Cities and the Environment (CATE)

Volume 7
Issue 1 *Urban Long-Term Research Area Exploratory Awards (ULTRA-Ex)*

Article 5

8-25-2014

Knowledge to Serve the City: Insights from an Emerging Knowledge-Action Network to Address Vulnerability and Sustainability in San Juan, Puerto Rico

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This paper presents initial efforts to establish the San Juan Urban Long-Term Research Area Exploratory (ULTRA-Ex), a long-term program aimed at developing transdisciplinary social-ecological system (SES) research to address vulnerability and sustainability for the municipality of San Juan. Transdisciplinary approaches involve the collaborations between researchers, stakeholders, and citizens to produce socially-relevant knowledge and support decision-making. We characterize the transdisciplinary arrangement emerging in San Juan ULTRA-Ex as a knowledge-action network composed of multiple formal and informal actors (e.g., scientists, policymakers, civic organizations and other stakeholders) where knowledge, ideas, and strategies for sustainability are being produced, evaluated, and validated. We describe in this paper the on-the-ground social practices and dynamics that emerged from developing a knowledge-action network in our local context. Specifically, we present six social practices that were crucial to the development of our knowledge-action network: 1) understanding local framings; 2) analyzing existing knowledge-action systems in the city; 3) framing the social-ecological research agenda; 4) collaborative knowledge production and integration; 5) boundary objects and practices; and 6) synthesis, application, and adaptation. We discuss key challenges and ways to move forward in building knowledge-action networks for sustainability. Our hope is that the insights learned from this process will stimulate broader discussions on how to develop knowledge for urban sustainability, especially in tropical cities where these issues are under-explored.

Keywords
ULTRA-Ex; urban sustainability, social-ecological-systems; transdisciplinarity; interdisciplinarity; collaborative knowledge production; framings; knowledge-action systems; adaptive science; reflexivity; research network; vulnerability; San Juan

Acknowledgements
We are grateful to all the local organizations and community leaders that have participated and contributed to the San Juan ULTRA-Ex. This work was supported by the National Science Foundation under grant numbers 0948507 (Urban Long-Term Research Area Exploratory) and the USDA International Institute of Tropical Forestry. Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation (NSF).

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This special topic article: urban long-term research area exploratory awards (ultra-ex) is available in Cities and the Environment (CATE): http://digitalcommons.lmu.edu/cate/vol7/iss1/5

INTRODUCTION

Cities are increasingly sites of innovation and creative solutions toward sustainability (Rosenzweig 2011). City mayors, managers and policymakers across the world are taking up the challenging task of addressing sustainability and charting strategies to adapt to climate change (Wheeler and Beatly 2009; Grove et al. 2013). Examples in the US include comprehensive sustainable city plans in cities like Portland and New York City, and climate change adaptation programs developed in over fifteen US cities (Center for Climate and Energy Solutions 2014). The ability to foster innovation for sustainability rests in large part on building and delivering scientific know-how (Crow 2007). As numerous scholars have suggested, knowledge for sustainability should be transdisciplinary and participatory, involving collaborations between researchers, stakeholders, and citizens to integrate, synthesize, and produce socially-relevant, actionable knowledge (e.g., Miller et al. 2013; Shiroyama et al. 2012; Lang et al. 2012; Miller et al. 2011; Salas-Zapata 2011; Kasemir et al. 2003). Urban sustainability thus demands transformation in how we produce knowledge for the city.

Building transdisciplinary approaches, however, is a challenging task. Recent analyses and evaluations of transdisciplinary projects addressing sustainability show that while efforts are on the rise, various hurdles need to be overcome (Wiek et al. 2012). Some of these include incorporating knowledge from outside academia and sustaining the participation of these non-academic stakeholders, allowing enough time for capacity building, obtaining resources and support in a climate that encourages disciplinarity, and dealing with different values and political interests (Miller et al. 2013).

The San Juan Urban Long-Term Research Area Exploratory (ULTRA-Ex) is a long-term program aimed at developing transdisciplinary social-ecological system (SES) research to provide knowledge to support local decision-making and strategies aimed at addressing vulnerability and sustainability for the municipality of San Juan. Here we present results of the initial three years and the ways that we have tried to address the challenges of building transdisciplinary knowledge for the city through a knowledge-action network arrangement of scientists, policymakers, civic organizations and other stakeholders. While our approach resembles many of the principles and experiences found in the literature on transdisciplinary research processes, we describe in this paper the on-the-ground social practices and dynamics that emerged from developing this knowledge-action network in our local city context.

Because of the early stage of this long-term program, the efforts we describe are preliminary and their effect on city sustainability and adaptation efforts remains to be seen. However, interest and investments in long-term interdisciplinary/transdisciplinary urban ecological platforms (e.g., National Science Foundation Long-term Ecological Research Programs, USDA Forest Service Urban Field Stations, other ULTRA-Exs) and 'science-policy interfaces' (e.g., Decision Making Under Uncertainty centers) for urban systems are on the rise. Thus, our objective is to share insights we have learned that will stimulate broader discussions on how to meet the demands for knowledge required for studying sustainability. In particular, our experiences can be useful to other tropical urban systems where these issues are under-explored.

The paper proceeds in three parts. First we review the principles of transdisciplinary research that have influenced our approach in developing the San Juan ULTRA program. We then describe the social practices, tools, and methods we employed on-the-ground, as well as the opportunities and barriers we encountered. In the final section and conclusion we discuss the challenges and future directions we propose to continue building an adaptive knowledge-action network for urban sustainability.

TRANSDISCIPLINARY PRINCIPLES AND PRACTICES FOR A KNOWLEDGE-ACTION NETWORK

Transdisciplinarity involves the collaboration of scientists, decision-makers and citizens in the process of developing collective knowledge that transcends traditional scientific disciplines and practice (Scholz et al. 2006; Morse et al. 2007; Wiek and Walter 2009). The emerging fields of social-ecological systems and sustainability science consider transdisciplinarity a core research approach to draw on the observations, knowledge and skills of multiple sectors and integrate their needs and interests towards generating solutions (Chapin et al. 2011; Clark et al. 2011, Salas-Zapata et al. 2011; Hirsh Hadorn et al. 2006). Through its focus on integrative and solutions-oriented practices, transdisciplinarity aims at producing socially-robust knowledge, meaning that it is both relevant and valid within and outside of the scientific community. In other words, it is contextualized (Nowotny et al. 2001). Finally, transdisciplinarity is reflexive in that it must be open to criticism and re-organization of the assumptions, framings, and practices behind the knowledge that is produced in order to foster adaptability and social-learning (Lang et al. 2012; Hendriks and Grin 2006; Miller et al. 2011).

The three characteristics of transdisciplinarity described above – integrative, socially-robust, and reflexive - influence our approach to social-ecological systems and sustainability research. To achieve knowledge integration Mieg et al. (2008) suggest a process of 'synthesis-first' in which stakeholder engagement and epistemic integration occurs in the beginning (or upstream) of the process of defining research questions as opposed to a knowledge transfer model when the integration is done at the end (or 'synthesis-then'). Integration demands epistemic pluralism, meaning that different paradigms, ways of knowing and framing of problems are recognized and considered essential to understanding a social-ecological system (Miller et al. 2010; Miller et al. 2011). Thus, in addition to addressing stakeholders' information needs and uses, transdisciplinary processes must be open and diverse enough to be inclusive of the multiplicity of perspectives and expectations found in the city.

The experiences and knowledge of those currently most affected by risks and hazards, such as marginal populations, are crucial to build socially-robust knowledge because they provide first-hand knowledge of how the social-ecological system is functioning (Leach et al. 2010). This knowledge 'from below' can serve as a window into the aspects that affect the adaptive capacity of the system (Scott 1998; Leach 2008). Knowledge about future needs and options is also essential for sustainability projects. In the context of sustainability science, anticipation is necessary to think about alternative future pathways that systems can take to prepare for change and to guide current decisions toward maximizing future alternatives or minimizing future threats (Karinen and Guston 2010; Wiek 2007). Creating socially-robust knowledge calls for collaborative settings that are anticipatory, such as participatory scenario

processes, that allow exploration of multiple visions, pathways and trade-offs (Wiek and Iwaniec 2013; Robinson et al. 2011; Kasemir et al. 2003).

Finally, increasing concern over how to best prepare societies to recognize, learn, and adapt to future change, such as climate change, is prompting calls for science that is adaptive (Moss et al. 2013) and reflexive (Smith and Stirling 2010; Miller et al. 2011). Adaptability implies not only the act of responding to change and surprise and steering the system into new pathways, but the awareness and anticipation to recognize when change is needed (Fazey et al. 2007). Reflexivity provides the self-awareness necessary for social learning and adaptation. Reflexivity refers to not only the awareness about system uncertainty and complexity, but also the effects that such awareness has on how we produce knowledge as producers and users come to terms with the impossibility of having full and complete knowledge of system dynamics (Leach 2008).

In practice, transdisciplinary programs take many forms, such as participatory action science (Kasemir et al. 2003), community-based collaborative research (Daniels and Walker 1996, Muñoz-Erickson et al. 2007), joint knowledge-production (Hegger et al. 2012), and boundary organizations (Guston 2001). Several models for linking science and practice, such as 'bridges' or 'highways', have influenced how these programs or organizations are conceptualized. An increasingly popular model is that of boundary management through boundary organizations that seek to manage the expectations between the science and policy sectors in terms of credibility, legitimacy, and saliency (e.g., Clark et al. 2011; Cash et al. 2003). While these organizational models have been successful in some natural resource management contexts, they can mis-represent the complex interactions between knowledge and society in contexts such as cities where its highly heterogeneous, and sometimes contested institutional conditions, may not fit with simplistic boundaries between science and policy (Muñoz-Erickson 2014a).

We prefer to characterize the arrangement emerging in San Juan ULTRA-Ex as a knowledge-action network based on the idea that knowledge production is a result of complex interactions between different actors through multiple points of communication, engagement, and negotiation to co-produce knowledge and social order. As such, instead of following a prescribed model for transdisciplinary research, we tried to follow a bottom-up approach to build a network that fits within the local governance context and already existing knowledge-action systems. Our definition of a knowledge-action network is of systems composed of multiple formal and informal actors (individuals, groups or organizations) where knowledge, ideas, and strategies for sustainability are being produced, evaluated, and validated (Muñoz-Erickson 2014a). Crucial to building a reflexive and adaptive approach, a fluid, network-like structure fosters adaptability by recognizing that the actors, knowledge, and strategies will change as issues and expectations for the system also change along the way. Thus, crucial nodes (actors or organizations) that have the relevant expertise can be activated as needed. Others have described these networks as 'spider webs' of connectivity in which there are nodes and complex linkages, with old actors disappearing and new ones entering (Vogel et al. 2007).

THE SAN JUAN ULTRA-EX APPROACH

San Juan ULTRA-Ex initiated from a national call for proposals by the National Science Foundation and the USDA Forest Service to establish a network of long-term research sites in cities. With most Americans living in cities, producing relevant and useful knowledge on urban areas to improve the social and environmental conditions of cities was a major motivation behind the establishment of ULTRA-Exs (Grove et al. 2013). We proposed using a social-ecological systems (SES) lens to look at coupled human-environmental dynamics taking into consideration multiple spatial and temporal scales (Redman et al. 2004; Anderson and Elmqvist 2012). The SES approach goes beyond urban ecological frameworks that have traditionally focused on *ecology in the city* and is directed towards a holistic look of the city as a social-ecological system, i.e. *ecology of the city* (Grove et al. 2013; Grimm et al. 2000; Picket et al. 1997).

The San Juan ULTRA-Ex was established in part because of the realization that the social and ecological issues confronting San Juan – such as vulnerabilities to climate-associated disturbances (e.g., flooding, sea level rise), economic fluctuations associated with high, and potentially higher over time, fossil fuel costs, and reduction of land cover and ecosystem services (e.g., water quality, urban heat island) - were too complex to be addressed by a single discipline, organization, or sector (Lugo et al. 2012; Muñoz-Erickson et al. 2014). In addition, while various local initiatives have emerged in the municipality to address sustainability (e.g., municipal sustainable land use plan and civic stewardship groups), these efforts have been fragmented and lack the coordination necessary to address and deliberate the political and scientific resources needed to forge future pathways for the city as a whole. Thus, from its inception, the program sought to bring together the various knowledge, needs, expectations, and visions of city stakeholders into how we develop science for the city.

The focus on the municipality of San Juan was intentional since what happens here affects the rest of the Island, and even Caribbean region. As the capital of Puerto Rico and located in the San Juan Metropolitan Area (SJMA) where nearly half of the Island's populations resides, the municipality is the center of economic, political, and cultural activity of the Island (Figure 1). San Juan also has one of the largest economies in the Caribbean. In addition, because much of the essential infrastructure for all of Puerto Rico is located in San Juan and the SJMA (e.g., airports, maritime ports, central government agencies, etc.), issues affecting the vulnerability and resilience of this city make the rest of the Island vulnerable as well (Puerto Rico Climate Change Council 2012). Finally, as one of the oldest cities in the U.S., San Juan provides a unique historical perspective on urban development and sustainability. Our focus for San Juan ULTRA-Ex was on the municipality's main watershed, the Río Piedras River Watershed (RPRW). The RPRW has an area of 49 km^2 and it is almost fully contained within municipal boundaries (Lugo et al. 2011). The RPRW was crucial to the historical development of the municipality and surrounding regions as the main supplier of gravity-fed water for its residents. The rapid urbanization (and suburbanization) that occurred since the 1950s, however, transformed the landscape and the RPRW no longer provides this important service to the municipality. Today, most residents are aware of the river's existence only when it floods the city, causing significant interruptions in transportation networks and leaving sectors of the city paralyzed for hours, if not days.

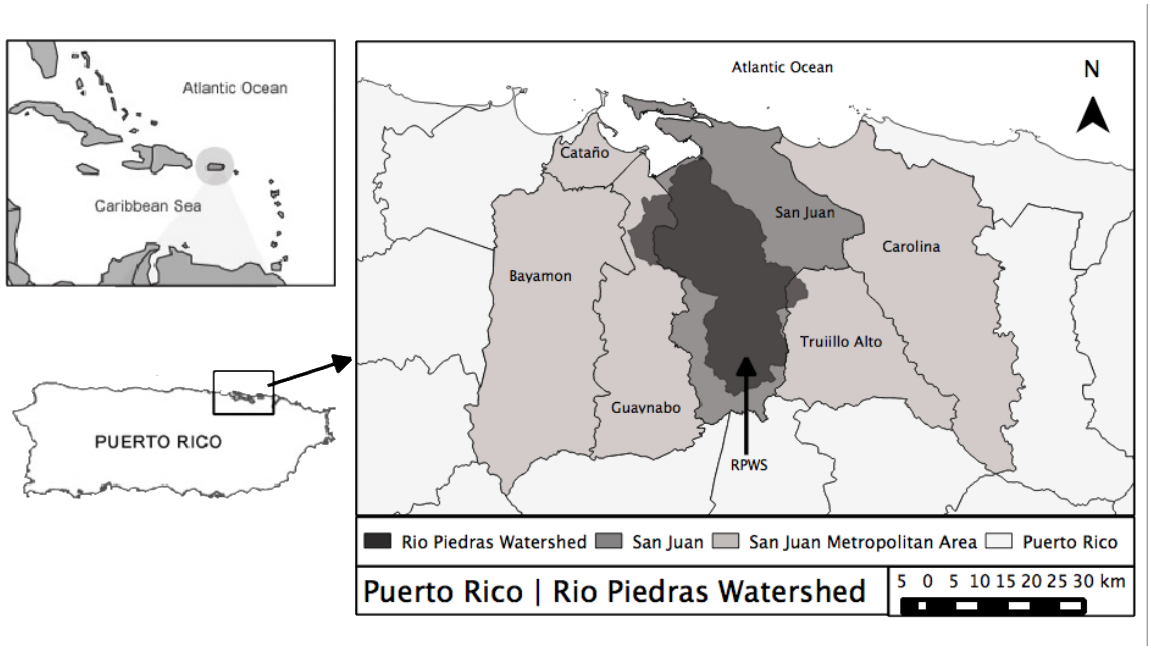

Figure 1. Map of Puerto Rico and the Caribbean (left panel), and the San Juan Metropolitan Area (SJMA) and the Río Piedras River Watershed (right panel).

The San Juan ULTRA-Ex addressed three main research questions: 1) How do biophysical, socio-economic, and institutional factors influence the vulnerability of the RPRW Social-Ecological System, and how have they changed spatially and temporally over the past 70 years?; 2) What are some possible alternative scenarios and indicators for the future development of the RPRW?; and 3) What organizational networks and policies support these scenarios, and to what extent do these influence the vulnerability and adaptive capacities necessaries for urban sustainability? To address these questions, we developed a SES approach framework that included three cross-cutting concepts -- vulnerability, resilience, and sustainability -- as the links between understanding how SES function and the long-term viability of the system given social and political goals (Eakin and Luers 2006; Turner II et al. 2003) (Box 1, Figure 2). Together, these concepts provided a common lexicon to integrate the various disciplinary perspectives in our research group. We provide more extensive discussion about the theoretical framework and scientific findings from our efforts to study the city as a social-ecological system in other papers (e.g., Lugo et al. 2012; Muñoz-Erickson et al. 2014).

Box 1. Theoretical Framework for the San Juan ULTRA-Ex Social-Ecological Systems Research

Our theoretical framework links the cross-cutting concepts of vulnerability, resilience, and sustainability. Vulnerability is a system property that illustrates the condition of the SES that is to be affected by a disturbance (Brooks et al. 2005; Downing et al. 2005) based on the current situation of SES elements and state of relations between social structures, human agency and response, and the natural environment (and vice-versa) (McLaughlin and Dietz 2008). For a systems perspective, resilience contributes understanding about the threshold responses to disturbance, and the multi-scale and feedback interactions of dynamic social-ecological systems (Holling 1973; Walker 2004). The last component of our framework is sustainability, which provides the link between system condition, policy goals, and future development trajectories. Like vulnerability, we understand sustainability as a concept that describes the condition of the SES, as well as its ability to maintain ecological and social processes over time and in response to changing external forces. More importantly, sustainability also adds a normative (value-based) dimension to studying the SES by recognizing that there are multiple socially desirable or undesirable state domains, and these domains are defined and maintained by political values, institutional structures and cultural factors (Norton 2005). Therefore, sustainability involves the identification of desirable, yet sometimes conflicting, development trajectories, and the potential of the SES to move towards any one of them.

Informed in part by SES models previously developed in the literature, such as the Human Ecosystem Framework by Machlis et al. (1997) and the Integrated Science for Society and the Environment (Collins et al. 2011), we developed a model to describe the structure and dynamics that emerge in our local urban environment with the interaction among plants, animals, microbes, people, technology, and institutions. This model has six main components: (1) *external drivers* that power and affect the city and its vulnerability, including climatic effects and declining availability and/or volatility of fossil fuels and other energy sources, as well as food, water, and materials; (2) the gray infrastructure that describes the built environment (e.g., streets, building, storm water infrastructure); (3) the green infrastructure, the green and blue areas (e.g., forests, rivers, wetlands) that are produced by the urban environment; (4) urban dynamics and metabolism, which describe urban development patterns and connectivity, and the processes of production and consumption in both social and natural subsystems of the SES; (5) governance, including the diverse set of individual actors and organizational networks that allows cities to improve their ability to respond to local and global conditions and improve delivery of services to people; and (6) social dynamics, including networks, inequity, health, and poverty that affect social vulnerability. A key difference of our framework is an explicit category that addresses the interactions and metabolism of a city, such as, (a) urban development patterns and connectivity; (b) SES interactions, and (c) fluxes of energy and materials. We also take the model one step further by considering cultural and institutional elements that are critical to building adaptive capacity and sustainability as integral parts of the SES system.

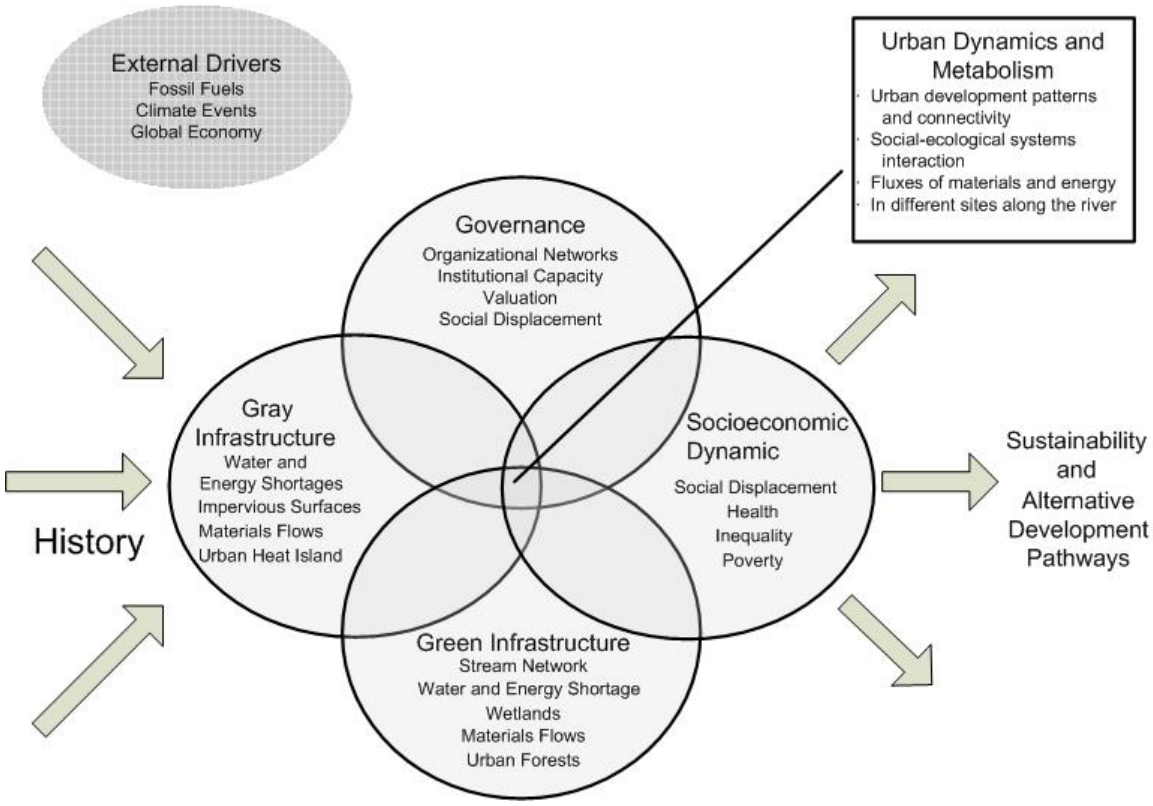

Figure 2. Social-ecological system (SES) model for San Juan ULTRA-Ex. In the intersection of the four circles is Urban Dynamics and Metabolism.

The San Juan ULTRA-Ex did not reside in a specific locality nor did it create a formal organization, but rather followed an eclectic approach and had a porous organizational structure, with new actors coming in and out. In other words, consistent with the idea of a knowledge-action network, this network was meant to be polycentric (Jasanoff 2003). Thus, while our leadership resides mostly at the USDA Forest Service and the University of Puerto Rico, multiple organizations and institutions were involved in decision-making and implementation of the research process. This also implies that to be inclusive of a wide range of ways of knowledge-making methods, we focused on diverse points of interactions between different actors, or 'social spaces'. In other words, we needed to go beyond simply engaging frequent groups, or 'usual suspects', through simple modes of communication and participation, such as participatory workshops (Leach et al. 2010; Vogel et al. 2007). Figure 3 illustrates the social practices we employed on-the-ground in relation to the adaptive, social learning process we strive for. A flexible and contextual approach allowed us to forge the necessary personal relationships to build credibility and legitimacy among existing scientific and political networks. As we describe below, this process involved an intensive focus on examining existing social and cultural dynamics and interacting with local stakeholders and communities on their terms and territories (e.g., coffee houses, offices, etc.). Next we describe these practices in more detail.

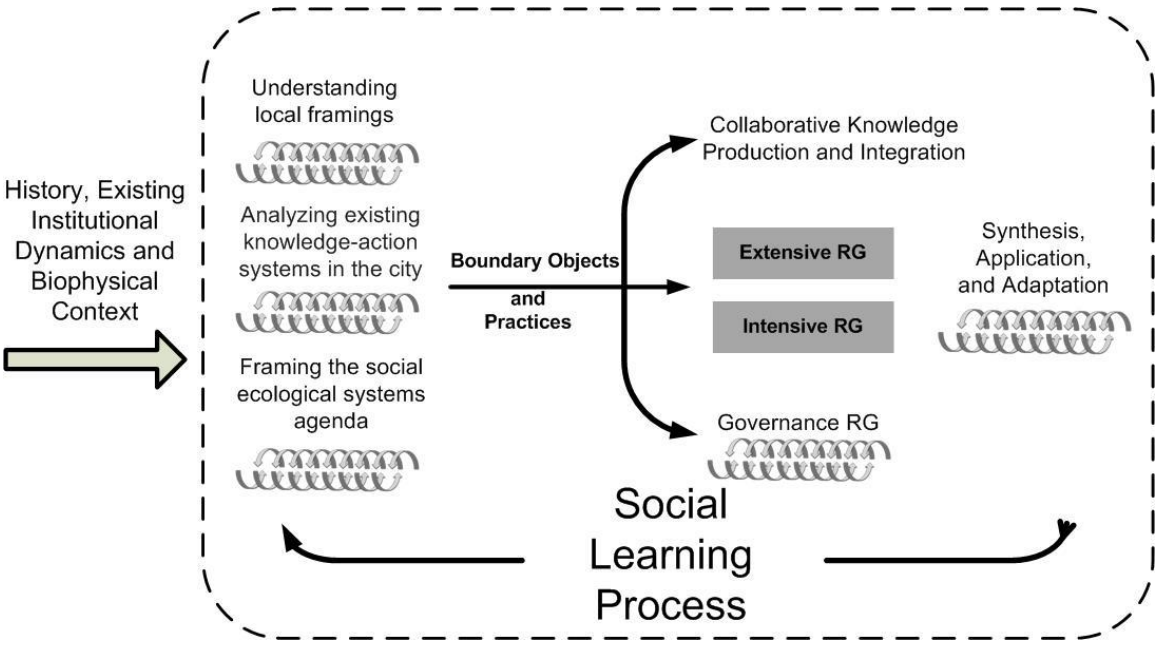

Figure 3. Procedural model to represent the different stages and practices of the San Juan ULTRA-Ex transdisciplinary process. The spirals represent the points at which the research network and process was 'open' to stakeholder engagement and integration, whereas the boxes represent 'closed' points to allow implementation of research group (RG) activities.

Understanding local framings

As a way to initiate the 'synthesis-first' process of knowledge integration, our first step was to conduct an extensive review of the ecological, social, economic, and political issues interacting in San Juan. In addition to reviewing existing natural and social scientific literature and data for the municipality, we sought to understand local concerns and priorities through review of policy, media, and gray literature (see Muñoz-Erickson 2012). This review became the basis of an island-wide call to local scientists and stakeholders to review the context and seek out participation in the development of a social-ecological research agenda for San Juan. The large response and overwhelming interest we received from the initial call to explore the city as a social-ecological system was not anticipated in a setting where scientists traditionally worked separately in disciplinary silos and most ecologists working on the Island were not studying the city.

Another crucial step to setting the context was understanding how different scientists, stakeholders and citizens 'frame' social and ecological values and issues for the city. In other words, what meanings do they attach to the urban environment, what problems do they see the municipality is facing and, particularly important for framing sustainability, what are their expectations of the municipality and visions of the future. Framing, in the context of science and social-ecological systems, refers to the ways of understanding, bounding, and talking about the system (Leach et al. 2010). Through framing one can understand why and how different people prioritize certain elements of the system, and ensure that as many system components as possible were considered and characterized prior to narrowing down a research agenda. Not understanding this context may result in the definition of research questions and methodologies

that do not adequately address system components, dynamics, or vulnerabilities from the local perspective. Hence, not socially-robust.

Framing was not just crucial to understand how stakeholders see the system. Awareness of how scientists' frame research problems provided a window into the paradigms and epistemic cultures that influence theoretical and methodological approaches and which also affect the dynamics, and success, of interdisciplinary processes (Evans and Martin 2006). An example of these differences in framing was evident in the definition of the study boundary. To ecologists it was important to have a 'natural' boundary, such as a watershed, whereas for social scientists and policy stakeholders a socially-robust 'urban' or administrative definition in terms of political or socio-demographic boundaries was important. In the end, we compromised by adopting a flexible boundary, beginning with the Río Piedras River Watershed boundary, given that this watershed is almost entirely contained within San Juan municipal boundaries. However, we agreed that researchers may extend the boundary outside of the watershed if their research objectives and social priorities so require. The framing of the RPRW boundary has had a large effect locally as the San Juan ULTRA-Ex identity and credibility is now strongly associated with this geographic unit. Municipal planners and administrators, for instance, seek out the expertise of San Juan ULTRA-Ex collaborators when matters of the Río Piedras river and the RPRW are concerned.

To assess local framings we used multiple qualitative methods influenced by a rapid assessment process (Beebe 2001), such as interviews, field trips throughout the watershed with stakeholders, continuous phone and email communications, and most importantly, formal and informal meetings in relevant social or organizational settings (e.g., special events, public meetings, community gatherings, local coffee shops, etc.). A key approach to this initial understanding of local framings was done through a survey to analyze the existing knowledge-action system that we describe next.

Analyzing existing knowledge-action systems in the city

Building the knowledge-action network of ULTRA-Ex required first that we understood the knowledge-action systems already present in the science and political context of San Juan. We gained first-hand knowledge of existing local frames and the socio-political dynamics using the knowledge-action systems analysis (KASA) approach. The KASA approach analyzes the social networks, future visions, and practices underlying the production of knowledge by governance actors to advance specific policies, decisions, and actions related to sustainability (Muñoz-Erickson 2014a). The tool involves multiple analytical steps, including: 1) knowledge mapping using social network analysis; 2) identifying central actors and examining knowledge-power relations in the network; 3) analyzing dominant and marginal visions for the future of the city; 4) exploring influences of knowledge systems on vision divergence; and 5) assessing boundary dynamics.

We surveyed different organizations from multiple sectors, including governmental, non-government, academic, civic, and private actors, to collect data for the knowledge-action systems analysis. We asked them various questions about how their organization worked to produce and use policy-relevant knowledge for the governance of the urban environment. Thus, the objective

was to go beyond examining stakeholder information needs or objectives and to assess what they actually *do*: how they know the city (their knowledge systems), how they obtain knowledge, who they collaborate with, how they frame problems and strategies, and how they envision the future of the city. We complemented survey data with participant observations, interviews, and document analysis to get a broad range of discourses and social dynamics that might have been missed in the survey. Using multiple quantitative and qualitative methods, such as network and discourse analysis, the tool provides a 'map' of the governance landscape and how diverse social actors frame, know, and understand the urban environment. We found a diverse network of actors contributing diverse knowledge types (e.g., scientific, applied, local, organizational) thus showing potential for innovation in governance (Figure 4). Several political and cultural factors, however, such as the dominance of traditional economic and technocratic planning expertise over other ways of knowing, came up as potential barriers to collaborative knowledge production and development of sustainable strategies. More details on the methodology and results of this analysis can be found in Muñoz-Erickson (2014a) and Muñoz-Erickson (2014b).

While the primary objective of this KASA study was scientific, the results provided important 'applied' knowledge for the planning and development of the San Juan ULTRA-Ex knowledge-action network. For instance, the heterogeneous network of knowledge that resulted, including organizations not traditionally viewed as experts (i.e., civic groups), allowed us to identify actors beyond the traditional groups of stakeholders to involve them in the transdisciplinary process. We also found that multiple visions of the future of the city co-existed, which allowed us to anticipate potential pathways of sustainability that we plan to explore in relation to social-ecological system conditions in the future. Finally, this study established a baseline of existing knowledge-power dynamics in governance that we can monitor overtime to examine governance transformation, and as we later describe, will allow us to reflect on the role that San Juan ULTRA-Ex has had on building knowledge for sustainability. Overall, by characterizing how existing networks know and understand the city – or how the city thinks (Muñoz-Erickson et al. 2014) – we provided the foundation for the actors, networks, problems, and resources we need to address as we build our knowledge-action network.

Framing the social-ecological research agenda

Once we understood existing framings and gained a broader understanding of how knowledge-action systems worked in the city we developed the collaborative process of defining research agendas and questions. As part of the rapid assessment methods previously mentioned, we sought the assistance of community leaders and residents to orient us in how to design the participatory process, anticipate points of contention with the community, and identify ways to communicate how their participation is important and how they will benefit beyond merely providing input to the research process. In addition, numerous one-to-one interactions with local scientists, decision-makers, activists and community leaders prior to inviting them to join research proposal meetings were necessary to explain the intentions of the project and discuss how they could contribute. This allowed us to gain credibility and legitimacy in the existing network. For instance, the ties of the project to the National Science Foundation, and not a state or local government effort, lent credibility to the project and eased the anxiety of some groups to work in a collaborative setting. These efforts then set the foundation for the participatory mapping workshops we held with different stakeholders, including residents, NGOs, government

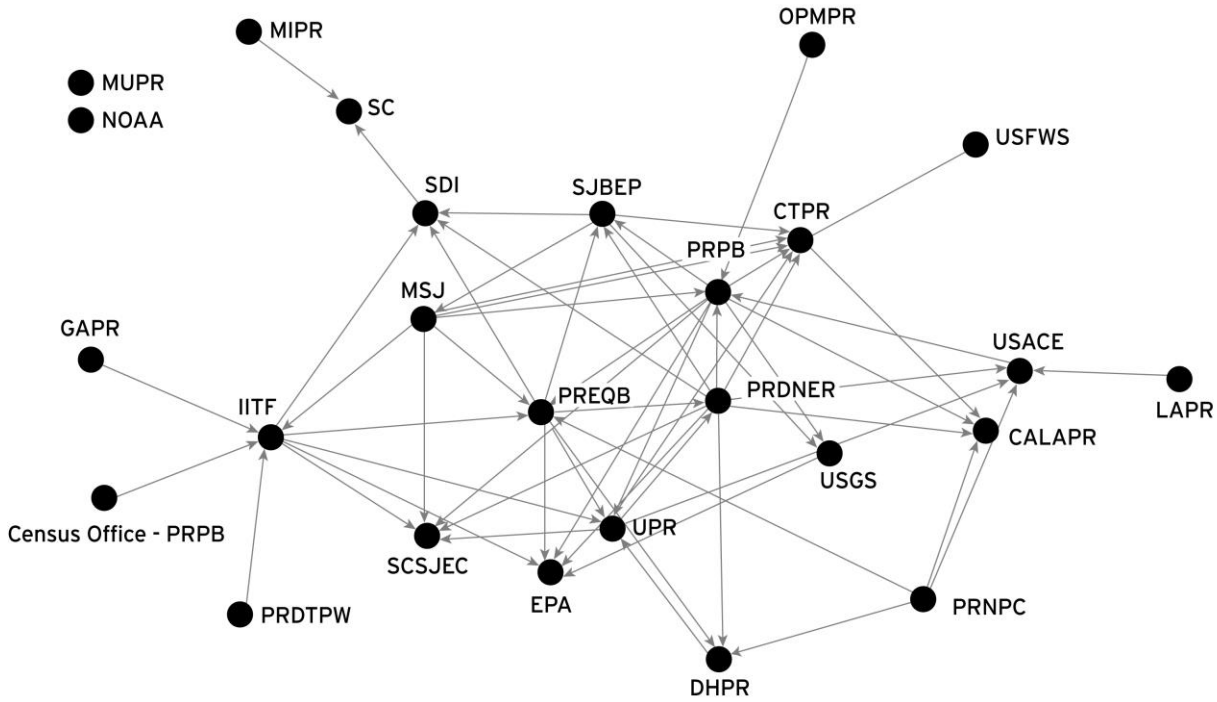

Figure 4. Network of organizations involved in producing and sharing knowledge about land use and green areas in San Juan. Listing of organizations is alphabetical. Census Office – PRPB, Census Office of the Puerto Rico Planning Board; CALAPR, College of Architects and Landscape Architects of Puerto Rico; CTPR, Conservation Trust of Puerto Rico; DHPR, Department of Housing of Puerto Rico; USFWS, US Fish and Wildlife Service; EPA, Environmental Protection Agency; IITF, International Institute of Tropical Forestry (USDA Forest Service); GAPR, General Archive of Puerto Rico; LAPR, Land Authority of Puerto Rico; MIPR, Misión Industrial of Puerto Rico; MUPR; Metropolitan University of Puerto Rico; MSJ, Municipality of San Juan; NOAA, National Oceanic and Atmospheric Administration; OPMPR, Office of Permits Management of Puerto Rico; PRDNRE, Puerto Rico Department of Natural Resources and the Environment; PRDTPW, Puerto Rico Department of Transportation and Public Works; PREQB, Puerto Rico Environmental Quality Board; PRNPC, Puerto Rico National Parks Company; PRPB, Puerto Rico Planning Board; SCSJEC, Special Commission of the San Juan Ecological Corridor; SDI, Sustainable Development Initiative; SJBEP, San Juan Bay Estuary Program; SC, Sierra Club; UPR, University of Puerto Rico; USACE, US Army Corps of Engineers; USGS US Geological Survey.

representatives, and other sectors to collaborate in identifying potential changes that could enhance or degrade the functioning of the watershed, identifying research problems and localities that required attention, and developing scenarios for watershed models (Figure 5).

A key challenge to building these collaborations was found in the scientific community. Although as we mentioned previously, the conceptual motivation from scientists was present, the institutional conditions to facilitate scientists to cross disciplinary boundaries were lacking. Unlike the increasing trend for interdisciplinarity in the mainland US context, the local academic institutional context imposes hard epistemological divisions between the natural sciences and the social sciences. Even more difficult is crossing the artificial boundaries separating science and society. To bridge these scientific visions and to improve communications we organized multi-stakeholder meetings, interdisciplinary workshops, and field trips with the explicit intent to have

natural and social scientists deliberate on their own frames and paradigms about the city, including the assumptions, beliefs, and expectations of their particular disciplines. These were crucial to ensure that not one discipline overpowered others in the framing of the research agenda and to develop the pluralistic epistemic community described next.

As it happened, the initial response we described in the first step decreased as some realized that the interdisciplinary and collaborative nature of this effort was more time and socially intensive than what they wanted or could participate in, and that it involved adaptations in their professions (e.g., learning and training in other disciplines). In the end, and as we will discussed later, an epistemic community resulted from the core natural and social scientists who were committed to a different research process and were willing to adapt. Two key factors were instrumental in managing and sustaining the group that emerged. One was the social competency of the Program Manager (part of her training as a doctoral student in sustainability) that allowed her to understand and mediate epistemological differences to find common ground. The other was the reputation and recognition of the Principal Investigator as a respected scientist by both natural and social scientists (both locally and nationally). Both were instrumental in maintaining core group cohesion and conflict resolution. The result of these efforts was a successfully funded proposal and research agenda for ULTRA-Ex that allowed us to study and produce knowledge about the city from multiple perspectives.

Figure 5. Images from the San Juan ULTRA-Ex participatory mapping workshops where multiple workshops identified areas of risks and values in the city or needing protection from development to protect watershed function. The bottom images show examples of the conservation scenarios that resulted from the participatory mapping workshops.

Collaborative knowledge production and integration

The approach presented thus far involved intensive social interactions and 'spaces' through a flexible and fluid arrangement for the scientists to build trust and legitimacy in the existing knowledge-action network. However, establishing norms and expectations is also necessary for creating an institutional structure conducive to collaboration. The work of building the institutional structure of our ULTRA-Ex was just as intensive as the research process itself, and this paid off when the time came to integrate and synthesize the various research components of the project. Focusing as much on questions of how we should organize ourselves and interact in doing the research helped us build a pluralistic epistemic community, one where the diversity of disciplinary perspectives and methodologies needs to be understood and is encouraged, not suppressed (Miller et al. 2011). The goal was not necessarily to develop a shared way of thinking (as in the way that Hass (1992) thinks of epistemic communities). Rather the structure we preferred was designed to embrace diversity and continuous deliberation of the concepts, assumptions, and methodologies different researchers were using and how they are integrated (or not) to the broader research objectives. In this way, the structure is meant to foster social learning and not necessarily consensus.

An example of this structure was the designation of research groups to focus on different scales of the system and on the intensity of the data collection process, instead of by disciplinary or thematic perspectives. We applied a framework suggested by Zimmerman et al. (2009) to guide social and ecological data sampling and integration using extensive (coarse level data usually at the watershed and city scales) and intensive (site specific data usually at the neighborhood or parcel scales) approaches. The extensive study explored the temporal and spatial relationships between social, infrastructural, governance, and biophysical processes in the RPRW based on historical information, new data collection and synthesis of vulnerability through spatial modeling at the level of the watershed. The intensive study involved gathering primary information about the preferences, attitudes, knowledge and valuation of RPRW residents as they relate to green (vegetation) and blue (e.g., streams) areas. Management decisions and resident choices at the household level were examined in relation to socio-economic factors. Intensive studies allowed us to address mechanisms that operate within urban systems using smaller spatial scales than those addressed at the watershed scale.

Both the extensive and intensive research groups were led by a paired team of natural and social scientists and were composed of scientists representing multiple disciplines. Training students from the natural and social sciences to work together to implement the projects was also a key objective for each research group. In addition, the Program Manager and the Information Manager, both experienced in working with collaborative groups, were instrumental to in building the necessary information infrastructure to foster integration and knowledge sharing among the research groups.

A challenge for this structure was to recognize when to 'open up' to allow diverse actors and perspectives into the research process, and when to 'close down' the process so as to move forward with the project and 'get work done'. A reflexive approach brings up an 'efficiency paradox' because it implies a balance between opening up and closing down (Voss and Kemp 2005). Opening up is necessary to allow in a diversity of ideas, knowledge, and values but this

brings greater complexity to the process of knowledge production. Closing down is necessary to do the work and have the ability to act, but the timing of closing may cause rigidity. Voss and Kemp (2005) argue that the issue is not a matter of either/or, but of doing both throughout the process. As such, we had a third research group to focus specifically on governance and decision-making. This group ensured explicit attention to our stakeholder and community networks as part of our research questions as well as maintained communication and engagement with stakeholders. This helped us recognize when 'opening up' was necessary during the research process (see Figure 3).

Boundary practices and hybrid objects

Boundary objects were particularly effective at helping build and maintain a plural epistemic community. Boundary objects are hybrid constructs that integrate scientific and political elements to aid negotiation among scientists and stakeholders with different interests and knowledge systems (Mieg et al. 2008; White et al. 2010). These objects can be material, such as maps, models, decision-support tools, or abstract, as in theoretical concepts that cut across multiple disciplines. The multiple tools that we developed turned out to be useful boundary objects in San Juan ULTRA-Ex. Our theoretical SES framework (Box 1 and Figure 2) served as a conceptual boundary object to 1) integrate across the myriad of things we were interested in from our respective disciplines and 2) transcend disciplinary boundaries by focusing on the SES problem and context.

Another example was the development of a network of sampling points across the watershed. Selecting sampling points across the watershed and city such that they met both natural and social science research criteria challenged us to articulate differences in expectations that disciplines have for collecting data, including qualitative data. For instance, ecologists and environmentalists were advocating for a sampling approach based on sub-watersheds, whereas social scientists and planners often use US Census geography as the starting point. This exercise took several meetings and deliberations and in the end we came up with a hybrid approach that considered physical, social, and statistical criteria for data collection. The approach consisted of a nested sampling scheme to address the multi-scale nature of our SES (Figure 6) (Seguinot-Barbosa and Hernández García 2011). In this way, the sampling network served as a boundary object for the scientists to deliberate and negotiate decisions about sampling, as well as interact in data collection and synthesis through common areas.

Synthesis, application, and adaptation

A primary objective was to synthesize knowledge about the system and move forward with the application of this knowledge. Ultimately we were asking, what do we know about the San Juan and the RPRW social-ecological systems? What story can we tell about the system's vulnerability, adaptive capacity, and sustainability? This required an intensive collaborative process to integrate the various components within the extensive, intensive, and governance projects, and most importantly, across these studies to develop an overall picture of the status and function of the social-ecological system. Once the various groups collected their data, we met in Synthetic Workshops to analyze and interpret results as a group, find consistencies or inconsistencies among findings, and highlight key messages. These workshops were very

intensive but they also helped individual researchers step back from their investigation and once again see the broader picture. It also assisted in the discussions we had with stakeholders during our symposiums where they also helped interpret the story that was emerging from scientific results.

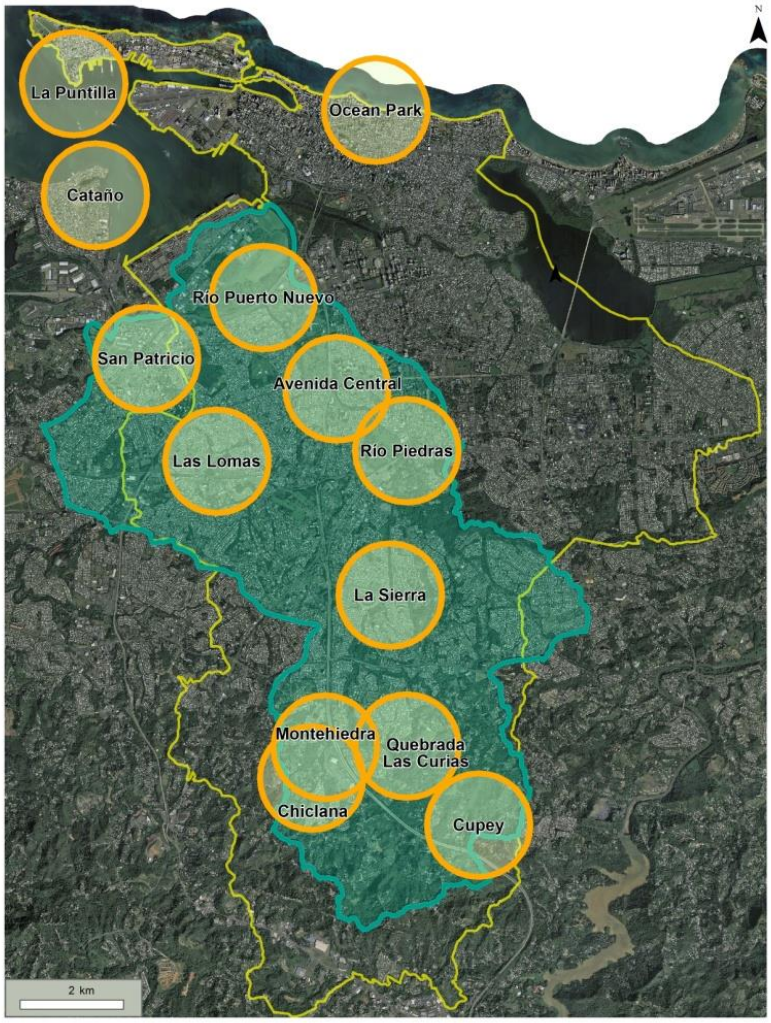

Figure 6. Social-ecological sampling grid for the RPRW and San Juan. The yellow boundary delineates the municipality and the colored area delineates the watershed and sub-watersheds of the RPRW. The 13 orange circles are the half-kilometer buffer surrounding each point (Seguinot-Barbosa and Hernández-García 2011).

Following the flexible knowledge-action network approach, we used multiple methods to communicate, share, and apply the scientific results with stakeholders and the broader public. For instance, during our Annual Meetings, in addition to sharing results through scientific presentations, we built in the knowledge acquired through a variety of educational activities targeted to different ages, such as photo and map exhibitions, oral history documentaries, environmental fairs, workshops at schools, bulletins, and information sign posts throughout the watershed that are linked to our website to access scientific information for that particular site. The function of our Community Outreach Coordinator, a long-time resident and civic organizer in the Río Piedras community, was crucial to identify mechanisms, 'spaces', and outlets for engagement and communication with the broader public that fit the local context. Not only was he well connected to local networks and served as a key node, but he was adept at using community-based cultural activities, such as the arts, as a way of engaging interactions between

the public and scientists. Figure 7 shows an image of a recently painted graffiti mural to honor a shrimp species that was recently rediscovered in the Río Piedras river. The artist attributes his knowledge about the species to interactions he had with our Community Outreach Coordinator.

Figure 7. Graffiti mural of shrimp species, *Palaemon pandaliformis*, rediscoverd in the Río Piedras, a new record for Puerto Rico. Muralist is Edgardo Larregui.

We found that a diverse and flexible process of engagement that follows local dynamics and ways of organizing, rather than a prescriptive approach to transdisciplinary practice, was also conducive to stimulate information flow and mutual learning with stakeholders. After several years of trying unsuccessfully to engage the previous municipal administration in the San Juan ULTRA-Ex, the new administration reached out to us recently to establish a commission for knowledge sharing and producing knowledge about the RPRW. The factors shaping the relationship between municipal decision-makers and ULTRA-Ex are complex. Indeed, some are shaped by historical science-policy interactions beyond ULTRA-Ex and the scope of this paper. Yet, one factor that facilitated our relationship with the new administration was that our credibility was established prior to them taking office and it was they who set up the collaborative arrangement that fit their needs. This arrangement has also allowed knowledge to feed back to the scientists, as we are now aware of emerging concerns and research needs for the Municipality. Thus we are now adapting our research agenda and focusing research efforts on flood hazard and storm water management in the RPRW, including the role of green infrastructure and ecosystem services. Our network approach allows us to still maintain a core research program on the overall SES conditions of the watershed, while also activating new researchers, graduate students, and stakeholders to address specific applied issues that have urgency to the city.

DISCUSSION AND CONCLUSION: CHALLENGES IN BUILDING KNOWLEDGE-ACTION NETWORK FOR URBAN SUSTAINABILITY

We have outlined the knowledge-action network that emerged from the development of the San Juan ULTRA-Ex to address the vulnerability and sustainability of this urban social-ecological system. We employed a variety of engagement and collaborative practices, methods and tools to facilitate the integration among scientific, stakeholder, and citizen knowledge and framings in analyzing the vulnerability of the city and visions for the future. Multiple points of interactions with stakeholders in different social 'spaces' allowed for a diverse and flexible process of identifying actors and sectors and adapting engagement processes to their particular needs and concerns. While our approach was influenced by transdisciplinary research principles, in practice we developed an eclectic approach of varied social interactions to fit our specific context. Our goal was not to strictly follow a prescribed model for transdisciplinary research, but rather to infuse the local governance context with collaborative knowledge events in multiple sites and at multiple times. As scientists, our most important outcome was the recognition that these social interactions were just as important for analytical rigor in social-ecological system science as are technical tools.

We have also experienced three key challenges to building a diverse and fluid knowledge-action network. One is the balancing of 'opening up' and 'closing down' the process. In other words, balancing inclusiveness of knowledge with efficiency in knowledge generation. We found that an iterative process of opening up was important. For instance, broad inclusiveness is crucial in the beginning and final phases of a project, therefore using methods that allow greater representation and deliberation of ideas and ways of seeing are more appropriate at these stages. Other points may be more technical and may require a specific set of expertise to review and provide critique, such as smaller extensive and intensive research groups. At times, we had to recognize that the timing and structure was beyond our control, such as with the participation of the Municipality, and let these relationships run their course. Most importantly, the recognition of this balancing act was a crucial first step in building a reflexive and adaptive process.

Another challenge we encountered was in managing diverse boundaries and expectations, especially as they relate to the perceptions that participants have of the roles of science and politics. As Vogel et al. (2007) note, it is during the multiple and diverse points of interactions when a problem is negotiated and framed that power relations among actors come into focus. In our case we found that while in practice these boundaries are blurred (e.g., framing the research agenda was as much political as scientific), there is a certain amount of comfort in maintaining the perception that science and politics are separate domains in governance. For instance, we found that collaboration with some stakeholder groups, such as NGO's, was more productive when we assumed a 'research' role and had them take on the 'action' role so as to not overstep in their turf. This also facilitated local capacity building efforts.

Awareness of these boundaries and expectations from the onset of the process ensures that communications pathways are open and differences are negotiated throughout the process. One of the ways we addressed this from the start was with the knowledge-action system analysis. Few studies or efforts on transdisciplinary research exist that analyze pre-existing institutional

dynamics, including politics of expertise that may pose potential barriers, before investing in a new intervention. The KASA approach used an inclusive definition of knowledge and the actors that produce and use it. Breaking down knowledge stereotypes is necessary, meaning that we do not make *a priori* assumptions of who are the experts, producers and users of knowledge, but recognize that there are broader civic epistemologies at play as well. Because the way we conceptualize the co-production of knowledge can strongly shape how we design knowledge-action systems (Muñoz-Erickson 2014a), this knowledge about knowledge became crucial to build a reflexive and adaptive knowledge-action network for San Juan ULTRA-Ex.

Lastly, another crucial challenge to a knowledge-action network was sustaining its fluid structure and maintaining social relevance. The network-like structure sought to keep the program from being viewed as a single formal organization and better reflect the multi-actor governance landscape, also has its pitfalls. A loose network can dissolve if adequate leadership, goals, and norms are not well established and communicated (Vogel et al. 2007). However, it is this flexibility that helps link existing knowledge and facilitate flow where it is needed, thus allowing local stakeholders to feel ownership of the process. A future challenge then is to build knowledge-action networks that have the leadership, established roles, and motivation to maintain a level of stability, while also remaining open and flexible to recognize when the external system is changing. The network must recognize when a new network configuration is needed to reflect the changing social-ecological context and political needs with new actors, new research agendas, and new social arenas if appropriate.

Monitoring the knowledge-action network as it changes through time will be necessary to address the challenges we have discussed, and to measure the outcomes of the network on sustainability governance. The implementation of the KASA as a monitoring and evaluation tool at multiple time periods of this long-term research program will allow us to examine how the networks, knowledge systems, visions and frames of the various actors, including San Juan ULTRA-Ex participants, are changing in the future. Following the adaptive and reflexive goals of the transdisciplinary approach, we view this process as an experiment to track and evaluate its outcomes. Although great effort was directed upstream of the research process, these practices do not represent an endpoint. The iterative implementation and monitoring of these practices are necessary to track our effect on the system and be reflexive about the way we are understanding, addressing, and representing the social-ecological system. They are intrinsic to an adaptive knowledge-action system.

The preliminary stages of the San Juan ULTRA-Ex knowledge-action network makes it difficult to yield generalized lessons about this particular approach and its effects in governance for sustainability in San Juan. Yet, the challenges and the ways that we have overcome these have provided us with insights about factors that impede and facilitate social learning. Our experience points to challenges and opportunities of building transdisciplinary research capacities in cities, especially for tropical urban social-ecological systems. Moving forward, our hope is that this approach not only to generates important and useful scientific knowledge for the San Juan, but that it is also a force in governance to promote overall adaptive capacity and innovation potential for healthy and livable cities, particularly in a coastal urban setting vulnerable to climate changes.

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