4.

Ernstson, H., van der Leeuw, S. E., Redman, C. L., Meffert, D. J., Davis, G., Alfsen, C., & Elmqvist, T. (2010). Urban transitions: On urban resilience and human-dominated ecosystems. *Ambio, 39*(8), 531–545.

Frantzeskaki, N., McPhearson, T., Collier, M. J., Kendal, D., Bulkeley, H., Dumitru, A., Walsh, C., et al. (2019). Nature-based solutions for urban climate change adaptation: Linking science, policy, and practice communities for evidence-based decision-making. *BioScience, 69*(6), 455–466. https://doi.org/10.1093/biosci/biz042.

Ghofrani, Z., Sposito, V., & Faggian, R. (2017). A comprehensive review of blue-green infrastructure concepts. *International Journal of Environment and Sustainability, 6*(1), https://doi.org/10.24102/ijes.v6i1.728.

Gieryn, T. F. (2000). A space for place in sociology. *Annual Review of Sociology, 26*(1), 463–496.

Granovetter, M. S. (1973). The strength of weak ties. *American Journal of Sociology, 78*(6), 1360–1380.

Gulati, R., & Gargiulo, M. (1999). Where do Interorganizational networks come from? *American Journal of Sociology, 104*(5), 1439–1493. https://doi.org/10.1086/210179.

Handcock, M. S., Hunter, D. R., Butts, C. T., Goodreau, S. M., & Morris, M. (2008). Statnet: Software tools for the representation, visualization, analysis and simulation of network data. *Journal of Statistical Software, 24*(1), 1–11. https://doi.org/10.18637/jss.v024.i01.

Henry, A. D., Lubell, M., & McCoy, M. (2011). Belief systems and social capital as drivers of policy network structure: The case of California regional planning. *Journal of Public Administration Research and Theory: J-PART, 21*(3), 419–444.

Houston, J. B. (2018). Community resilience and communication: Dynamic interconnections between and among individuals, families, and organizations. *Journal of Applied Communication Research, 46*(1), 19–22. https://doi.org/10.1080/00909882.2018.1426704.

Hunter, D. R. (2007). Curved exponential family models for social networks. *Social Networks, 29*(2), 216–230. https://doi.org/10.1016/j.socnet.2006.08.005.

Jasny, L., Johnson, M., Campbell, L. K., Svendsen, E., & Redmond, J. (2019). Working together: The roles of geographic proximity, homophilic organizational characteristics, and neighborhood context in civic stewardship collaboration networks in Philadelphia and New York City. *Ecology and Society, 24*(4), https://doi.org/10.5751/ES-11140-240408.

Jedd, T., & Bixler, R. P. (2015). Accountability in networked governance: Learning from a case of landscape-scale forest conservation. *Environmental Policy and Governance, 25*(3), 172–187. https://doi.org/10.1002/eet.1670.

Johnson, M. L., Locke, D. H., Svendsen, E., Campbell, L. K., Westphal, L. M., Romolini, M., & Grove, J. M. (2019). Context matters: Influence of organizational, environmental, and social factors on civic environmental stewardship group intensity. *Ecology and Society, 24*(4), https://doi.org/10.5751/ES-10924-240401.

Kabisch, N., Korn, H., Stadler, J., & Bonn, A. (2017). *Nature-based solutions to climate change adaptation in urban areas: Linkages between science, policy and practice.* Springer.

Karlberg, M. (1997). Testing transitivity in graphs. *Social Networks, 19*(4), 325–343. https://doi.org/10.1016/S0378-8733(97)00001-4.

Keeler, B. L., Hamel, P., McPhearson, T., Hamann, M. H., Donahue, M. L., Prado, K. A. M., Arkema, K. K., et al. (2019). Social-ecological and technological factors moderate the value of urban nature. *Nature Sustainability, 2*(1), 29–38. https://doi.org/10.1038/s41893-018-0202-1.

Kleinbaum, A. M., Stuart, T. E., & Tushman, M. L. (2013). Discretion within constraint: Homophily and structure in a formal organization. *Organization Science, 24*(5), 1316–1336.

Koskinen, J., & Daraganova, G. (2013). Exponential random graph model fundamentals. *Exponential random graph models for social networks: Theory, methods, and applications* (pp. 49–76). Cambridge University Press. https://doi.org/10.1017/CBO9780511894701.008.

Lafortezza, R., Chen, J., van den Bosch, C. K., & Randrup, T. B. (2018). Nature-based solutions for resilient landscapes and cities. *Environmental Research, 165*(August), 431–441. https://doi.org/10.1016/j.envres.2017.11.038.

Lemos, M. C., & Agrawal, A. (2006). Environmental governance. *Annual Review of Environment and Resources, 31*(November), 297–325. https://doi.org/10.1146/annurev.energy.31.042605.135621.

Lieberknecht, K. (2018). Our world is changing. Our water infrastructure should, too. *Austin American statesman.* October 26, 2018 https://www.statesman.com/opinion/

20181026/commentary-our-world-is-changing-our-water-infrastructure-should-too.
Lusher, D., Koskinen, J., & Robins, G. (2013). *Exponential random graph models for social networks: Theory, methods, and applications.* Cambridge University Press.
McPhearson, T., Andersson, E., Elmqvist, T., & Frantzeskaki, N. (2015). Resilience of and through urban ecosystem services. *Ecosystem Services, 12*(April), 152–156. https://doi.org/10.1016/j.ecoser.2014.07.012.
McPhearson, T., Pickett, S. T. A., Grimm, N. B., Niemelä, J., Alberti, M., Elmqvist, T., ... Qureshi, S. (2016). Advancing urban ecology toward a science of cities. *BioScience, 66*(3), 198–212. https://doi.org/10.1093/biosci/biw002.
McPherson, M., Smith-Lovin, L., & Cook, J. M. (2001). Birds of a feather: Homophily in social networks. *Annual Review of Sociology, 27*, 415–444.
Meerow, S. (2020). The politics of multifunctional green infrastructure planning in New York City. *Cities, 100*(May), 102621. https://doi.org/10.1016/j.cities.2020.102621.
Meerow, S., Newell, J. P., & Stults, M. (2016). Defining urban resilience: A review. *Landscape and Urban Planning, 147*(March), 38–49. https://doi.org/10.1016/j.landurbplan.2015.11.011.
Morris, M., Handcock, M. S., & Hunter, D. R. (2008). Specification of exponential-family random graph models: Terms and computational aspects. *Journal of Statistical Software, 24*(1), 1–24. https://doi.org/10.18637/jss.v024.i04.
Munang, R., Thiaw, I., Alverson, K., Liu, J., & Han, Z. (2013). The role of ecosystem services in climate change adaptation and disaster risk reduction. *Current Opinion in Environmental Sustainability, Terrestrial systems, 5*(1), 47–52. https://doi.org/10.1016/j.cosust.2013.02.002.
Normandin, J.-M., Therrien, M.-C., Pelling, M., & Paterson, S. (2019). The definition of urban resilience: A transformation path towards collaborative urban risk governance. In G. Brunetta, O. Caldarice, N. Tollin, M. Rosas-Casals, & J. Morató (Eds.). *Resilient cities*. (pp. 9–25). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-76944-8_2.
Norris, F. H., Stevens, S. P., Pfefferbaum, B., Wyche, K. F., & Pfefferbaum, R. L. (2008). Community resilience as a metaphor, theory, set of capacities, and strategy for disaster readiness. *American Journal of Community Psychology, 41*(1–2), 127–150. https://doi.org/10.1007/s10464-007-9156-6.
North, D. C. (1991). Institutions. *The Journal of Economic Perspectives, 5*(1), 97–112.
Nowell, B., Steelman, T., Velez, A.-L. K., & Yang, Z. (2018). The structure of effective governance of disaster response networks: Insights from the field. *The American Review of Public Administration, 48*(7), 699–715. https://doi.org/10.1177/0275074017724225.
Ostrom, E. (1990). *Governing the commons. Political economy of institutions and decisions.* Cambridge University Press.
Ostrom, E. (2000). Collective action and the evolution of social norms. *The Journal of Economic Perspectives, 14*(3), 137–158.
Ostrom, V., Tiebout, C. M., & Warren, R. (1961). The organization of government in metropolitan areas: A theoretical inquiry. *The American Political Science Review, 55*(4), 831–842. https://doi.org/10.2307/1952530.
Page, G. E. G. W., & Susskind, L. (2007). Five important themes in the special issue on planning for water. *Journal of the American Planning Association, 73*(2), 141–145. https://doi.org/10.1080/01944360708976147.
Patel, S. S., Brooke Rogers, M., Amlôt, R., & James Rubin, G. (2017). What do we mean by "community resilience"? A systematic literature review of how it is defined in the literature. *PLoS Currents, 9*(February), https://doi.org/10.1371/currents.dis.db775aff25efc5ac4f0660ad9c9f7db2.
Peters, B. G. (2011). *Institutional theory in political science: The new institutionalism.* Bloomsbury Publishing USA.
Pfefferbaum, R. L., Pfefferbaum, B., Van Horn, R. L., Klomp, R. W., Norris, F. H., & Reissman, D. B. (2013). The Communities Advancing Resilience Toolkit (CART): An intervention to build community resilience to disasters. *Journal of Public Health Management and Practice: JPHMP, 19*(3), 250–258. https://doi.org/10.1097/PHH.0b013e318268aed8.
Pfefferbaum, R. L., Pfefferbaum, B., Zhao, Y. D., Horn, R. L. V., McCarter, G. S.". M."., & Leonard, M. B. (2016). Assessing community resilience: A CART survey application in an impoverished urban community. *Disaster Health, 3*(2), 45–56. https://doi.org/10.1080/21665044.2016.1189068.
Pickett, S. T. A., Cadenasso, M. L., Childers, D. L., McDonnell, M. J., & Zhou, W. (2016). Evolution and future of urban ecological science: Ecology in, of, and for the city. *Ecosystem Health and Sustainability, 2*(7), e01229. https://doi.org/10.1002/ehs2.1229.
Pierre, J. (1999). Models of urban governance: The institutional dimension of urban politics. *Urban Affairs Review, 34*(3), 372–396. https://doi.org/10.1177/10780879922183988.
Pierre, J. (2011). *The politics of urban governance.* Macmillan International Higher Education.
Provan, K. G., & Kenis, P. (2007). Modes of network governance: Structure, management, and effectiveness. *Journal of Public Administration Research and Theory, 18*(2), 229–252. https://doi.org/10.1093/jopart/mum015.
Revi, A., Satterthwaite, D., Aragon-Durand, F., Corfee-Morlot, J., Kiunsi, R., Pelling, M., ... Sverdilik, A. (2014). Towards transformative adaptation in cities: The IPCC's fifth assessment. *Environment and Urbanization, 26*(1), 11–28. https://doi.org/10.1177/0956247814523539.
Richter, S. M. (2020). Revisiting urban land change in the continental US: an exploratory analysis of urban expansion and imperviousness. *Landscape and Urban Planning (In review)*.
Rivera, M. T., Soderstrom, S. B., & Uzzi, B. (2010). Dynamics of dyads in social networks: Assortative, relational, and proximity mechanisms. *Annual Review of Sociology, 36*(1), 91–115. https://doi.org/10.1146/annurev.soc.34.040507.134743.
Romolini, M., Bixler, R. P., & Grove, J. M. (2016). A social-ecological framework for urban stewardship network research to promote sustainable and resilient cities. *Sustainability, 8*(9), 956. https://doi.org/10.3390/su8090956.
Romolini, M., Grove, J. M., Ventriss, C. L., Koliba, C. J., & Krymkowski, D. H. (2016). Toward an understanding of citywide urban environmental governance: An examination of stewardship networks in Baltimore and Seattle. *Environmental Management, 58*(2), 254–267. https://doi.org/10.1007/s00267-016-0704-4.
Rosenzweig, C., Solecki, W. D., Romero-Lankao, P., Mehrotra, S., Dhakal, S., & Ibrahim, S. A. (Eds.). (2018). *Climate change and cities: Second assessment report of the urban climate change research network*(1 ed.). United Kingdom; New York, NY: Cambridge University Press.
Scott, T. A., & Greer, R. A. (2019). Polycentricity and the hollow state: Exploring shared personnel as a source of connectivity in fragmented urban systems. *Policy Studies Journal, 47*(1), 52–76. https://doi.org/10.1111/psj.12289.
Scott, T. A., & Ulibarri, N. (2019). Taking Network Analysis Seriously: Methodological Improvements for Governance Network Scholarship. *Perspectives on Public Management and Governance, 2*(2), 89–101. https://doi.org/10.1093/ppmgov/gvy011.
Snijders, T. A. B., Pattison, P. E., Robins, G. L., & Handcock, M. S. (2006). New specifications for exponential random graph models. *Sociological Methodology, 36*(1), 99–153. https://doi.org/10.1111/j.1467-9531.2006.00176.x.
Strauss, A., & Corbin, J. M. (1998). *Basics of qualitative research: Techniques and procedures for developing grounded theory.* SAGE Publications.
Therrien, M.-C., Jutras, M., & Usher, S. (2019). Including quality in social network analysis to foster dialogue in urban resilience and adaptation policies. *Environmental Science & Policy, 93*(March), 1–10. https://doi.org/10.1016/j.envsci.2018.11.016.
Therrien, M.-C., Tanguay, G. A., & Beauregard-Guérin, I. (2015). Fundamental determinants of urban resilience: A search for indicators applied to public health crisis. *Resilience, 3*(1), 18–39. https://doi.org/10.1080/21693293.2014.988915.
TWDB (2017). Water for Texas: 2017 state water plan. Texas Water Development Boardhttp://www.twdb.texas.gov/waterplanning/swp/2017/index.asp.
Vargo, J., Dana Habeeb, B. S., Liu, P., & Russell, A. (2016). The social and spatial distribution of temperature-related health impacts from urban heat island reduction policies. *Environmental Science & Policy, 66*(December), 366–374. https://doi.org/10.1016/j.envsci.2016.08.012.
Walker, B., & Salt, D. (2012). *Resilience practice: Building capacity to absorb disturbance and maintain function* (1 ed.). Washington: Island Press.
Wasserman, S., & Faust, K. (1995). *Social network analysis: Methods and applications.* Cambridge, UNKNOWN: Cambridge University Press. http://ebookcentral.proquest.com/lib/utxa/detail.action?docID=1042406.