Opportunities and constraints related to the production and use of knowledge for climate change adaptation efforts in urban, energy, and water systems

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Kathleen Marie Ernst
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DEDICATION

In memory of my Grandma Rita, who taught me that writing is a daily practice that, if done well, could make someone’s day.

This work is dedicated to my partner, Sasha, our children Selah and Leon, and our neighbors at the edge of town in Norrköping – I hope you have moved out of the one-room-cabins and I am so thankful you made it to Sweden.

Thanks to all of you for teaching me about resilience and adaptation.

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ABSTRACT

Urban, energy, and water system decision-makers are increasingly focused on preparing for the impacts of climate change. These impacts combine with social, economic, and environmental changes to create nuanced localized effects across systems. Climate change adaptation efforts have largely been organized by sector, even though coupled systems approaches could identify negative consequences and mutually-beneficial actions that occur across systems. These insights are missed when coupled systems are not considered in adaptation efforts. However, constraints inhibit adaptation processes within coupled systems. For example, United States energy-water nexus adaptation is constrained by insufficient data and information, path dependence, and institutional fragmentation and disorganization. Many adaptation decision-making constraints have been identified, but less is understood about what inhibits knowledge production for adaptation. Climate knowledge production environments in Sweden are analyzed in Chapter II to identify constraints. This analysis reveals that climate knowledge producers in Sweden encounter constraints related to knowledge production and dissemination; stakeholder engagement; and institutional, professional, and funding environments. These climate knowledge system production constraints can exacerbate or create new constraints within adaptation decision-making processes. Exactly how knowledge systems influence adaptation is unclear, because the evaluation of knowledge systems for adaptation has rarely been pursued. This lack of evaluation persists, despite the proliferation of knowledge systems for adaptation decision-making to enhance resilience. In Chapter III, a knowledge system evaluation framework is presented and applied to two urban resilience knowledge systems to address this concern. The knowledge system evaluation framework enables assessment of the transferability, scalability, and use of a knowledge system. The findings in this dissertation provide insights focused primarily on the production and use of knowledge for climate change adaptation. Specifically, reflexivity of the knowledge production process is necessary to improve knowledge systems for adaptation; and coupled systems, tradeoffs, and co-beneficial opportunities need consideration or acknowledgement within knowledge systems to avoid negative consequences and missed co-benefits. Finally, if creating effective knowledge for adaptation is the goal of knowledge-making institutions, then they should adapt their frameworks, incentives, plans, and strategies to support the development of actionable information for adaptation decision-making processes.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Urban, energy, and water system decision-makers are primarily focused on complying with policies and regulations, and ensuring that their systems are now, and will remain operable in the future (de Bremond et al., 2014; Porter et al., 2015; Treuer et al., 2017). These goals increasingly necessitate the consideration of how climate changes will combine with social, economic, and environmental changes to impact the systems that decision-makers manage. Therefore, climate change adaptation (referred to throughout this dissertation as 'adaptation') has emerged, especially over the past decade, as a risk management strategy to cope with the adverse impacts of climate change (Mimura et al., 2014).

While adaptation efforts have increased, specific policies and regulations for adaptation at the state and national level largely remain voluntary and piecemeal, and typically lack specific guidance and funding (Arnott et al., 2016; Bulkeley, 2010; Porter et al., 2015). Also, climate change impacts occur disparately across systems (Sovacool and Sovacool, 2009); vulnerabilities often remain unseen for decision-makers who rely on historic information for planning (Bazilian et al., 2011); and decision-makers are typically more responsive to policies, regulations, or economics and not climate trends when planning for the future (Adger et al., 2005; O'Neill and Handmer, 2012; Preston, 2013). However, when economics are the main criteria for decision-making, adaptation appears unnecessary prior to 2050 for many systems (Adger et al., 2005; O'Neill and Handmer, 2012; Preston, 2013). These factors, in addition to path dependence, create systems that are difficult to change without policies or regulation.

In the absence of elements that decision-makers commonly respond to, many research-based efforts have emerged to provide knowledge to support adaptation decision-making efforts (Cash et al., 2003; Dilling and Lemos, 2011; Moss et al., 2014; Vaughan and Dessai, 2014). Like most of the adaptation actions that have occurred, much of the information produced for adaptation decision-making has been organized by sector (Hughes, 2015; IPCC, 2014; Melillo et al., 2014; Mimura et al., 2014; Woodruff and Stults, 2016). This focus on sector-specific information and planning for adaptation does not consider the interdependencies and overlaps of related systems which can lead to maladaptation, tradeoffs, ineffective outcomes, and missed co-beneficial adaptation strategies (Ernst and Preston, 2017). These outcomes are identified and discussed in the first chapter of this dissertation: *Adaptation opportunities and* *constraints in coupled systems: Evidence from the U.S. energy-water nexus* which was published in January 2017 in *Environmental Science & Policy.*

In Chapter I, the United States (U.S.) energy-water nexus is used as a case study of coupled systems to identify constraints to adaptation that exist when coupled systems are considered within adaptation decision-making processes. Specifically, insufficient data and information, path dependence, and fragmented and disorganized institutions are identified as constraining factors limiting coupled systems adaptation efforts within the U.S. energy-water nexus (Ernst and Preston, 2017).

Next, Chapters II and III focus specifically on the regularly identified constraint to adaptation – *insufficient data and information* (Amundsen et al., 2010; Biesbroek et al., 2011; Ekstrom and Moser, 2014; Ernst and Preston, 2017; Huitema et al., 2012; Jantarasami et al., 2010; Jones and Boyd, 2011). Specifically, Chapter II, *Identifying climate knowledge systems production constraints in Sweden,* explores the limitations to producing actionable information for adaptation decision-making processes. The climate knowledge system production process in Sweden is analyzed in Chapter II using participant observations and semi-structured interviews at climate knowledge system-producing institutions across Sweden including the Swedish Meteorological and Hydrological Institute, the National Center for Climate Change Adaptation (for Sweden), and the International Project Office for Coordinated Regional Downscaled Climate Information. Data was collected over ten months to identify constraints that climate knowledge system producers in Sweden face as they endeavor to create actionable information for urban, energy, and water system decision-makers. Climate knowledge system producers (referred to in this dissertation as 'knowledge-producers') face constraints related to producing and disseminating actionable information; stakeholder engagement; and working within funding, professional, and institutional environments that are not well-aligned to the goal of creating actionable information for decision-makers at the local or regional level. Chapter II was submitted to the journal *Global Environmental Change* on August 5th, 2018.

Chapters I and II of this dissertation, and many other publications, identify numerous limitations within existing climate knowledge systems to inform adaptation decision-making processes and enable adaptation actions that are effective across systems (Cash et al., 2003; de Bremond et al., 2014; Dilling and Lemos, 2011; Kirchhoff et al., 2013; Liu et al., 2008; Vaughan et al., 2016; Wall et al., 2017). However, knowledge systems for adaptation have not been evaluated despite numerous calls to do so (Cash et al., 2003, 2006; Miller et al., 2010; Moss, 2016; Muñoz-Erickson et al., 2017; “Validation required,” 2010). In response to the call for the evaluation of climate knowledge systems, a methodological framework that analyzes climate knowledge systems is developed and applied to two climate knowledge systems focused on building urban resilience in Chapter III, *Applying the knowledge system evaluation framework to two urban resilience cases in the United States.* The knowledge system evaluation (KSE) framework assesses knowledge system alignment to resilience, the robustness of a knowledge system, the decision-relevant scales within a knowledge system, and the use of a knowledge system over time. The KSE framework is applied to the Urban-Climate Adaptation Tool (referred to in this dissertation as the ‘Urban-CAT’) and the Maine Flood Resilience Checklist (referred to in this dissertation as the ‘Maine Checklist’) to test its applicability as an analytical entry point for analyzing knowledge systems for adaptation and to offer insights regarding the extent to which knowledge systems influence decision-making processes and enhance urban resilience. Chapter III will be submitted to the journal *Environmental Science & Policy* in August 2018.

Each of the three chapters are presented next in the form of three separate manuscripts intended for publication followed by a short conclusion, a reference list, and the appendices for the entire dissertation.

CHAPTER I

ADAPTATION OPPORTUNITIES AND CONSTRAINTS IN COUPLED SYSTEMS: EVIDENCE FROM THE U.S. ENERGY-WATER NEXUS

A version of this chapter was originally published by Kathleen Marie Ernst and Benjamin L. Preston:

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This article was submitted to the peer-reviewed journal *Environmental Science & Policy* in September 2016, then revised and resubmitted in January 2017. The revised submission was published in January 2017. All work for the article was completed by Kathleen Marie Ernst under the supervision and advisement of Benjamin L. Preston.

Abstract

Over the past decade, adaptation has emerged as an important risk management strategy to address climate change and avoid adverse consequences. These endeavors overwhelmingly focus on actions within sectors and thus fail to account for coupled effects across systems. This paper focuses on adaptation constraints that arise from the interdependencies of coupled systems, and the opportunities that emerge when adaptation strategies integrate such interdependencies. Three general constraints to adaptation in coupled systems are identified and detailed using evidence from the United States energy-water nexus: insufficient data and information, path dependence, and institutional fragmentation and disorganization. Adaptation constraints within the energy-water nexus are especially difficult to avoid or overcome at local and regional scales owing to complex, but poorly integrated, governance structures. This indicates that some degree of national coordination is an important enabling condition to overcome constraints and enable adaptation throughout the energy-water nexus.

Introduction

Over the past decade, adaptation has emerged as an important risk management strategy to address climate change and avoid adverse consequences (Mimura et al., 2014). This was highlighted in the 2015 Paris Climate Change Agreement, which acknowledges adaptation as an essential response to climate change to protect people and ecosystems (UNFCCC, 2015). While adaptation efforts have increased recently, they generally remain focused on discrete sector-specific actions (Mimura et al., 2014). For example, numerous climate change publications including the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report (AR) and the United States (U.S.) National Climate Assessment organize adaptation by sector (IPCC, 2014; Melillo et al., 2014), as do various adaptation plans (Hughes, 2015; Woodruff and Stults, 2016).

Inherent limitations to applying a sector-specific approach in the pursuit of adaptation exist (Adger et al., 2005). The concept of a sector is a convenient heuristic for organizing adaptation efforts and aligning information and actions to stakeholder groups, economic indicators, or jurisdictional elements. In practice, however, sectors represent complex systems of physical, social, political, and economic processes. These systems are often coupled – they interact, overlap and have effects on the inputs, constraints, and outcomes of each other. For example, the coupling of energy and agriculture systems is evident in the environmental, economic, and social consequences that stemmed from the implementation of U.S. federal incentives for bioenergy (Preston et al., 2015). These incentives exacerbated competition for corn which led to rapid increases in ethanol-related corn production, particularly compared to food-related corn production, and contributed to decade-level high prices for corn and ethanol during the 2012 U.S. drought (Preston et al., 2015).

This paper focuses on adaptation constraints that arise from the interdependencies of coupled systems, and opportunities that emerge when adaptation strategies integrate such interdependencies. This paper argues that such interdependencies are the norm, not the exception, and thus the dominant framing of adaptation responses as sector-specific is a “failure of understanding” that must be addressed in the development of robust adaptation responses (Preston and Kay, 2010 based on Clark, 2002, p. 115). In contrast, reorienting framing toward *holistic adaptation,* or adaptation concerned with complete systems, has the potential to identify mutually beneficial adaptive responses to climate change and to produce more effective outcomes than adaptation focused on a single system.

This paper proceeds with a theoretical review of consequences that arise when adaptation planning does not consider coupled systems. This is followed by a review of the foundational literature on adaptation constraints to establish context for subsequent discussion. The practical implications of coupled systems for adaptation are then explored by using evidence from the U.S. energy-water nexus (EWN). The paper concludes with a discussion of pathways to overcome constraints and pursue opportunities related to adaptation implementation within the U.S.-EWN and lessons that can be applied to adaptation more broadly.

Adaptation within coupled systems

Despite the need for a holistic framing of adaptation, there is little academic literature and few practical examples detailing adaptation approaches within coupled systems (Moser, 2009). Moser (2009) notes widespread acknowledgement that cross-sector adaptation is necessary but that most entities have postponed this challenge. Examples of adaptation efforts show the narrow focus of adaptation implementation: Norwegian municipalities used the past to guide adaptation efforts (Amundsen et al., 2010); U.S. federal lands pursued adaptation within units without integration (Jantarasami et al., 2010); and Swedish municipality efforts lacked sectoral coordination (Storbjörk, 2010). Failure to consider coupled systems in adaptation efforts can result in four consequences: unrecognized tradeoffs, maladaptation, ineffective outcomes, and missed ancillary or co-benefits of strategies.

Externalities lead to unrecognized tradeoffs when adaptation efforts are not holistic. The IPCC-AR5-Working Group 2 reported examples of potential tradeoffs that may occur when adaptation planning does not consider multisystem interactions (Table 1). For example, while increased pesticide use may adapt crops to new conditions, it also creates externalities in related systems including increased: costs for farmers, pollutants to the environment, human exposure to pollutants, and greenhouse gas (GHG) emissions (Klein et al., 2014). The distribution and severity of unrecognized tradeoffs displaced onto related systems may be unequal and unjust which will exacerbate existing inequalities or create new ones.

A second consequence of sector-specific adaptation is maladaptation, which is defined as adaptive actions that adversely impact or increase vulnerability in other systems or groups (Barnett and O’Neill, 2010, p. 211). Barnett and O’Neill (2010) use the construction of the Wonthaggi desalination plant for Melbourne to detail five types of maladaptation: 1) the energy-intensive desalination process

Table 1 Potential adaptation tradeoffs: selected examples from Table 16-2 in Chapter 16 of the IPCC-AR5 (Klein et al., 2014, p. 918)

Sector	Adaptation Objective	Adaptation Option	Real/Perceived tradeoff
Agriculture	Maintain yields; suppress pests/invasives	Increase chemical fertilizers/ pesticides	Adverse impacts of pesticide use on non-target species; increased: GHG emissions; human exposure to pollutants; discharge of nutrients/chemical pollution
Biodiversity	Enhance regulations for at-risk species	Protect critical habitat	Addresses secondary not primary pressures; property rights concerns; regulatory barriers to development
Coasts	Protect assets from inundation/erosion	Sea walls	High direct/opportunity costs; equity concerns; coastal wetland ecological impacts

increases GHG emissions; 2) the contested Aboriginal-owned location of the plant and increased utility costs overburden vulnerable populations; 3) the aforementioned social costs and environmental costs such as reduced flows of the Murray river create opportunity costs; 4) the use of seawater for desalination masks freshwater availability and undermines conservation efforts; and 5) the scale and permanence of the project create path dependence. In Melbourne, the sole-pursuit of ensuring water availability is achieved at the expense of related systems that must then manage the resultant maladaptation. When multiple, related systems pursue adaptation singularly, maladaptations transfer onto other systems thereby increasing vulnerability and not effectively reducing climate risk across systems. Additionally, when adaptive actions that generate maladaptation are coupled, effects on related systems become even more pronounced.

The case of the Wonthaggi desalination plant also details ineffective outcomes of adaptation focused on a single system. For one, the plant has never been used – the first water order was announced in March 2016 amid calls that it was unnecessary, and as of December 2016, the plant has not initiated the month long process to begin operation (Willingham, 2016). Despite never operating, plant owners are paid 1.8 million dollars per day to ensure operability (Willingham, 2016). While the plant is often referred to as a water “insurance policy” (Willingham, 2016), other measures that consider coupled systems like pursuing treated wastewater, captured rainwater, and conservation could enable more effective water savings and ensure water availability for less cost (Barnett and O’Neill, 2010) even when shortages are not dire.

In addition to negative consequences of single-system adaptation, ancillary or co-beneficial adaptation opportunities are often missed. For one, low-regrets and demand-management actions are frequently overlooked in favor of supply-management and infrastructure-based actions (Pittock, 2011). Emphasizing the latter neglects opportunities to lessen system and resource demand through conservation or efficiency measures. For example, pursuing energy efficient retrofitting in U.S. homes could reduce household energy demand by as much as 40% (Council on Environmental Quality, 2009). These efforts have multiple co-benefits including: reduced GHG emissions “by up to 160 million metric tons annually”; potential annual cost savings of 21 billion dollars on household energy bills (Council on Environmental Quality, 2009); more jobs (U.S. building energy efficiency investments could create “3.3 million cumulative job years of employment” – Fulton, 2012, p. 3); avoided energy supply expansions; and lessened water demand for electricity generation. Second, considering coupled systems in adaptation helps identify opportunities for synergistic technologies like utilizing waste heat “for desalination and combined heat and power”, using water systems “for energy storage or electricity demand management”, and capturing “energy generation in man-made water conduits” (U.S. D.O.E., 2014, p. x, 129). While holistic adaptation could help avoid negative consequences and realize multisystem benefits, it will also experience constraints.

Current discourse on adaptation constraints

The concept of adaptation constraints has emerged within the climate change adaptation literature to describe “*factors that make it harder to plan and implement adaptation actions*” (Eisenack et al., 2014; Klein et al., 2014, p. 907). The term ‘constraint’ is often used to describe an impediment to adaptation, while ‘barrier’ and ‘obstacle’ are contextualized similarly (Klein et al. 2014, p. 906). Constraints are essentially simplified constructs that help clarify why adaptation is difficult (Biesbroek et al., 2014). Constraints are not exclusive to adaptation and often emerge within complicated policy-making situations (Biesbroek et al., 2014).

Constraints originate from three fundamental sources: the actors that are adapting, the context in which adaptation occurs (e.g. the socioeconomic, environmental, and institutional details of the situation), or the system at risk to climate change where the adaptation occurs (Moser and Ekstrom 2010; Ekstrom and Moser 2014; Eisenack et al. 2014). Often the agency, scale, and scope of adaptation dictates which constraints are encountered (Adger et al., 2009; Moser and Ekstrom, 2010). Constraints occur at different stages of adaptation and are not fixed in time; rather, as some are overcome, others may emerge and a few become persistent (Porter et al., 2015). For example, British local governments prioritized climate information constraints in the early 2000s, but years later funding and staff deficits were identified as the most significant adaptation constraints (Porter et al., 2015).

Given a broad range of constraints are identified in the literature, some effort has been made to structure the discourse through categorization (Biesbroek et al., 2013; Eisenack et al., 2014). Table 2 provides a snapshot of selected adaptation constraints from recent literature. This table was constructed iteratively using a convenience sample from relevant peer-reviewed literature, government reports and a Google Scholar™ search for articles published from 2010-2015 with “barriers” OR “constraints” AND “adaptation” in the title that yielded 151 results when citations were excluded. Google Scholar was chosen because comparatively, it captures a wider array of literature than other databases (Preston et al., 2015a). In light of Porter et al. (2015) and the timeliness of constraints, 2010 was chosen as the earliest publication year in an effort to identify recent adaptation constraints. The table itself was iteratively constructed. Constraints were identified while reading articles and then were grouped together in a table. The search and resultant table illuminate the breadth of adaptation constraints mentioned in recent literature but are by no means exhaustive of relevant sources or adaptation constraints.

Table 2 Barriers to adaptation mentioned in selected literature from 2010-2015.

Barrier	Example/Description	Citation(s)
Adaptation Deficits		
Lack of resources/information /knowledge/data	Stakeholders desire useful/understandable information (Bierbaum et al., 2013).	Amundsen et al., 2010; Biesbroek et al., 2011; Ekstrom and Moser, 2014; Jantarasami et al., 2010; Jones and Boyd, 2011; Moser and Ekstrom, 2010; Porter et al., 2015; Storbjörk, 2010
Lack of willingness to act/change	Unwilling to change strategies despite recognizing changes (Jones and Boyd, 2011).	Jantarasami et al., 2010
Lack of awareness/communication	Unclear "responsibility, leadership…lack of agreement over options and goals" (Ekstrom and Moser, 2014, p. 65).	Biesbroek et al., 2011; Porter et al., 2015; Storbjörk, 2010
Lack of knowledge of climate change impacts	Municipalities wanted information on impacts in unfamiliar situations (Amundsen et al., 2010).	Ekstrom and Moser, 2014; Porter et al., 2015; Storbjörk, 2010
Lack of capacity/continuity (knowledge loss)	"Years pass between…floods and risks are forgotten…we have been taken by surprise many times" (Storbjörk, 2010, p. 245).	Amundsen et al., 2010; Carmin et al., 2012
Lack of integrated/cross-sectoral planning	Inadequate contact between officials/units across sectors (Storbjörk, 2010).	Amundsen et al., 2010
Lack of stakeholder consideration	Opposing views/erosion of trust enabled the Rotterdam "Water Plaza" cancellation.	Biesbroek et al., 2014
Decision-Making Barriers		
Stakeholder fear/distrust	Aboriginal communities fear views are not adequately considered.	McNamara et al., 2012, p. 12
Focus on historical trends	Cities without historical experience of impacts are less likely to adapt.	Amundsen et al., 2010; Storbjörk, 2010
Conflicting climate information/decision-making timescales	"Changes in the climate system and…impacts are difficult to relate to the dynamism of societal changes and short-termism in decision-making."	Biesbroek et al. 2011: 4
Perceived opposition	Insufficient public support for adaptation.	Jantarasami et al., 2010
Previous conflicts	"Actors interpret…events that happened in previous projects…as priors to other decision-making processes"	Biesbroek et al., 2014, p. 114
Safety/public health concerns	Drowning concerns regarding the Rotterdam "Water Plaza".	Biesbroek et al., 2014
Institutional Barriers Biesbroek et al., 2011; Eisenack et al., 2014; Ekstrom and Moser, 2014; Jantarasami et al., 2010; Jones and Boyd, 2011; Moser and Ekstrom, 2010		
Uncertain/unclear roles/responsibilities	Administrative re-organization split erosion management creating confusing/hindering action	Amundsen et al., 2010; Biesbroek et al., 2011

Table 2. Continued.

Barrier	Example/Description	Citations
Fragmentation/un-coordination	Deficit of connection/coordination of institutions/organizations/individuals/policies (Biesbroek et al., 2011 p. 6).	Biesbroek et al., 2013; Evans et al., 2012
Void (Lack of leadership/unclear guidance)	Deficit of institutions enabling/facilitating/stimulating adaptation (Biesbroek et al., 2011, p. 5).	Ekstrom and Moser, 2014; Moser and Ekstrom, 2010; Storbjörk, 2010
Risk-aversion	Gendered risk perceptions enabled reluctance to accept aid (Jones and Boyd, 2011).	Porter et al., 2015
Operating procedures	Moving/reintroducing populations go against U.S. National Park Service operating procedures (Jantarasami et al., 2010).	Storbjörk, 2010
Cultural/Social Barriers		
Attitudinal	Opting to wait-and-see/inaction due to hurt political interests (Ekstrom and Moser, 2014).	Eisenack et al., 2014; Porter et al., 2015
Socially constructed gender/race/ethnicity/ class/caste barriers	Limited political power/land access increased Janajati caste member's vulnerability to flooding.	Jones and Boyd 2011
Legal Barriers		
External environmental laws	Some land managers feel the U.S. Endangered Species Act hinders options.	Jantarasami, Lawler, and Thomas 2010
Outdated management plans	Inadequate Murray-Darling Basin water-sharing inter-flood interval guidelines.	Jenkins et al., 2012
Land ownership mosaic	Ownership of land alters the governance of land.	Jantarasami, Lawler, and Thomas 2010: 8
Financial/Economical Barriers	Dalit caste members lack access to loans/assistance (Jones and Boyd, 2011).	Amundsen et al., 2010; Eisenack et al., 2014; Moser and Ekstrom, 2010
Market barriers	Global market integration creates costs.	Evans et al., 2012
Technological Barriers	Some technologically advanced options may be beyond planner's knowledge creating uncertainty (Amundsen et al., 2010).	Jones and Boyd, 2011
Political Barriers	Elected officials may delay adaptation because of costs/complexities/perceived consequences (Eisenack et al., 2014).	Amundsen et al., 2010; Ekstrom and Moser, 2014; Moser and Ekstrom, 2010

Coupled systems constraints to adaptation: The U.S. Energy-Water Nexus

Energy and water systems are inextricably linked. Most forms of energy production need water, and water distribution and treatment is dependent on access to available and affordable energy (Goldstein et al., 2008). The U.S.-EWN is complex and spatially varied, with distinct regional differences (Tidwell et al., 2014a, 2013) that are dependent on multiple factors including: energy demand and production, water demand and supply, population density, use characteristics, energy fuels, infrastructure, biophysical characteristics, policies, regulations, and management practices (Tidwell et al., 2013). U.S.-EWN connections demonstrate the complicated nature of coupled systems and highlight the need to pursue adaptation holistically.

Adaptation constraints within the U.S.-EWN are seemingly endless and can easily become over-contextualized. This paper does not attempt to identify every adaptation constraint in the U.S.-EWN. Rather, this paper concentrates on constraints that are present across, or emerge from, the U.S.-EWN. In other words, constraints attributed to the interaction of systems. This focus aligns with the current call within adaptation literature to move towards generalized approaches that produce outcomes across cases to better inform adaptation (Biesbroek et al., 2013; Eisenack et al., 2014; Ekstrom and Moser, 2014; Moser, 2009; Moser and Ekstrom, 2010). *General adaptation constraints* are present across systems, are difficult to solve at local or regional scales, and require multilevel governance approaches to overcome. When overcome, general adaptation constraints can potentially eliminate multiple context-specific constraints and enable adaptation decisions in energy, water, urban and agriculture systems. Three general adaptation constraints prominent in the U.S.-EWN are discussed next.

Insufficient data and information

Data and information needs are frequently highlighted as constraints to adaptation (see Table 2), emphasizing a broad need for information across systems. Insufficient data constraints within the U.S.-EWN involve missing, unconsolidated, conflicting, uncertain, proprietary, and confidential data challenges (Goldstein et al., 2008; Hussey and Pittock, 2012; Macknick et al., 2011; Tidwell et al., 2014b; U.S. D.O.E., 2014, 2011). Hussey and Pittock (2012) note that nearly all articles in a EWN special issue of *Ecology and Society* cite data issues as major impediments to research and decision-making. Additionally, Stillwell et al. (2011) and Perrone et al. (2011) identify data barriers as their largest obstacle for EWN studies in the state of Texas and the city of Tucson.

Data gaps exist across the U.S.-EWN particularly regarding water consumption, energy use in water services, hydraulic fracturing, saline and brackish aquifers, stream flow, annual/monthly time series water demand, and hydropower operation; as well as population, industry, agriculture, climate, environment, and energy projections (U.S. D.O.E., 2014). Many public U.S.-EWN data are difficult to integrate because data are typically collected by an agency for a specific purpose, and are often outdated, aggregated, or unstandardized (Goldstein et al., 2008; Perrone et al., 2011). For example, the U.S. Energy Information Administration (EIA) relies on power plants to report water use without providing reporting standards. These data are incomplete, inaccurate (GAO, 2009a), and do not correlate with calculations, particularly at regional levels, largely due to unreported and low-quality data (e.g. standard water use recording mechanisms are not required; estimates are used when data are lacking but no estimation methodology is used/documented; combinations of fuel/cooling technologies are unaccounted for) (Averyt et al., 2013). Additionally, certain fuel technologies, cooling systems, and combinations thereof lack adequate water use calculation methodologies (Macknick et al., 2011). The inclusion of these data into models increases uncertainty, and may be counterproductive, particularly at local and regional scales.

Sharing data across the U.S.-EWN has complex human dimensions. First, difficulties arise due to the proprietary and confidential nature of some data (Goldstein et al., 2008; U.S. D.O.E., 2014). For example, reservoir data are necessary for basin-scale models, but these data are often classified or inaccessible (U.S. D.O.E., 2014). Additionally, some consulting companies hinder data sharing across the U.S.-EWN by claiming ownership over information, some of which is explicitly public (Goldstein et al., 2008). Competing interests also stall data sharing – many water sector stakeholders believe that sharing pumping and storage data creates disadvantages when negotiating with other water providers (Goldstein et al., 2008). When data are shared, it is often via personal relationships on a case-by-case basis (Goldstein et al., 2008). These practices reinforce existing affiliations and conflicts within the U.S.-EWN and inhibit research, model development, and the creation of information for decision-making.

Information-related constraints within the U.S.-EWN principally relate to the production and utilization of information. While a proliferation of climate adaptation information is available, this knowledge may be unhelpful when actors require specific information for decision-making (de Bremond et al., 2014; Nordgren et al., 2016). Typically, adaptation information is organized by sector in assessment reports focused on hazard descriptions and their potential consequences that are then funneled to decision-makers (Cash and Moser, 2000; de Bremond et al., 2014; Nordgren et al., 2016). Sorting through this uncoordinated information and finding much of it un-usable for specific decisions may hinder adaptation action (Nordgren et al., 2016). Additionally, evidence suggests that the "models, tools and methods developed by the research community have either not sufficiently evolved or have not been effectively delivered to guide adaptation" (de Bremond et al., 2014; Klein and Juhola, 2014; Preston, 2013; Preston et al., 2015b, p. 482). Conventionally, climate information research assumes that translation for decision-making is unnecessary because information is "useful and usable" (Dilling and Lemos, 2011, p. 682); however, in practice, conceptual divides between stakeholders and researchers exist and can hinder understanding (Feldman and Ingram, 2009; Meerow and Stults, 2016). For example, adaptation research prioritizes vulnerability assessments or general plans; whereas energy stakeholders want information that incorporates specific needs and multiple potential factors, driving forces and policy responses at decision-relevant scales to be actionable (de Bremond et al., 2014; Nordgren et al., 2016). Without these elements of utility, the decision-maker will not utilize the information.

Path Dependence

Path dependence, defined as "the dependence of future societal decision processes and/or socio-ecological outcomes on those that have occurred in the past" (Preston, 2013), is a key process influencing adaptation (Klein et al., 2014). U.S.-EWN stakeholders often favor decisions that create path dependence like investing in large, long-term infrastructures, and technical and engineering-based solutions (de Bremond et al., 2014). Alternatively, flexible and low-regrets measures like wetlands conservation, floodplain restoration, energy-efficient water systems, water-efficient energy systems, and sewerage-sourced power systems are often overlooked because they are typically less familiar and perceived constraints hinder implementation (Pittock, 2011). For example, in de Bremond et al. (2014), southeastern U.S. energy stakeholders prioritized incremental upgrades and expansions of infrastructure while ecosystem-based options and transformational adaptations were avoided.

Continued reliance on water-intensive thermoelectric generation (Scott et al., 2011; Sovacool and Sovacool, 2009) exacerbates constraints across the U.S.-

EWN and hinders adaptation. This path could create “tradeoffs between the water needed to cool new power plants and the water needed for drinking, irrigation, fisheries, and agriculture” (Sovacool and Sovacool, 2009, p. 2771). For example, recent fuel changes have occurred in the U.S. energy sector in partial response to swift natural gas development and a focus on curtailing carbon dioxide (CO_2) emissions (U.S. D.O.E., 2014). While these changes may result in fewer CO_2 emissions, they could also increase other GHG emissions and constrain water supplies. Some low-carbon technologies like pulverized coal with carbon capture, concentrated solar power, and nuclear power consume large amounts of water (Macknick et al., 2011; Tidwell et al., 2013). These technologies reinforce the need to consider the water implications of adaptive strategies within the energy system.

Some U.S.-EWN constraints could be avoided by overcoming path dependence in water allocation systems. The arid western U.S. is highly adapted to support agriculture with infrastructures and institutions in place that support irrigation based on past economic and climate conditions (Libecap, 2010). Some of these systems encourage inefficient water use (U.S. D.O.E., 2014) and are ineffective in light of diversifying demands and uncertain supplies (Libecap, 2010). Additionally, path dependence to cheap freshwater withdrawals persists (Sanders, 2015) making it an attractive source for thermoelectric cooling even though using multiple water sources could decrease the percentage of western U.S. watersheds with projected water use exceeding total water availability from 61% to 8% (Tidwell et al., 2014b). Path dependence, by definition, is difficult to overcome and requires institutional coordination; however, U.S.-EWN institutions are fragmented and disorganized.

Fragmented and disorganized institutions

Often cited as an adaptation constraint, the fragmentation and disorganization of institutions within the U.S.-EWN creates numerous constraints at local and regional institutional, jurisdictional, management, and economic scales. Generally, U.S. energy and water sectors are regulated and managed independently, with research and interest regarding the U.S.-EWN growing over the past decade (Bazilian et al., 2011; Hussey and Pittock, 2012; Stillwell et al., 2011; U.S. D.O.E., 2014, 2006). U.S.-EWN decision-making takes different forms across policy frameworks which creates inconsistent legislation and inadequate implementation, information, and integration across institutions (Hussey and Pittock, 2012). These institutional inconsistencies exacerbate information-related constraints and enable the proliferation of uncoordinated information across institutions (Averyt et al., 2013; GAO, 2009b; Goldstein et al., 2008; Perrone et al., 2011). The complex institutional environment of the U.S.-EWN is concerning because, for many stakeholders, adaptations are most influenced by policy, governance, and shifting demands – not climate change (de Bremond et al., 2014). Additionally, institutional inconsistencies enhance stakeholder uncertainty (de Bremond et al., 2014), which reinforces path dependence because stakeholders with little institutional guidance on adaptation outcomes typically rely on pre-existing methods and plans (Patt et al., 2010). For example, the concept stationarity was declared "dead" within water management (Milly et al., 2008), but an alternative has yet to be widely accepted so it remains (Lins and Cohn, 2011; Marlow et al., 2013). Therefore, institutional complexity, path dependence, and information-related constraints are tightly coupled constraints making them particularly pervasive.

The often-unique structure of the U.S.-EWN muddles adaptation planning, especially regarding who has the authority and resources to make decisions. U.S.-EWN management occurs across scales from the local level to river basins and larger, crossing multiple administrative, jurisdictional, and institutional boundaries leading to territorial mismatches at administrative and physical levels (Goldstein et al., 2008; Perrone et al., 2011; Preston et al., 2015; Scott et al., 2011). Efforts to integrate U.S.-EWN planning has been limited with no coordinated federal or state approach (Hussey and Pittock, 2012; Sovacool and Sovacool, 2009).

When U.S.-EWN decision-making is fragmented, externalities may increase one sector's efficiency while creating demand in another (Hussey and Pittock, 2012). Consider the following projected U.S. energy sector changes. First, primary generation fuels are shifting away from coal and towards natural gas (60% of added capacity), renewable energy (29%), and nuclear energy (four plants totaling 8%) (U.S. D.O.E., 2014). Second, Section 316(B) of the Clean Water Act, implemented in May 2014, requires that water intake technologies at power facilities represent the "best technology available" (U.S. E.P.A., 2014). While dry-cooling and hybrid systems are possibilities, their cost and efficiency create adoption barriers (Macknick et al., 2011; Sanders, 2015; Tidwell et al., 2014a, 2014b). Therefore, most water intake technologies will be recirculating systems, which withdraw less, but consume more water than the once-through systems they are replacing (Macknick et al., 2011; Sanders, 2015; Tidwell and Pebbles, 2015; U.S. D.O.E., 2014). Third, new power plants will use a greater variety of water sources compared to existing systems, which mostly use surface water (75%) –

30% of planned power plants will use groundwater sources as compared to 13% of existing systems (U.S. D.O.E., 2014).

From the perspective of the energy sector, these changes reduce vulnerability (de Bremond et al., 2014; Tidwell et al., 2014a), decrease CO_2 emissions, and lessen impacts on aquatic species (U.S. D.O.E., 2014); however, they create externalities in related systems. These changes are particularly concerning in the southeastern U.S. because: primary generation fuels are moving towards natural gas and water-intensive nuclear power; thermoelectric cooling systems increasingly utilize groundwater (U.S. D.O.E., 2014); and thermoelectric cooling technology changes occurring mostly in the eastern U.S. will double the amount of water used at most plants (Macknick et al., 2011). These modifications are additionally coupled with increasing population and increasing hot and dry days further constraining water supplies and leading to less efficient energy and water systems. The projected changes in the southeastern U.S. will create externalities in water and land systems that are difficult to examine without a holistic consideration of related systems.

Discussion

Adaptation within the U.S.-EWN is necessary to avoid adverse climate change consequences. However, constraints to U.S.-EWN adaptation exist. Additionally, change-enabling elements are absent: adverse impacts occur disparately across the nexus (Sovacool and Sovacool, 2009) complicating who should adapt; climate-related vulnerabilities remain unseen for decision-makers that utilize historic information for planning (Bazilian et al., 2011); and even when vulnerabilities are acknowledged, decision-makers are unlikely to respond to climate trends – rather, policy, regulatory, or economic changes enable adaptation (de Bremond et al., 2014). However, adaptation may appear unnecessary before 2050 if economics are the primary decision-making criteria (Adger et al., 2005; O'Neill and Handmer, 2012; Preston, 2013). These factors, aided by path dependence, create systems unlikely to change without regulatory or policy reform.

Reform will be most effective from the top down, led by national (i.e., federal) action. The U.S.-EWN is rife with well-documented vulnerabilities, and dependent on inefficient paths and adaptations initiated in the context of stationarity (Hussey and Pittock, 2012; Libecap, 2010; Perrone et al., 2011; Pittock, 2011; Sanders, 2015; Scott et al., 2011; Sovacool and Sovacool, 2009; Stillwell et al., 2011; Tidwell et al., 2014b; U.S. D.O.E., 2006, 2014). These elements describe the conditions for transformational adaptation: "large vulnerability…and severe climate change that threatens to overwhelm even robust human-environment systems" (Kates et al., 2012, p. 7158). However, national-level U.S.-EWN reform will require huge investments in thoroughly planned infrastructures and the overhauling of institutions to focus on multisystem holistic adaptation. These transformations are unlikely in the current U.S. national governance context.

Absent national-level leadership, U.S.-EWN adaptation will occur at smaller scales, within discrete systems, and will therefore be less efficient and effective. At best, sub-national U.S.-EWN adaptation will be fragmented, much like U.S. urban adaptation (Bulkeley, 2010). This comparison may be too optimistic, as urban scales have clearer governance structures than the U.S.-EWN (Goldstein et al., 2008; Perrone et al., 2011; Scott et al., 2011). However, sub-national opportunities exist. A first step could be addressing the constraints mentioned previously. First, the availability and quality (collection, geolocation, methodologies) of relevant U.S.-EWN data needs improvement (Averyt et al., 2013; Macknick et al., 2011). Additionally, more hydropower, hydraulic fracturing, water demand/availability, and system resource consumption data is needed (U.S. D.O.E., 2014). Third, researchers and stakeholders should be able to access and analyze U.S.-EWN data alongside projections of decision-relevant systems and scales.

Next, efforts should focus on creating and disseminating actionable information. Actionable information needs: human agency (includes specific stakeholder needs/perspectives/contexts); should be useful at decision-relevant scales; and must incorporate multiple factors, driving forces, and policy options (de Bremond et al., 2014). Stakeholder engagement and participation is essential to create actionable information (Bierbaum et al., 2013; de Bremond et al., 2014; Liu et al., 2008). This engagement should be integrated across development stages (Bierbaum et al., 2013) so information is iteratively co-produced and customized (de Bremond et al., 2014; Lemos et al., 2012). Information should be credible, legitimate (understandable/transparent), and salient (contextually relevant) to be effective (Cash et al., 2003). These attributes are prioritized through "boundary management" which requires communication (inclusive/frequent/two-way), translation (shared terminology/criteria for credibility), and mediation (multiple perspectives, transparency, rules of conduct/decision-making) (Cash et al., 2003; Feldman and Ingram, 2009; Liu et al., 2008; Tribbia and Moser, 2008). In order for these efforts to be effective and scalable, funding agencies and institutions must support analyses, timelines, and outcomes that create and utilize actionable information (O'Brien, 2012; Preston et al., 2015b).

Actionable information is essential to holistic adaptation, but it is not a panacea to constraints. Rather, it is most beneficial in systems that have consistent and coordinated institutions and funding (Nordgren et al., 2016; Porter et al., 2015). However, U.S.-EWN institutions are uncoordinated, and funding levels vary across the nexus (Hussey and Pittock, 2012; Scott et al., 2011; Sovacool and Sovacool, 2009). Integrated, multisystem planning is ideal when efforts involve new infrastructures or increased resource consumption to explore synergistic technologies or locations. Regional Transmission Organizations, state utility commissioners, or state environmental and energy offices could coordinate integrated planning efforts at decision-relevant scales (Tidwell and Pebbles, 2015). Multisystem efforts could occur in proactive regions, but integrated planning is unlikely throughout the U.S.-EWN without national-level coordination (Bierbaum et al., 2013).

Single-system holistic adaptation may occur quicker than multisystem efforts because sector-specific adaptation information and planning is prevalent (Adger et al., 2005; Mimura et al., 2014; Nordgren et al., 2016). Single-systems should prioritize increasing resilience and flexibility through conservation, efficiency, and ecosystem restoration (Pittock, 2011); pursuing low-water energy fuels, locations outside stressed watersheds, or alternative thermoelectric cooling systems (especially in eight percent of western U.S. watersheds that are severely water-constrained) (Tidwell et al., 2014b); and considering related resources (Tidwell and Pebbles, 2015) and systems early enough to avoid constraints. In accordance with holistic adaptation, all single-system adaptations should avoid dependence pathways by neither exacerbating climate change nor limiting future adaptation options.

Conclusions

Considering coupled systems in adaptation is essential as multiple emerging threats are encountered, not only climate change (Klein et al., 2014), and as adaptation progresses from planning to implementation (Mimura et al., 2014; Woodruff and Stults, 2016). Examples of adaptation actions highlight the considerable effort actors undertake to overcome constraints: grants are combined to create the longevity needed for successful knowledge co-production (Bartels et al., 2013); adaptation actions depend on a champion actor (Porter et al., 2015), and most adaptation actors come from well-resourced locales (Hughes, 2015).

Currently, the little adaptation implementation that occurs happens autonomously, often in response to previously experienced impacts (Klein et al., 2014; Mimura et al., 2014). Prioritizing holistic adaptation now before implementation is prevalent may increase synergistic actions and avoid negative consequences in related systems. These lessons apply beyond the U.S. – developed countries could focus on efficient multisystem transitions, while developing countries have the opportunity to avoid committing to unsustainable system-level pathways.

Challenges to holistic adaptation exist. Divides between researchers and stakeholders (Feldman and Ingram, 2009; Meerow and Stults, 2016) and intellectual and institutional path dependence keep adaptation information and planning either too general or sector-specific (Amundsen et al., 2010; Nordgren et al., 2016; Storbjörk, 2010). Additionally, diverse and disparate physical, jurisdictional, administrative, and institutional scales complicate analyses and planning (Goldstein et al., 2008; Perrone et al., 2011; Scott et al., 2011). Also, the approach and availability of funding for adaptation generally, and multisystem adaptation specifically is unclear (Nordgren et al., 2016; Porter et al., 2015). These obstacles must be overcome for holistic adaptation to succeed beyond well-resourced systems with motivated actors (Bartels et al., 2013; Hughes, 2015; Porter et al., 2015; Tribbia and Moser, 2008).

Notable gaps in the literature include uncovering essential elements of actionable information, understanding how researchers influence actionable information, and analyzing multisystem adaptation options with generalizable methods that include information on costs, benefits, and impacts on related systems across scales. Future research should address the aforementioned gaps and additionally focus on analyzing multisystem adaptation efforts at sub-national scales, identifying opportunities to improve researcher and stakeholder interactions, and assessing adaptation options based on flexibility and dynamism to minimize path dependence.

Adapting energy systems to climate change without considering water systems and vice versa creates unseen consequences that make achieving even modest adaptation objectives difficult. Holistic adaptation – adaptation concerning complete systems – is presented as a path forward to maximize benefits and minimize costs of adaptation actions. Failure to adopt a holistic approach to adaptation reinforces the focus of adaptation benefits on a single system and displaces costs that may exacerbate climate change and its consequences onto related systems.

CHAPTER II

IDENTIFYING CLIMATE KNOWLEDGE SYSTEMS PRODUCTION CONSTRAINTS IN SWEDEN

Abstract

Climate change adaptation efforts continue to increase as the impacts of climate change persist and become more apparent. However, many adaptation efforts fail to result in adaptation actions. This inaction has been linked to many constraining factors including a lack of actionable information for adaptation processes. We wonder if climate knowledge producers face constraints as they try to create and deliver actionable information for adaptation decision-making processes? We draw on semi-structured interviews and participant-observations across climate knowledge systems production environments in Sweden to answer our research question and find that knowledge-producers engage in research, coordination, and communication to varying degrees and experience knowledge-production and -dissemination constraints, as well as, funding, professional, institutional, and stakeholder-related constraints. Some constraints are experienced differently by climate knowledge system producers depending on their specific role, institutional affiliation, agency, and experience. Additionally, some climate knowledge systems production constraints create or exacerbate additional constraints for other stakeholders participating in adaptation decision-making processes. These constraints limit the effectiveness of climate knowledge systems for adaptation decision-making. While overcoming the constraints identified in this paper would make progress towards more adaptation implementation, addressing climate knowledge system constraints while ignoring the need for support and guidance (beyond providing actionable information) for adaptation efforts would not yield widespread adaptation actions.

Introduction

Climate change is increasingly apparent, as are the losses and damages related to its impacts (IPCC, 2014; Melillo et al., 2014; Mimura et al., 2014). When these consequences are coupled with the current growth of fossil fuel emissions (Friedlingstein et al., 2010; Preston et al., 2013), the pursuit of adaptation to avoid adverse outcomes is both a present necessity and a substantial future challenge.

Climate change adaptation (referred to hereafter as adaptation) efforts have increased, particularly over the past decade, but many of these efforts have struggled to implement tangible adaptation actions (Lesnikowski et al., 2013, 2011; Mimura et al., 2014; Woodruff and Stults, 2016). Many reasons have been provided in peer-reviewed literature for this phenomenon including, but not limited to, a lack of requirements, policies, guidance, support, trust, and actionable information (Amundsen et al., 2010; Bierbaum et al., 2013; Biesbroek et al., 2011; Ekstrom and Moser, 2014; Jantarasami et al., 2010; Jones and Boyd, 2011; McNamara et al., 2012; Moser and Ekstrom, 2010; Storbjörk, 2010). An ongoing question in the adaptation discourse is the extent to which the widespread perception among decision-makers of the inability to appropriately resource adaptation efforts is an inherent limit to adaptation or simply an inconvenient constraint that can be overcome.

Of the various constraints on adaptation that have been described, a lack of actionable information is one of the most common (Cash et al., 2003; de Bremond et al., 2014; Dilling and Lemos, 2011; Kirchhoff et al., 2013; Liu et al., 2008; Vaughan et al., 2016; Wall et al., 2017), despite the now widespread, and growing, availability of climate knowledge (Lesnikowski et al., 2011; Porter et al., 2015). While knowledge and information are often assumed to be beneficial to decision-making processes, when that information is not actionable, it can impede, rather than facilitate, decision-making (de Bremond et al., 2014; Nordgren et al., 2016). For example, information can be too general, or too focused on a single sector (Amundsen et al., 2010; Cash and Moser, 2000; de Bremond et al., 2014; Nordgren et al., 2016; Storbjörk, 2010); or it may require tailoring, interpretation, or integration with other information before it can be useful (de Bremond et al., 2014; Dilling and Lemos, 2011; Feldman and Ingram, 2009; Klein and Juhola, 2014; Meerow and Stults, 2016; Preston, 2013; Preston et al., 2015b). Alternatively, actionable information; or information developed at decision-relevant scales that coordinates many factors, options, and driving forces with iterative stakeholder input (Bierbaum et al., 2013; de Bremond et al., 2014; Lemos et al., 2012; Liu et al., 2007), is recognized as an enabling factor for sustainable development (Barnett and O'Neill, 2010; Bierbaum et al., 2013; Cash et al., 2003; de Bremond et al., 2014; Dilling and Lemos, 2011; Lemos et al., 2012; Magnan and Ribera, 2016). A few studies have pushed back on the notion that climate information and its availability are such pervasive barriers to adaptation citing adequate amounts of climate information and an increased understanding of future changes among decision-makers (Porter et al., 2015; Porter and Dessai, 2017). Instead, these information-related barriers highlight an unwillingness to make decisions based on an ultimately uncertain future; and a lack of guidelines, resources, and support for taking adaptation actions (Porter et al., 2015).

In analyzing the role of knowledge in adaptation, it is useful to frame knowledge not just as a commodity, but rather as a complex system comprised of users (e.g., stakeholders and decision-makers), producers (e.g., climate scientists, application developers, urban planning or geographic information systems analysts), and the infrastructure, objects, and processes that mediate the interactions between them. Hence, the conceptualization of knowledge and information for adaptation as a knowledge system allows for a more rigorous investigation of not just whether knowledge is or is not useful to, or applied in, adaptation decision-making, but the origins of the knowledge itself and the assumptions associated with its creation. For example, research tends to focus on interactions between stakeholders (Adger et al., 2009; Moss, 2016; O'Brien and Wolf, 2010; Vulturius and Gerger Swartling, 2015), the type of information decision-makers need (Cash et al., 2003; Dilling and Lemos, 2011; Meadow et al., 2015; Muñoz-Erickson et al., 2017; Vincent et al., 2017), and the decision-making process (Adger et al., 2003). Yet, hardly any research has taken a direct approach to analyzing the contexts and processes of knowledge production (Miller et al., 2018), how "knowledge is acted upon" (Muñoz-Erickson et al., 2017, p. 8), or the constraints that knowledge system producers face as they endeavor to create and effectively disseminate actionable information for adaptation decision-making.

In this paper, we seek to understand the factors that hinder the development of effective knowledge systems for adaptation (referred to here as 'climate knowledge systems'). Specifically, the guiding question we endeavor to answer with this study is:

What constraints do climate knowledge system producers face in effectively producing and delivering actionable information for adaptation decision-making?

We consider how climate knowledge system producers (referred to here as 'knowledge-producers') generate, translate, and communicate information for adaptation decision-making processes; and what factors influence their processes, decisions, priorities, and actions. We draw on semi-structured interviews with knowledge-producers in Sweden and participant-observations in Swedish climate knowledge system production contexts to answer our research question.

Conceptualizing climate knowledge systems

Knowledge systems are abstract and all-encompassing which could be why their terminology and conceptualization across peer-reviewed literature remains murky (Moss, 2016). The seminal work by Cash et al. avoided a concrete definition of "knowledge systems for sustainability", but stated they could be individual tools, worksheets, models, and assessments designed to harness science and technology to link knowledge to action (2003, p. 8087). Knowledge systems can also be more complex by integrating multiple knowledge systems together (Cash et al., 2003; Miller et al., 2010; O'Brien, 2012; Porter et al., 2015). Miller et al. presents a definition of a knowledge system "as a suite of interconnected individual, social, and/or institutional practices by which knowledge claims get formulated (what we might call knowledge-in-the-making), validated, circulated, and put to use in making decisions" (2010, p. 2).

We conceptualize knowledge systems as interconnected processes of knowledge creation and dissemination that encompass the bounded knowledge systems discussed in Cash et al. (2003) (e.g. decision-support tools, integrated assessment models, climate services, vulnerability assessments), as well as their integration with other knowledge systems that create larger, context-specific knowledge systems of specific decision-making processes (Miller et al., 2010). In other words, we define knowledge systems as the processes and practices of knowledge production, dissemination, and use related to decision-making.

Knowledge systems consist of four elements that are influenced by actors, institutions, and processes: production, validation, circulation, and consumption (Miller et al., 2010). Production refers to how knowledge systems are created and by whom; validation refers to how knowledge systems are evaluated and by whom; circulation refers to how knowledge systems are exchanged and by whom; and consumption refers to how knowledge systems are applied within decision-making processes and who is involved (Miller et al., 2010). Our study focuses primarily on the interplay between the actors, institutions, and processes of climate knowledge systems production and circulation for adaptation decision-making.

Knowledge systems encompass the accepted knowledge used in decision-making (Silva and Stocker, 2018). Since decision-making and knowledge-making occur within social contexts with pre-existing power structures and inequalities, some types of knowledge are typically included within knowledge systems, while others are not (e.g. linear, reductionist, mechanistic knowledge systems are more often included in decision-making contexts while complex, pluralistic, and traditional ecological knowledge systems are not) (Bremer and Glavovic, 2013; McNamara et al., 2012; Silva and Stocker, 2018). These power structures can reinforce the incorrect notion that some possess knowledge while others simply need exposure to that knowledge to make sound decisions (Miller et al., 2010, p. 4). Additionally, the pre-existing social contexts and power relations in knowledge systems create and reinforce the conditions and outcomes of governance, the framing of questions being asked, the methodologies used, the actors who participate, how assumptions are defined, and how uncertainty is dealt with in decision-making processes (Muñoz-Erickson et al., 2017). These elements persist in all knowledge systems.

Methods

The theoretical framing for this study combines “thick”, actor-oriented, and reflexive research approaches to analyze climate knowledge systems in Sweden for adaptation decision-making processes (Adger et al., 2003; Klein and Juhola, 2014; Preston et al., 2015c). Adger et al.’s “thick” environmental decision-making analysis, built upon Geertz’s “thick” description theory (1973), examines actors, institutions, and processes to enable generalizability while also recognizing the importance of context (2003). Through this lens, we considered the processes of climate knowledge systems production and dissemination as parts of adaptation decision-making processes and investigate the actors and institutions therein.

Next, we focused on the roles, responsibilities, and agency of climate knowledge system actors and institutions based upon actor-oriented and reflexive approaches to adaptation research (Klein and Juhola, 2014; Preston et al., 2015c). These approaches highlight the facilitative roles that knowledge-producers play within adaptation decision-making processes, and the importance of considering their agency which has hardly been discussed in peer-reviewed literature to date (Klein and Juhola, 2014; Preston et al., 2015a, 2015c).

If one seeks to improve the design of climate knowledge systems, it is also important to engage the emerging reflexivity within adaptation research and practice. Adaptation is not yet well understood, and more scrutiny and critical reflections are necessary to move the burgeoning field forward (Preston et al., 2015c). Preston et al. (2015c) emphasize that adaptation is not inherently beneficial and that researchers should seek to understand how decisions can be made with social legitimacy and ethical considerations enabling the inclusion of more perspectives and knowledge forms to enhance the usefulness of adaptation processes. Without reflexivity in adaptation research the limitations of existing climate knowledge systems, methodologies, and adaptation decision-making processes may go unrecognized.

We combined these theoretical approaches to investigate knowledge-producers and climate knowledge systems for adaptation decision-making in Sweden. Sweden was chosen as the primary focus of our study to provide a similar national context across institutions, because national and international adaptation-focused institutes in Sweden are co-located, and because Sweden is recognized as a leader in the development of climate knowledge systems (Massey et al., 2015). Data were collected between September 2016 and August 2017 at twelve distinct “learning events” (conferences, workshops, seminars, and meetings) throughout Sweden, and in knowledge-producer work environments at the Swedish Meteorological and Hydrological Institute which encompasses both research and consulting activities and houses the Rossby Centre (focused on climate research), the Coordinated Regional Climate Downscaling Experiment International Project Office, and the Swedish National Knowledge Centre for Climate Change Adaptation.

We conducted semi-structured interviews and participant-observations to obtain data on the perspectives and agency of knowledge-producers; and on the processes of climate knowledge systems production and dissemination for adaptation decision-making. Semi-structured interviews are designed to be flexible and to engage interview subjects, and may lead to insights that are not discussed or observed within a group (Rubin and Rubin, 2012). Participant-observation is designed to increase familiarity with actors by partaking in their environment which increases rapport and also enables first-hand observations of nuances and/or contextual details that are hard for subjects to articulate or even acknowledge (DeWalt and DeWalt, 2011; Kitchin and Tate, 2013). Anytime participant-observation was conducted at learning events, the participant-observer[1] was introduced and briefly explained the purpose of the observation. The participant-observer took field notes during learning events and recorded a summary of observations after each event ended.

In total, 38 semi-structured interviews were used for this study. Interviews lasted between 15 and 90 minutes, with most interviews averaging approximately 45 minutes. Interview subjects worked across 21 institutions in Sweden (most with multiple institutional affiliations), and were identified through their participation in a learning event or through the snowball sampling method (Hay, 2000). Knowledge-producers were asked similar questions about experiences, roles, and constraints related to creating or disseminating climate knowledge systems, but interview subjects had agency over the direction of semi-structured interviews and specific constraints were brought up by the interview subject themselves, not the interviewer.

We used two qualitative methods in twelve learning events that involved multiple participants to triangulate our data and identify consistent findings. Data triangulation strengthens the credibility of qualitative studies by combining multiple methods, perspectives, and sources to investigate research questions and uncover generalizable or transferable observations across the methods used, cases studied, and subjects interviewed (Baxter and Eyles, 1997). We recognize that some findings from our study may be generalized across many contexts, and data triangulation helps identify those generalizations by ensuring that findings are robust (i.e. consistently present across the cases, methods, and subjects analyzed).

We analyzed interview data first, by reviewing all interview notes and highlighting any instances that identified climate knowledge systems production constraints. Then we iteratively grouped the identified constraints together based on topics that emerged within the data. Next, we reviewed participant-observation data, identified climate knowledge systems production constraints, and iteratively grouped these constraints together based on topics that emerged across the data. Then, we created a document that included constraints that were consistently identified across interview and participant-observation data. This review was

[1] The corresponding author conducted all participant observations for this study. No participants objected to observations during the study.

completed by December 2017. We conducted a second review of the data in February of 2018 using the same analytical steps. After both reviews were complete, we compared the first and second analysis documents to identify consistencies and inconsistencies. These reviews helped us distill our findings and identify climate knowledge system production constraints that were consistently identified across methods, cases, and contexts. These findings are discussed next.

Results

Every knowledge-producer interviewed for this study played a unique role that combined research, coordination, and communication of climate knowledge systems for adaptation decision-making. Figure 1 provides a visual representation of the knowledge-producers interviewed for this study on a spectrum of climate knowledge systems production. This approximation provides context for the various roles knowledge-producers play over time and across projects.

Knowledge-producers on the production side of the spectrum (referred to here as 'researchers') typically create new knowledge and information that serve as climate knowledge system inputs; and develop and disseminate climate knowledge systems. Knowledge-producers on the intermediary side (referred to here as 'intermediaries') typically add supporting information or synthesize data to explain how a location may be impacted; and package and communicate climate knowledge systems. The Climate Knowledge Systems Production (CKSP) Spectrum can help visualize where constraints emerge, who may be most prepared to overcome certain constraints, and how some constraints may create or exacerbate each other.

The CKSP Spectrum adds context to the climate knoweldge system production constraints that are detailed in Table 3. Some constraints were predominately identified by intermediaries, but likely affect all knowledge-producers and vice-versa. A few constraints only affect researchers or intermediaries. In some cases, a constraint that emerged on one side of the spectrum may create or exacerbate an additional, but separate constraint on the other side of the spectrum. Constraints in Table 3 are organized into four categories and detailed next.

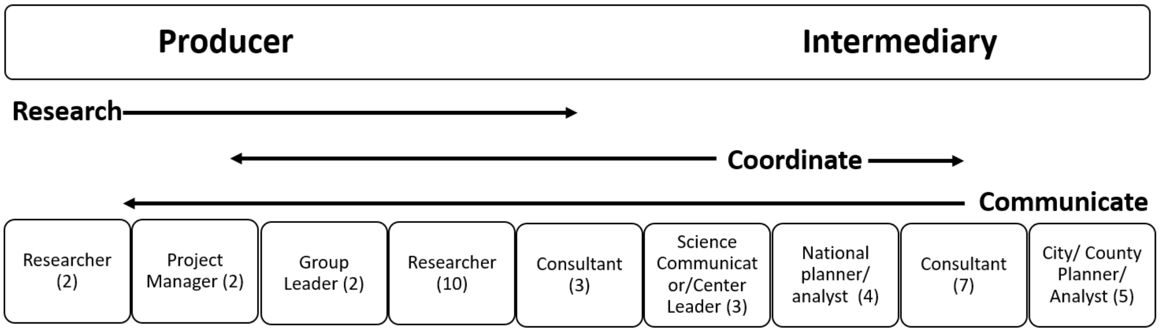

Figure 1 The Climate Knowledge Systems Production (CKSP) Spectrum visualizes knowledge-producers interviewed for this study. Research, coordination, and communication activities vary across the CKSP spectrum, but are emphasized where indicated. Numbers in parenthesis indicate the number of subjects interviewed. Interview subjects were uniquely varied across the spectrum, but categories were organized for clarity.

Knowledge-production constraints

Knowledge-production constraints concerned challenges related to creating actionable information for adaptation decision-making processes. Specifically, knowledge-producers noted that modelling processes were complicated, and that some data refinement was difficult to produce. Some intermediaries noted that the constant updating of information, specifically climate information from researchers, made translating and communicating information difficult.

Similarly, a lack of decision-relevant data (not only climate data), hindered climate knowledge systems production. For some researchers, land-use maps were not refined enough for modeling demands. For some intermediaries, information required for their models lacked guidance about how it was derived and how the results might influence other processes. Other knowledge-producers knew that stakeholders wanted climate information with refined spatial and temporal resolution, but that obtaining that resolution would be time- and resource-intensive and may not yield more clarity.

One constraint predominately identified by intermediaries, but present across the CKSP Spectrum was the lack of national- and/or European Union-level guidelines for adaptation planning. Uncertainty regarding how decision-makers and society will react to, mitigate, and plan for future changes compounded uncertainty within modelling processes. For example, one researcher noted that he could model the processes that influence sea-level rise, but he was uncertain about the extent of change to expect because of uncertainty regarding how society and decision-makers will act.

Table 3 Climate knowledge system production constraints

Constraint	Examples	Identified by	Producers most affected
Knowledge-Production Constraints			
Making useful information at relevant scales is difficult	Complicated modelling processes	Researchers	All
	Sub-city modeling/analysis new in most disciplines	Researchers	All
	Knowledge continuously updating/changing	Intermediaries	Intermediaries
Unknowns	Lack of data, particularly for smaller cities	All	All
	Demand for non-existent/higher resolution data	All	All
	Knowledge gaps	All	All
	Unmapped data	Intermediaries	Intermediaries
Lack of national/European Union-level guidelines	Compounds uncertainty	Intermediaries	Intermediaries
	Hard to collaborate beyond discipline/focus	Intermediaries	All
	Difficult to discern roles/responsibilities	Intermediaries	Intermediaries
	Lack information access	Mostly intermediaries	Mostly intermediaries
Knowledge-Dissemination Constraints			
Making climate knowledge useful	Hard to make scenarios relatable	Intermediaries	All
	Development/communication of data has improved, interpretation has not (unclear what the data means, how to use/integrate it)	Intermediaries	All
Unknowledgeable of stakeholder realities/ needs	Experience/perception that decision-makers want simplicity	All	All
Mismatched comfort with/ concepts of uncertainty	Decision-makers want clarity, producers want to identify/detail uncertainties	Mostly researchers	Mostly researchers
	Uncertainty (the concept according to science), and uncertainties are hard to explain	All	All
	Policy/decision-making/societal uncertainties compound uncertainty for knowledge-producers, which is not adequately communicated to decision-makers	All	All
Stakeholder-related constraints			
Not meeting expectations	Stakeholder fatigue	Researchers	All
	Stakeholder disappointment	Researchers	All
Time-consuming	Identifying stakeholders	Researchers	Researchers
	Tailoring information	Researchers	All
	Stakeholder engagement cuts into research time	Mostly researchers	Mostly researchers

Table 3. Continued.

Constraint	Examples	Identified by	Producers most affected
Funding, professional, institutional constraints			
Funding	Increasing/unsustainable proportion of project-based funding	Mostly researchers	Mostly researchers
	Balancing funding expectations/deliverables	Researchers	All
Roles	Balancing research/consulting roles	Mostly researchers	Mostly researchers
Prestige	Perception that (others think) climate knowledge systems work is not prestigious	Mostly researchers	Mostly researchers
	Perception that researcher commitment is lacking because of perception of prestige/other priorities	Intermediaries	All

Knowledge-dissemination constraints

Knowledge-dissemination constraints concern the applicability, communication, and uptake of climate knowledge systems. These constraints focus on interpreting climate-related information, understanding stakeholder decision-making environments, and effectively communicating uncertainties within climate knowledge systems.

Some knowledge-producers lacked knowledge of adaptation decision-making realities. In some cases, knowledge-producers created a climate knowledge system that was difficult, or even impossible, to integrate into decision-making platforms or frameworks. In others, knowledge-producers did not connect with stakeholders who would use the climate knowledge systems, so relevant details were not being discussed. Stakeholder interactions often involved a workshop with presentations while knowledge-producers rarely interacted in decision-making work environments. Also, when knowledge-producers asked use-related questions during workshops, oftentimes the stakeholders who used climate knowledge systems directly were not present. Decision-makers were most commonly upper-level managers or planners who typically only used the output of climate knowledge systems.

Overall, intermediaries felt they lacked knowledge of how multiple types of information coalesce within climate knowledge systems. Many intermediaries felt that climate information from the production side of the CKSP Spectrum was inadequately communicated to them, hindering their ability to add value to climate knowledge systems.

Concern about communicating uncertainty was the most commonly identified constraint across the CKSP Spectrum. Many knowledge-producers acknowledged that they focus on the uncertainties within climate knowledge systems, whereas they perceived that decision-makers want a clear, single number to plug into plans. Some knowledge-producers identified this desire for clarity as a decision-maker oversight and were reluctant to envision a situation where they would feel comfortable providing the perceived or actual clarity desired by decision-makers. Decision-makers looked for guidance from knowledge-producers, while knowledge-producers (researchers and those with a scientific background in particular) wanted to assess all angles of uncertainty and make incremental progress on their efforts, not to provide decision-making inputs with confidence.

Knowledge-producers felt uncertainty was hard to explain, especially the amount and types of uncertainty in climate knowledge systems. For example, one researcher noted that uncertainty surrounding future flooding involved uncertainties in regulation, land use, and climate change adaptation actions (or lack thereof). Ranges in outputs she provided were largely based on unknowns within the human system, but she communicated methodological, climate system, and human system uncertainties equally to decision-makers.

Stakeholder-related constraints

Researchers identified most of the stakeholder-related constraints on climate knowledge systems production, but they are likely present across the CKSP Spectrum. Specifically, researchers identified stakeholder fatigue and disappointment as climate knowledge system production constraints. Researchers noted that sometimes the same decision-makers were used in multiple projects and not always to their advantage. Others noted that the information produced in some projects was not useful for decision-makers. Sometimes researchers made progress on a methodology which created new research findings, but these new insights did not always produce better information for decision-makers.

Very few knowledge-producers interviewed for this study (none on the production side of the CKSP Spectrum) had undergone training or education focused on stakeholder-related work or knowledge co-production. Researchers were most likely to have a doctorate in the physical sciences (i.e. climatology, forestry, oceanography, hydrology), while a few had a doctorate in an engineering field. For consultants and intermediaries, engineering was the primary discipline of focus. This preference for educational backgrounds in engineering and the physical sciences persisted across all knowledge-producers, even amongst communication- and coordination-focused positions.

Knowledge-producer skills related to stakeholder-based work were primarily obtained through direct experience, but direct stakeholder experience did not typically occur until knowledge-producers moved into mid-career and/or project management stages. Knowledge-producers most comfortable with climate knowledge systems development and working with stakeholders were consultants, or had experience working as a consultant. Direct experience as a consultant made a noticeable difference in how knowledge-producers, and their professional cohorts, approached climate knowledge systems production and dissemination.

Most early-career researchers did not engage with stakeholders. Researchers highlighted the need to publish during early-career stages as the primary reason they were not involved. Also, some early-career researchers did not speak Swedish fluently which limited communication with local stakeholders who could converse in English, but predominately used Swedish. However, researchers worked on projects across the European Union, so an inability to speak Swedish fluently would not exclude researchers from working with stakeholders.

Some researchers thought stakeholder-interactions were time-consuming. Identifying stakeholders, tailoring information, and stakeholder communication took more time than was allocated or expected. A few noted that stakeholder-related work took time away from research or proposal writing. All researchers interviewed for this study emphasized regular and prestigious scientific output and the ability to find and secure funding as primary indicators of career success and advancement. Alternatively, when researchers discussed stakeholder-related work they emphasized their interests in doing so (approximately half of those interviewed) and the need to adhere to funding requirements (almost all of those interviewed). No researchers mentioned stakeholder-related work in relation to professional success or promotion unless it related to the ability to procure funding.

Funding, professional, or institutional constraints

Knowledge-producers identified numerous constraints related to shifts in funding and professional roles; and, at least a perceived lack of prestige regarding climate knowledge systems production. First, many researchers noted that the funding landscape had become more project-based over about the past decade. One researcher mentioned that their project-based funding had doubled since 2006 while internal funding remained unchanged; and in other cases, declined. For other researchers, project-based funding had more than doubled.

Many knowledge-producers noted they were funded entirely on project budgets and that their baseline funding had diminished over approximately the last fifteen years. As project-based funding increased, researchers were still tasked to complete the same objectives as before, but with a lower proportion of base funding. Less time was allocated for administrative duties, grant writing, and model development which are not typically project-funded activities. Tasks unrelated to projects were sometimes squeezed into project timelines. Many senior-level knowledge-producers noted that most of their time is spent on project management and grant writing – tasks that can be difficult to fit into project-heavy budgets.

Many knowledge-producers detailed occasions when they could not provide the necessary information in the amount of time projects specified. Some researchers detailed a process for incrementally improving information over multiple projects, but these improvements were not always provided to decision-makers from previous projects. To avoid this occurring, some linked projects together so the same stakeholders would eventually receive actionable information. Others pursued multiple projects that would benefit from the same or similar methodological processes or would plan their research improvements first and then try to find projects that tangentially related to their plans.

Lastly, many researchers noted that climate knowledge systems production was not perceived as prestigious. Researchers perceived that stakeholder-related work and climate knowledge systems development was viewed as applied research that did not produce the novel insights that fundamental research would produce. One researcher noted a colleague said he only took on climate knowledge systems work temporarily until basic research funding came through. Others felt it was difficult to produce the scientific results necessary for prestigious publications within a climate knowledge systems-focused project. Most researchers indicated that climate knowledge systems development is perceived as necessary in the current funding context, but that it is not perceived as prestigious or particularly helpful for career advancement, though no interview subject stated that they personally felt this way.

Encountering climate knowledge system production constraints

All knowledge-producers involved in this study encountered some climate knowledge system production constraints. When knowledge-producers overcame constraints, they tended to overcome many of the same constraints repeatedly across multiple projects and contexts. Some constraints were foreseen by knowledge-producers and time was budgeted to overcome or avoid them. Others were unseen and unplanned for. Addressing unforeseen constraints took time, attention, and resources away from already tight timelines and budgets and were not always effective. For example, one knowledge-producer group continually worked with the same stakeholders, overcoming many stakeholder-related constraints for certain projects. The knowledge-producers understood the context of the situation, established trust among stakeholders, and had a firm grasp of what decision-makers wanted. Sometimes decision-makers did not get the information they needed from a project, but they maintained the relationship and assumed useful information would come from the next project.[2] This mutual understanding created a continuous relationship that worked across projects which helped knowledge-producers avoid taking the time to identify stakeholders, lengthy interactions with new stakeholders, and the need to produce both useful information and publishable insights for each project. Also, knowledge-producers were better able to maintain their publication plans, which did not always fit with project or decision-makers' timelines.

Some decision-makers on these continuous projects were growing fatigued and disappointed. They wanted to plan for other adaptation risks but were continually being brought into projects involving one risk-type they had thoroughly planned for. At least one researcher recognized that this was occurring and tried to maintain the relationship by expanding the risks considered and researchers involved but was having a hard time doing so. The transition towards other adaptation risks was not occurring, because the established relationship was centered around a research group focused on a specific discipline and it was proving difficult to move beyond or diversify that relationship.

Other approaches to mitigate or avoid climate knowledge system production constraints commonly displaced constraints or other consequences onto other stakeholders. For example, some knowledge-producers only improved aspects of climate knowledge systems that were publishable and did not focus on creating useful information (leaving decision-makers without actionable information); others used work from other projects because they did not have enough time budgeted to complete their tasks (resulting in un-tailored information that was not what stakeholders were asking for); some limited or avoided communicating with stakeholders because it took too much time (resulting in

[2] Decision-maker interactions occurred during participant-observations.

information that may be difficult to interpret or to apply to the specific case); and a few knowledge-producers focused on creating actionable information and then finding part of that process that was publishable (ensuring decision-makers had actionable information, but potentially at the cost of publication outputs and timelines). Each attempt to move past constraints varied in effectiveness and influenced other parts of the climate knowledge systems production process.

Discussion

The climate knowledge system production constraints identified in this study limit the effectiveness of climate knowledge systems for adaptation decision-making processes. We discuss potential pathways to overcome some of these constraints next.

Evaluate and reward stakeholder outcomes

More could be done to optimize stakeholder outcomes in climate knowledge systems production environments. One approach could be to emphasize, evaluate, and measure stakeholder outcomes as indicators of project success or completeness as much as, or more than, scientific output. Scientific output has become quantifiable and enables quick, albeit imperfect evaluation to measure progress, however this evaluation does not necessarily indicate effectiveness in decision-making (Ford et al., 2013; McNamara et al., 2012). Project outcomes are harder to evaluate, but without their evaluation, these outcomes are easy to de-emphasize when compared to something as visible, measurable, and recognizable as scientific output.

Additionally, there should be some recognition across institutions that scientific-output and stakeholder outcomes are not inherently complimentary (McNamara et al., 2012) and may sometimes be difficult to achieve simultaneously. Some project funding models like the Mistra Swedish Research Program on Climate, Impact, and Adaptation (Mistra-SWECIA) have increased the duration of some grants to prioritize stakeholder engagement (Hewitt et al., 2013; Jönsson and Gerger Swartling, 2014). If funding moves towards prioritizing and evaluating stakeholder outcomes however, professional incentive structures must also change to reward different types of professional accomplishments (Gerger Swartling et al., forthcoming; Porter and Dessai, 2017). Without changes across multiple organizational scales (i.e. beyond funding institutions) (O'Brien, 2012; Preston et al., 2015b), contributing to climate knowledge systems may continue to be perceived as secondary to pursuing currently recognized indicators of success.

Provide and reward stakeholder-focused science co-production and communication training

Knowledge co-production and science communication training for knowledge-producers could help alleviate many knowledge-production constraints. Additionally, the direct experience that current or former consultants bring to climate knowledge systems production environments could be better recognized, rewarded, and sought-out.

Also, early-career knowledge-producers should be better-integrated into knowledge-dissemination contexts. Excluding early-career knowledge-producers in knowledge dissemination contexts occurred within this study, and similar findings were reported in Jönsson and Gerger Swartling (2014)[3]. This approach leaves early-career researchers lacking in both training and experience with stakeholders, which may be especially needed in the current funding context (Vaughan et al., 2016). Additionally, individuals with expertise in science communication and/or knowledge-coproduction should be considered as potential knowledge-producers. Increasing interdisciplinarity among knowledge-producers could lessen some of the knowledge-dissemination and stakeholder-related constraints observed in this study.

Climate knowledge systems production could be improved by convening with more types of stakeholders beyond planners and managers. Specifically, analysts and technicians who work directly with climate knowledge systems could provide more knowledge and experience based on the limitations and usability of climate knowledge systems. The lack of interaction and engagement from stakeholders who work directly with climate knowledge systems limits the potential of stakeholder interactions.

Create flexible climate knowledge systems and adaptation decision-making processes

Some climate knowledge system production constraints will be ever-present, like constraints that concern the constant tide of increasing information about the future (Safford et al., 2017) and the uncertainty inherent in modelling future processes that have yet to occur (Sharifi and Yamagata, 2016; Tonmoy et al., 2014; Tonn, 2000). These constraints may be lessened by increasing the

[3] Senior scientists were conducting stakeholder interactions to enable more research time for younger researchers.

flexibility of climate knowledge systems and adaptation decision-making processes (Muñoz-Erickson et al., 2017). Research could focus on identifying methods and approaches to update information and models quickly, effectively communicate changes to stakeholders, and develop decision-making processes that are prepared to continually account for new and updated information.

Recognize, detail, and reduce uncertainty within human systems for decision-making

The inherent uncertainty in modelling a future where humans influence the magnitude of change, is an ever-present aspect of modelling future processes (Sharifi and Yamagata, 2016; Tonmoy et al., 2014; Tonn, 2000). Inherent uncertainty within the human system influences how climate and environmental changes manifest on the landscape and cannot be reconciled through decreases in operational uncertainty (i.e. by creating a better model or having more data) (Tonn, 2000). These realities and limits could be more fully explained (and re-explained) to decision-makers to build a greater understanding of the role that different types of uncertainty play in modelling future processes (Moss, 2016; Tonn, 2000). Additionally, some knowledge-producers could benefit from an increased understanding of the many ways uncertainty emerges within climate knowledge systems.

Knowledge-producers could do more to detail the confidence in their methods and outputs (Moss, 2016), and to discuss the human components of uncertainty to greater detail. Similar to results in this study, Moss (2016) found that some researchers were reluctant to emphasize uncertainties within tools and provide confidence intervals, but those that did more fully agreed on major multidisciplinary and interdisciplinary conclusions.

Alternatively, decision-makers could assign more parameters to their decision-making environment by clearly outlining which scenarios and future options they will consider if more simplicity within climate knowledge systems is desired. These parameters increase use value uncertainty (i.e. uncertainty caused when estimates or parameters are used in decision-making), but they may also decrease the operational uncertainties of climate knowledge systems by reducing potential scenarios and options considered within the climate knowledge system (Tonn, 2000). Decision-makers can assign these parameters with or without the help of other stakeholders.

Conclusions

Constraints identified in this study occurred across climate knowledge system production contexts in Sweden but are not an exhaustive list of all climate knowledge system constraints on adaptation. Rather, they represent a useful starting point to better understand the challenges knowledge-producers encounter as they try to create and disseminate effective climate knowledge systems.

Some knowledge-producers in Sweden succeeded at producing and disseminating actionable information for decision-makers despite existing constraints by prioritizing the creation of usable information, having a lessened focus or priority on producing high-profile research, producing non-existent data and information outside of their professional scope or discipline, participating in iterative communication and multiple meetings with decision-makers, and working with boundary organizations. Skelton et al. (2017) reported similar findings in the Netherlands – a few knowledge-producers overcame constraints through great personal motivation and by sacrificing preeminent science to produce usable science.

Successful climate knowledge systems production cases could be analyzed to identify opportunities to recognize, reward, and potentially scale-up successful efforts. However, the processes that enable the creation of actionable information for adaptation decision-making are not yet well supported in climate knowledge system production environments in Sweden, and likely in other contexts as well (Porter and Dessai, 2017; Skelton et al., 2017). Like Porter et al. (2017) found in the United Kingdom, knowledge-producers in Sweden are not indifferent to users, and do not ignore them, but instead feel constrained by institutional and systematic priorities and incentives.

Future work could focus more specifically on expanding the Climate Knowledge System Production Spectrum towards climate knowledge system intermediation and use. Further identification of climate knowledge systems production constraints should focus on identifying generalizable constraints and envisioning pathways to overcome them to avoid becoming hyper-focused on identifying numerous context-specific constraints.

The creation and dissemination of actionable information for adaptation is limited by climate knowledge systems production environments (Porter and Dessai, 2017; Skelton et al., 2017). To produce widespread actionable information, actors and institutions must change to recognize, reward, and support methods that enable the creation and effective dissemination of climate knowledge systems. However, producing and disseminating robust climate knowledge systems without adequate funding, staff, guidance, and support for adaptation efforts has not yet yielded (Amundsen et al., 2010; Eisenack et al., 2014; Moser and Ekstrom, 2010; Porter et al., 2015), and likely will not yield widespread adaptation actions. The production and dissemination of effective climate knowledge systems must be met with adequate support and guidance to ensure that adaptation efforts are prevalent.

CHAPTER III

APPLYING THE KNOWLEDGE SYSTEM EVALUATION FRAMEWORK TO TWO URBAN RESILIENCE CASES IN THE UNITED STATES

Abstract

Urban decision-makers are increasingly focused on enhancing community resilience in anticipation of more frequent and intense impacts from climate variability and change. These impacts will manifest in complex and nuanced ways, particularly when coupled with additional social, economic, and environmental shifts that vary across contexts. Given these challenges, urban decision-makers are seeking new knowledge, and new ways of using existing knowledge, to support decision-making processes. In response, a broad range of knowledge systems have been developed for urban areas. Yet, to date, little research has directly evaluated these systems. The Knowledge System Evaluation (KSE) framework addresses this gap by providing both conceptual clarity surrounding knowledge systems and a structured, generalizable methodology to guide research on knowledge systems for urban resilience. The KSE framework combines data and information on knowledge, their use in decision-making over time, and evidence of tangible actions taken. The KSE framework was developed with two urban resilience knowledge systems – the Urban-Climate Adaptation Tool and the Maine Flood Resilience Checklist. Initial testing indicates that the KSE framework can assess the transferability, scalability, and use of knowledge systems in urban resilience decision-making. Any evaluation using the KSE framework requires a thorough understanding of the contextual details of each case and understanding what factors may influence knowledge systems development and subsequent decision-making processes and outcomes. Yet, as an analytical entry point for the evaluation of knowledge systems, the KSE framework can offer insights regarding the extent to which knowledge systems influence urban resilience decision-making processes.

Introduction

As the frontlines of disaster preparedness and relief, cities are increasingly focused on enhancing their resilience to prepare for, and adapt to, the mounting impacts of climate change. Urban areas often lead climate change adaptation and resilience building efforts, particularly in the United States (U.S.) (Arnott et al., 2016; Bierbaum et al., 2013; Bulkeley, 2010). Occasionally these processes are supported by the state or federal government, but explicit policies and regulations rarely guide them (Arnott et al., 2016; Bierbaum et al., 2013; Bulkeley, 2010). Often, urban decision-makers turn towards specialized knowledge to inform resilience decision-making efforts when little policy or regulatory guidance exists (Kirchhoff et al., 2013; McNie, 2013).

Knowledge systems for urban resilience have proliferated to help urban decision-makers make sense of, and adapt to, changing realities (McNie, 2013; Moss, 2016; Vaughan et al., 2016; Woodruff and Stults, 2016). These initiatives typically involve the creation of a knowledge system, with varying forms of collaboration with decision-makers, that is meant to eventually be applied beyond the original decision-making context. As relatively new concepts, knowledge systems for urban resilience do not yet have widely-accepted methods, ethical norms, or evaluation processes (Cash et al., 2003; Miller et al., 2010; Moss, 2016; Muñoz-Erickson et al., 2017). Attempts to analyze knowledge systems specifically have rarely been presented (Muñoz-Erickson et al., 2017) or tested (Cash et al., 2003; Moss, 2016) despite calls for increased oversight to avoid loss of trust from decision-makers, and to learn more about decision-making processes, effectiveness, and outcomes (Cash et al., 2006, 2003; Moss, 2016; "Validation required," 2010). This lack of oversight is partly because the knowledge systems for urban resilience landscape is both diverse and evolving making it difficult to cement a generalizable evaluation methodology that will remain salient as knowledge systems change. Also, researchers and funders have predominately focused on creating and deploying knowledge systems with stakeholders in numerous "test-beds" with desires to expand these proofs-of-concepts quickly (Moss et al., 2010; Porter and Dessai, 2017; Skelton et al., 2017). The focus on the development of knowledge systems for urban resilience and not on evaluation has resulted in many knowledge systems but little understanding of their effectiveness or use in urban resilience decision-making processes over time.

In this paper, the Knowledge System Evaluation (KSE) framework is introduced as a methodological approach to evaluate knowledge systems for urban resilience. Conceptualizations of knowledge systems are discussed next, followed by an overview of the framework. Thereafter, the KSE framework is applied to two model knowledge systems and the potential limitations and opportunities for using the KSE framework more broadly are discussed.

Background: Conceptualizing knowledge systems

Knowledge systems are most simply defined as **knowledge-making for decision-making**. Knowledge systems encompass the accepted knowledge and information produced and used for decision-making (Silva and Stocker, 2018), how actors and institutions interact with that knowledge and the opportunities and constraints that knowledge places on decision-making processes (Muñoz-Erickson et al., 2017). Therefore, knowledge systems both inform, and are informed by, decision-making processes and institutional and governance structures (Jasanoff et al., 1998; Muñoz-Erickson et al., 2017).

Knowledge systems and decision-making are tightly coupled endeavors (Muñoz-Erickson et al., 2017). Efforts that aim to produce knowledge systems are typically focused on co-producing knowledge with stakeholders iteratively and collaboratively to create new knowledge for decision-making (McNie, 2013; Wall et al., 2017). Knowledge system co-production efforts have been widely idealized (Brown et al., 2013; Hegger et al., 2012; Muñoz-Erickson et al., 2017; Trencher et al., 2014), but in practice the implementation, effectiveness, and priority to ensure that knowledge systems are co-produced varies widely and has likely been overstated (Gerger Swartling et al., n.d.; Porter and Dessai, 2017; Skelton et al., 2017; Vulturius and Gerger Swartling, 2015). The overlaps created during knowledge co-production create synergies which makes knowledge systems more applicable (Bierbaum et al., 2013; de Bremond et al., 2014; Lemos et al., 2012; Liu et al., 2008), but also more complex, nuanced, and context-based necessitating the consideration of decision-making environments and processes for knowledge systems analysis (Miller et al., 2010; Moss, 2016; Muñoz-Erickson et al., 2017).

Despite their complexity and variance, every knowledge system involves the processes of knowledge production, validation, circulation, and consumption (Miller et al., 2010; Muñoz-Erickson et al., 2017). Institutions and actors interact within these processes to create and re-create practices, routines, discourses, methodologies and forms of reasoning (Miller et al., 2010). Munoz-Erickson et al. (2017) additionally highlight specific elements like values, standards, knowledge claims, and structures; as well as organizational, political, and operational complexities. Subjectivity is also highlighted as an important element within knowledge systems focused on whether trade-offs are considered, what estimates are used, what types of knowledge are included, if uncertainty or confidence is discussed or quantified and how data are weighted, what methodologies were used to create the knowledge system, and how a knowledge system is framed (Miller et al., 2010). As described below, the KSE framework builds on these essential components of knowledge systems, and in so doing, seeks to address the larger question of how the configuration and application of knowledge systems for urban resilience influence decision-making processes.

Methodology

Development of the KSE framework

The KSE framework was initially designed by using a model knowledge system as a guide. The Urban-Climate Adaptation Tool (Urban-CAT) is a data-based decision-support knowledge system focused on urban resilience and developed by a team of researchers from the Urban Dynamics and Climate Change Science Institutes at Oak Ridge National Laboratory (ORNL) who coordinated with city of Knoxville personnel between 2015 and 2017 (Nugent et al., 2017). The Urban-CAT combines data on ecological, socioeconomic, and infrastructure scales for 2010 with climate and population projections for 2025-2050 developed by ORNL. Climate projections were produced specifically for the Urban-CAT while population projections were provided by LandScan™, a global population database produced by the Geographic Information Sciences and Technology group at ORNL (Mckee et al., 2015). Data and projections are combined to identify locations suitable for green infrastructure placement on a geographic information system (GIS) map output at a 30-meter grid scale. Scales, indicators, and data can be manipulated by users within Urban-CAT to create multiple scenarios and decision-makers can access the Urban-CAT online (Omitaomu et al., 2016).

The authors of this paper participated in the development of Urban-CAT, which provided an opportunity to partake in the production of a knowledge system while developing the KSE framework. During the development of Urban-CAT, it became clear that it would be useful to have a framework for evaluating knowledge systems. To ensure the KSE framework was not developed to cater specifically to a single knowledge system, the KSE framework was refined by applying it to a second knowledge system, the Maine Flood Resilience Checklist (referred to herein as ‘the Maine Checklist’). The Maine Checklist was identified using the Climate Adaptation Knowledge Exchange (CAKEx) (www.cakex.org, last accessed May 1, 2018).

The CAKEx was used to search for knowledge systems because it provides useful and accessible information (contact information, cost, scale of analysis, target audience, type of tool); and because it is a curated exchange of knowledge systems (see Appendix A for more details on additional searches conducted). The CAKEx search was conducted on May 1, 2018 and two search filters were applied to filter by content type (“Tool”) and scale of project (“Community/Local”). The search returned 17 results. Next, the CAKEx entry page for each knowledge system was reviewed and the search results were refined to include knowledge systems with an associated entry page that specified the knowledge system was free to use, focused on the local level within the U.S., and had specific contact information. These actions refined the search to five knowledge systems that were reviewed for alignment to urban resilience, and the Maine Checklist was identified as the knowledge system most aligned. A KSE framework for the Maine Checklist was initiated on May 17, 2018 and finalized on July 6, 2018.

The Maine Checklist is a process-based facilitation-support knowledge system developed by a 2015-2017 National Oceanic and Atmospheric Administration Coastal Management Fellow in collaboration with the Maine Geological Survey (Sherwin, 2017). The Maine Checklist was created to guide coastal Maine communities through assessing their resilience to flood hazards and identifying priorities and actions based on extensive communication with personnel from multiple communities and Regional Planning Organizations (RPOs) in Maine, and other knowledge system producers to create, pilot, and refine the Maine Checklist. Many knowledge systems are linked within the Maine Checklist, but the knowledge system itself does not provide new data. Rather, the Maine Checklist is a series of questions organized by five sections (risk and vulnerability, critical infrastructure and facilities, community planning, social and economic vulnerability, and natural environment) to assess a community’s resilience to flood hazards. The Maine Checklist is procedural and explicitly states that a facilitator should provide guidance on completing it during a one- or two-day workshop with recommended participants.

Dimensions of the KSE Framework

The KSE framework consists of four dimensions: 1) the Element Overview organizes basic knowledge system information; 2) the Scalar Assessment compares a typology of decision-relevant scales with knowledge system; 3) the Resilience Assessment compares knowledge system alignment to resilience components and considerations; and 4) the Use Assessment tracks the use of a knowledge system, and any outcomes of that use, over time. The four dimensions of the KSE framework and their components are visualized in Figure 2 and explained next.

Element Overview

The Element Overview organizes basic information and knowledge system components (See Appendix B for an Element Overview template). Some elements are explicitly stated within knowledge system documents, while others can be identified by testing the knowledge system, and some may require communicating with knowledge systems producers to identify.

A simple knowledge system typology was developed for the KSE framework based upon Moss's (2016) distinction between systems that provide information (data-based) and support facilitation (process-based). As knowledge systems evaluation progresses, a more complex typology will likely emerge.

Methods used during the production and dissemination of a knowledge system should be acknowledged in the Element Overview. These include methods used to select, develop, validate, weight, or aggregate information; uncertainty

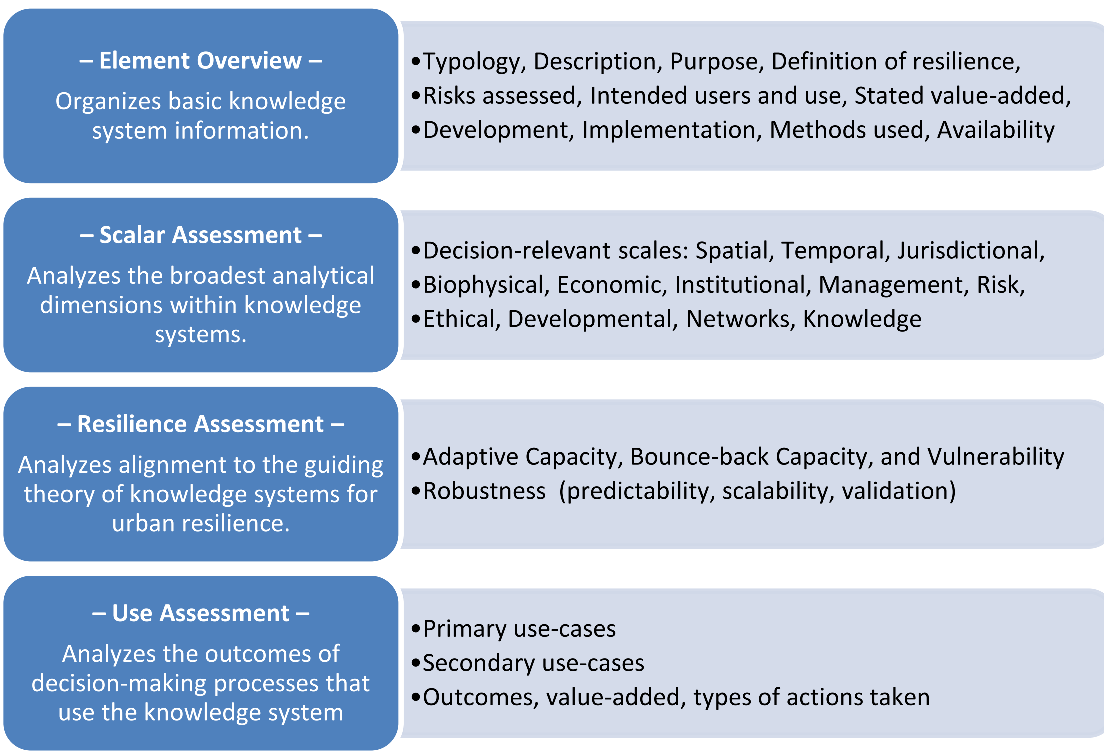

Figure 2 The four dimensions of the KSE framework and their components.

quantifications; and recognition of data issues or concerns like interdependencies or imbalances (Tran, 2016). These elements explore the considerations given to conducting and discussing uncertainty, peer-reviewed methodologies, and potential data issues and how clearly the knowledge system literature details these considerations.

Scalar Assessment

The Scalar Assessment identifies the decision-relevant scales addressed within each knowledge system and any levels that are represented within each scale. Scales are the broadest category of organization that bound a knowledge system, yet they often are not explicitly identified within knowledge systems. Scales are defined as the "spatial, temporal, quantitative, or analytical dimensions used to measure and study any phenomenon" and are divided by levels (i.e. units of analysis within a scale) (Cash et al., 2006 p. 2 based on Gibson et al., 2000).

The most common scales of analyses in human-environment interaction analyses are spatial, temporal, and jurisdictional scales though additional scales are relevant to decision-making (Buizer et al., 2011; Cash et al., 2006; Preston et al., 2015a).To assess scales, it must be understood that the construction of scales and levels within a knowledge system has inherent power relationships, is often contested, and is continually revised (Buizer et al., 2011; Swyngedouw and Heynen, 2003). The Scalar Assessment uses a typology of scales from Preston et al. (2015) (and expanded to include the social scale) to identify decision-relevant scales and levels represented in a knowledge system (See Table 4 for the scalar typology). Scales are useful concepts that help to identify and define the bounds of a system, yet they are often not explicitly identified or discussed within decision-making or knowledge systems.

Resilience Assessment

The Resilience Assessment examines knowledge system alignment to the concepts of resilience and robustness. To examine alignment with resilience, a knowledge system is assessed based on the consideration of adaptive capacity, bounce back capacity, and vulnerability. Combined, these elements to consider the ability of a city "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" as stated within Meerow et al.'s definition of urban resilience (2016, p. 39).

Table 4 Typology of decision-relevant scales adopted from Preston et al., 2015, p. 4.

Scales	Examples of Levels
Spatial	Individual—household—local—regional—national—global
Temporal	Hourly—daily—monthly—annual—decadal—millennial
Jurisdictional	Cities—counties—states/provinces—nations—multi-national—inter-national—global
Biophysical	Micro-organism—organism—species; Tree—forest—biome
Economic	Micro-Macro
Institutional	Bounded—unbounded
Management	Operating rules—policies—laws/regulations—constitutions
Risk	Negligible—manageable—intolerable
Ethical	Fair—unfair; Equal—unequal
Developmental	Under-developed—developing—rapid development—developed
Networks	Family—kin—society—trans-society
Knowledge	Specific—contextual; General—universal
Social	Friends—Acquaintances—Neighborhood—Community—Culture—Social network

Additionally, the Resilience Assessment considers whether a knowledge system is robust across systems. Specifically, robustness identifies whether a knowledge system is predictive (i.e. Does it use projections or consider future scenarios?), scalable (i.e. Is it useful across geographical and governance scales?), and if a knowledge system has been validated against real world data and knowledge. The Resilience Assessment was first applied to scales within a knowledge system and then combined into a comprehensive assessment of the knowledge system. Resilience Assessment templates are included in Appendix B for reference.

Use Assessment

The Use Assessment identifies how knowledge systems are used in decision-making processes and any outcomes related its use. Primary and secondary use-cases are identified for each knowledge system. A primary use-case exists if the knowledge system was developed specifically for that case. Primary-use cases are commonly included as a case study within knowledge system literature and documentation. Distinguishing primary and secondary use-cases enables the assessment of whether and how knowledge systems have been transferred beyond their primary use-case.

Use-cases are assessed based on any stated purpose, plans, or goals related to the use of a knowledge system, how knowledge system producers and users have interacted, how the knowledge system has been used, and whether any measurable actions have been taken after the knowledge system was used (a Use Assessment template is included in Appendix B). These data were obtained using published documents on the knowledge system, semi-structured interviews with knowledge system producers and users, and by applying the methodology to compare and characterize resilience outcomes from Lesnikowski et al. (2011).

The methodology from Lesnikowski et al. (2011) analyzes relevant city master plans; comprehensive annual financial reports; and adaptation, resilience, or sustainability-focused reports to capture any initiative or reference responding to adaptation, resilience, or other relevant issues (e.g. actions related to stormwater management or green infrastructure placement for the Urban-CAT KSE). Any action identified in communication with knowledge system users or producers should be noted, but additional documentation of the action should also be pursued. Actions will be categorized by component (implicit or explicit) and type which are described in Table 5 (Lesnikowski et al., 2011).

Lesnikowski et al. (2011) considers the use of an adaptation or resilience-focused knowledge system as a groundwork action, suggesting that progress has already occurred in use-cases. However, it is unclear whether and how the use of knowledge systems facilitates adaptation actions. Additionally, it is uncertain how quickly actions are implemented after knowledge systems are used and/or decision-making processes enter another phase. Identifying adaptation actions in use-cases may add clarity to these uncertainties.

Table 5 Typology of actions adopted from Lesnikowski et al., 2011, p. 3.

Name	Description
Statements of recognition	Demonstration of the ability to identify exposures/impacts.
Groundwork actions	Preparation steps for action with no explicit tangible policy/service changes (i.e. impact/vulnerability assessments, research on options, tools, recommendations for actions).
Adaptation actions	Changes to the built environment, the delivery of services, mandates, regulations to enhance resilience or in response to climate change impacts

Application, analysis and interpretation of the KSE framework

Data were collected to populate KSE frameworks for the Urban-CAT and the Maine Checklist by following the methodological steps detailed in Table 6. The KSE framework was populated as data was obtained so as much information was organized as possible before communicating with knowledge system producers and users. ‘

The Urban-CAT and the Maine Checklist KSE frameworks provide clarity on the scalability and use of knowledge systems, and how the configuration and application of knowledge systems influence decision-making processes. These results are interpreted specifically within the context of urban resilience and are discussed next.

Table 6 Methodological steps taken to populate the Urban-CAT and the Maine Checklist KSE frameworks.

Methodological steps taken to apply the KSE framework
1. Find the knowledge system and supporting documentation. Test the knowledge system (if applicable) and read supporting documentation. Conduct an internet and GoogleScholar™ search for additional information (e.g. project or knowledge system web pages, newspaper articles, gray literature, peer-reviewed publications).
2. Identify data changes or inconsistencies. Specify time and source components. Compile a list of questions related to changes or inconsistencies.
3. Identify knowledge system producers and users.
4. Contact knowledge system producers to discuss the knowledge system. - Explain goals of the project. - Discuss the use of the knowledge system in decision making, and any outcomes or added value related to the use of the knowledge system. Keep information on primary and secondary uses separate. - Inquire about the future of the knowledge system and any changes that have occurred. - Ask about inconsistencies and questions identified in Step 2. - Ask about connecting with knowledge system users.
5. Contact knowledge system users. Follow Step 4 as is appropriate.
6. Compare, contrast, correct, and standardize data into the KSE framework. Specify dates that data collection began and ended.

Results

The Urban-CAT and Maine Checklist results are presented separately and organized by Scalar Assessment, Resilience Assessment, and Use Assessment results. Each assessment is informed by the Element Overview. Particularly relevant KSE framework results are detailed in tables in this section, while all KSE framework results are attached in Appendices C and D.

The Urban-CAT KSE framework Results

The Urban-CAT: Scalar Assessment Results

The Urban-CAT includes spatial, temporal, jurisdictional, biophysical, economic, management, and risk scales. See Table 7 for Urban-CAT Scalar Assessment results. Some levels vary within scales based on the indicators being considered. For example, population, climate, and plant hardiness indicators are depicted spatially by 30-meter squared cells, and temporally using one historic timeline (1980-2005) and one future projection timeline (2025-2050) for climate and plant hardiness, and using the years 2010, 2030, and 2050 for population.

The Urban-CAT Social Vulnerability Index includes economic and risk scales that are spatially organized by census track but have no temporal information and use the Census American Community Survey from 2008-2012 for inputs. These scales include an economic (i.e. income) spectrum for the economic scale, and a spectrum of social vulnerability for the risk scale. These scales are spatially visualized across U.S. census tracts with a color gradient.

The jurisdictional scale is spatially divided by distinguishing between City of Knoxville and Knox County jurisdictional boundaries. The management scale presents areas suitable for green infrastructure and are spatially visualized based on different green infrastructure options suitable for a specific location.

Biophysical scales are included within the Urban-CAT, specifically soil hydrology (i.e. ranking of soil drainage), geology (claystone, limestone, dolostone, or sandstone), climate (minimum, maximum, average temperature and precipitation by month from 1980-2005 and 2025-2050), and plant hardiness (a range from 0-8).

While multiple scales are included within Urban-CAT, it is difficult to simultaneously visualize multiple scales on the map output and numerical information on scales or quantities within scales is not accessible. To do multi-scalar analysis within the Urban-CAT, some scales will need to be viewed individually, and their intensity is not well visualized unless compared with surrounding areas (i.e. a user can compare the Social Vulnerability Index of

Table 7 KSE Scalar Assessment: The Urban-CAT*

Scalar Typology	Scales included	Levels included
Spatial	Included, but varies across indicators	Parcels – neighborhoods - census tract – watershed basins - City of Knoxville, Knox County Population, climate, plant hardiness at 30 m square cells Economic, Risk scales by census tract
Temporal	Included within climate, population, plant hardiness zones	Population – 2010 – 2030 – 2050 Climate and Plant Hardiness Historic (1980-2005) – Projected (2025-2050) for: climate (minimum, maximum, average temperature and precipitation)
Jurisdictional	Included	City of Knoxville – Knox County
Biophysical	Included	Soil hydrology: poorly – well – excessively drained soil (spatial scale) Geology: claystone, limestone, dolostone Climate minimum, maximum, average temperature and precipitation for 1980-2005 and 2025-2050 Plant hardiness numbered range from 0-8
Economic	Included	Household socioeconomic status (spatial spectrum by census tract low-high)
Institutional	Not considered	
Management	Management	Green infrastructure suitability (spatial) – permeable pavers – bioretention basins – micro bioretention basins – managed vegetated areas – rainwater harvesting
Risk	Included as a consideration of social vulnerability	Vulnerable – Not vulnerable spectrum (composite of below indicators) Transportation access Socioeconomic status Household composition Minority status
Ethical	Not considered	
Developmental	Not considered	
Networks	Not considered	
Knowledge	Not considered	
Social	Not considered	

**Some text in Table 7 may be taken directly from Urban-CAT documents and is considered data.*

different locations within Knoxville but cannot get specific values for a location of interest in Knoxville). Therefore, Urban-CAT is helpful for spatially comparing different scales across space and time but does not provide insights into the conditions of a specific location beyond a visualized gradient.

The Urban-CAT: Resilience Assessment Results

Alignment to Resilience

The Urban-CAT assesses vulnerability but does not consider adaptive or bounce back capacity resilience components (See Table 8 for an overview of Urban-CAT Resilience Assessment results). Specifically, the Urban-CAT assesses vulnerability in the short- and long-term emphasizing social vulnerability and exposure to extreme temperature and precipitation. However, thresholds for exposure to extreme temperature and precipitation would need to be defined by knowledge system users. Additionally, the Urban-CAT literature (Nugent et al., 2017) defines resilience in accordance with Ross (2013) as a measure of eight components: climate, social community, capital, economic, institutional, infrastructure, and ecological. All components were considered except for the institutional component.

Alignment to Robustness

The Urban-CAT is not immediately transferable or scalable to other cases, because its current spatial extent is limited to east Tennessee. However, it is potentially spatially and contextually transferable to other U.S. cities, particularly those that are beginning to pursue green infrastructure strategies and that are focused on stormwater management. The major constraints to transferability and scalability are developing the climate data and projections and securing rights and permissions to use LandScan™ population projections (Mckee et al., 2015).

Population, climate, and plant hardiness projections make the Urban-CAT somewhat predictive, but no other indicators are predictive. Climate projections are presented as monthly minimum, maximum, and average temperature and precipitation projections for the range 2025-2050 (i.e. one January minimum temperature projection is provided for the year 2025-2050 for each 30-meter square raster cell throughout the spatial extent). Spatially explicit population projections are provided for the years 2010, 2030, and 2050. Plant hardiness projections specify which U.S. Department of Agriculture plant hardiness zones Knoxville will be in considering projected temperature and precipitation.

Table 8 KSE Resilience Assessment: The Urban-CAT

KSE Resilience Assessment summarized from the scale-based resilience assessments below		
Resilience component(s) considered	**Adaptive capacity**	Not considered
	Bounce-back capacity	Not considered
	Vulnerability	Primary consideration
Robustness	**Scalability**	Scalable throughout the U.S., but some climate data was derived specifically for the Urban-CAT and is only available for eastern Tennessee currently.
	Predictability	Most information is trailing.
		Climate and population projections are leading.
	Validation	Widely accepted system inputs, but have not been validated
Other concerns		Institutional scale was mentioned in literature and definition of resilience, but not included in the knowledge system.

The indicators used in Urban-CAT are widely used, but validation methodologies, uncertainty quantifications, and confidence intervals are not identified. Additionally, indicators with different spatial and temporal scales are combined into the map interface with little documentation for how to interpret these differences. Indicators can be turned on and off within Urban-CAT and most are difficult to visualize simultaneously. These factors add considerable user subjectivity to the use of Urban-CAT and these elements are not articulated within supporting documentation.

The Urban-CAT: Use Assessment Results

Knoxville decision-makers have used aspects of Urban-CAT in different capacities but have not yet used it to site locations of green infrastructure. See Table 9 for an overview of the Urban-CAT Use Assessment results. Still, elements of the tool have added value. Specifically, the drought analysis from Urban-CAT gave more precise estimates than what Knoxville was currently using, so Knoxville personnel have included that data into their Hazard Mitigation Plan. The Knoxville urban forester plans to alter recommendations for hardy trees to plant in Knoxville based on the plant hardiness projections in Urban-CAT.

Knoxville's use of Urban-CAT resulted in many groundwork actions, but no policy changes or changes to the built environment have been undertaken related to the use of Urban-CAT as of July 2018. The collaboration with ORNL is mentioned in the 2017 Sustainability Work Plan but is not discussed in other relevant documents (Comprehensive Annual Financial Reports, sustainability, stormwater, or urban forestry documents).

Table 9 KSE Use Assessment: The Urban-CAT

Use-cases and Actions	Urban-CAT
Suggested participants	No suggested participants
Suggested use-process	No suggested use process
Primary Use-Case	City of Knoxville, Tennessee decision-makers (sustainability manager, stormwater engineers, GIS analysts, urban planners)
Purpose/plans/Goals	Intended to use a straightforward, fast methodology (Urban-CAT) to highlight best areas for GI placement so that when development was initiated and stormwater management needed to be built the city could have potential sites available to work with rather than diverting to other costlier or less ideal locations.
Timeline/Stage of use	Two-year development process.
Interactions with knowledge-producers	Met about 4-5 times.
Use process	Used tool together at meetings, now is accessible online – urban forester uses it regularly
Explicit added value	Used drought analysis for hazard mitigation plan – more precise estimates than other data, going to the city council in a few months
	Changing recommendations for which trees to plant based on new USDA plant hardiness zones
Implicit added value	Brought together multiple departments that do not typically communicate much and increased collaborations with ORNL
	Better understand how other departments make decisions
	Ability to see the region, watershed, parcel and multiple factors together
	Can aggregate multiple factors together rather than take a subjective approach
Other knowledge systems used	None explicitly identified.
Written documentation	Collaboration is mentioned with ORNL, stated that it is in the "evaluation phase" http://knoxvilletn.gov/UserFiles/Servers/Server_109478/File/Sustainability/Sustainability%20Work%20Plan%202017.pdf, last accessed 06/16/2018
Secondary Use-Case(s)	None as of 06/23/2018

Implicitly, the exercise of using Urban-CAT enhanced collaborations with ORNL and brought different city decision-makers together who do not regularly meet. These meetings increased understanding of how different departments make decisions and enabled decision-makers to discuss and view Knoxville and the surrounding area using the Urban-CAT together. Users noted that bringing together multiple factors in Urban-CAT enabled them to view many scales together, and they perceived that this would help them take a less subjective approach to decision-making.

The Maine Checklist KSE framework Results

The Maine Checklist: Scalar Assessment Results

The Maine Checklist includes temporal, jurisdictional, and risk scales. See Table 10 for an overview of the Maine Checklist Scalar Assessment results. Temporally, the long-term and short-term are considered throughout the knowledge system but are not specifically defined. However, there are specific opportunities throughout the knowledge system use process to define these bounds.

The jurisdictional scale predominately focuses on the city departmental level and the city level, but also specifically considers the school level and business community level. Each of these levels is examined within the Maine Checklist and specific actions, responsibilities, and opportunities are identified for each level. The state level, Maine Emergency Management Agency (MEMA), and Federal Emergency Management Agency (FEMA) levels are discussed, but mostly regarding ways that these levels interact with the city level and business community levels and their associated and overlapping responsibilities.

The risk scale is the most considered throughout the Maine Checklist and is predominately focused on preparation and vulnerability to coastal hazards and flooding. The different levels are used depending on the different focus of specific parts of the checklist (i.e. the threatened and abandonment levels specifically pertain to critical infrastructure, natural resource areas, and housing stock).

The Maine Checklist: Resilience Assessment Results

Alignment to Resilience

The Maine Checklist considers each resilience component with a slight emphasis on vulnerability (see Table 11 for an overview of Maine Checklist Resilience Assessment results). The Maine Checklist is also well-aligned to its

Table 10 KSE Scalar Assessment: The Maine Checklist

Scalar Typology	Scales included	Levels included
Spatial	Not included	
Temporal	Included, but undefined	Long term—short term
Jurisdictional	Included	School/Business community - City departments (Land-use planning, hazard mitigation, emergency management) – City – State of Maine – MEMA – FEMA (NFIP-CRS)*
Biophysical	Not included	
Economic	Not included	
Institutional	Not included	
Management	Not included	
Risk	Included	Not prepared – preparations in process – prepared Not threatened – threatened and a plan is in place – abandonment plan Coastal Hazards: Vulnerable to potential future hazards – Very vulnerable to existing hazards Coastal/nuisance flooding – storm surge – sea level rise – coastal erosion/shoreline change
Ethical	Not included	
Developmental	Not included	
Networks	Not included	
Knowledge	Not included	
Social	Not included	

**Some text in Table 10 may be taken directly from Maine Checklist documents and is considered data.*
***Maine does not have counties, so they were not included.*

Table 11 KSE Resilience Assessment: The Maine Checklist

KSE Resilience Assessment summarized from the scale-based resilience assessments below		
Resilience component(s) considered	**Adaptive capacity**	Considered throughout the knowledge system
	Bounce-back capacity	Considered throughout the knowledge system
	Vulnerability	Considered throughout the knowledge system
Robustness	**Scalability**	Most transferable to other coastal city, county, or regional planning entities within the U.S. Critical infrastructure and facilities, community planning, and social and economic vulnerability scales are transferable beyond coastal geographies.
	Predictability	Not predictable. Many questions are based on status of an element.
		Much consideration for future conditions, but not predictable.
	Validation	Determined by the quality of the information provided by the participants. Not explicitly validated.
Other concerns		Many knowledge systems are linked throughout, without qualifying how data from each one could be used or interpreted.

stated definition of resilience: "the ability of a community to adapt to changing conditions, withstand disruption, and rapidly recover from emergencies" (Sherwin, 2017, p. 24).

Alignment to Robustness

The Maine Checklist can be immediately applied to secondary use-cases, though a facilitator is recommended. The Maine Checklist is best-aligned to assist coastal communities and communities in Maine. Maine RPOs have trained facilitators to implement the Maine Checklist for free, and Maine communities can receive a grant to put on a Maine Checklist workshop. The Risk and Vulnerability and Natural Environment sections are transferable to other coastal communities, while the other three sections (Critical Infrastructures and Facilities, Community Planning, and Social and Economic Vulnerability) are applicable across governance scales, spatial scales, and multiple contexts.

Transferability across Maine communities is likely because implementation plans were developed as the Maine Checklist was being developed. The creator of the Maine Checklist iterated with RPO staff during the Maine Checklist development and worked with state personnel to secure funding to support the implementation of the Maine Checklist. Some state personnel did not think communities would conduct the Maine Checklist without funding for it, so financial support was considered an important part of applying the Maine Checklist to multiple use-cases. Also, the knowledge system producer is currently employed with an RPO and oversees the implementation of the Maine Checklist.

The Maine Checklist primarily considers the current state of a community and is not predictive. Future conditions are considered, but primarily through the addition of existing knowledge systems or scenario development within the Maine Checklist process, neither of which are explicitly validated within knowledge system documentation.

The Maine Checklist: Use Assessment Results

The Maine Checklist has been used in Saco and South Portland, Maine thus far. See Table 12 for an overview of the Maine Checklist Use Assessment. Saco has added a new Sea Level Rise Chapter in their Comprehensive Plan that uses all the policies, strategies, and goals drafted during the Maine Checklist workshop. Saco has also updated the flood hazard information on their website and has taken and reported new actions towards the FEMA National Flood Insurance Program's (NFIP) Community Rating System as a direct result of completing the Maine Checklist Workshop.

Implicitly, Saco city staff noted that the process of completing the Maine Checklist was useful in terms of getting multiple, diverse decision-makers together and in identifying gaps, synergies, and potential opportunities for collaborations across city departments.

South Portland completed their Maine Checklist workshop in June 2018 and are currently implementing plans, actions, and strategies. No adaptation actions have been identified at this early stage. However, South Portland is using the Maine Checklist process to update their floodplain ordinance, identify action steps for their climate adaptation plan, and prioritize FEMA-NFIP Community Rating System action steps to take.

Implicitly, the Maine Checklist workshops increased overall understanding of resilience and sea level rise, provided some perceived legitimacy for the newer Sustainability Department, and brought a diverse group of participants together working towards common strategies.

South Portland and Saco cases both emphasized that the presence of a facilitator, and the suggestions the facilitator provided after each workshop as particularly useful and necessary to the Maine Workshop process and enabling specific outcomes from the process. As of June 28, 2018, Swan's Island and the Town of Orland are planning a Maine Checklist workshop.

Table 12 KSE Use Assessment: The Maine Checklist*

Use-cases and Actions	**The Maine Checklist**
Suggested participants	Planning staff, Municipal administrator, Code enforcement office, Floodplain manager, Emergency manager, Public works official, Economic development staff, Municipal engineer, Waterfront coordinator/harbormaster, Elected officials, Public safety officials, Conservation commission representative, Chamber of commerce representative, Neighborhood association representative, Local leader/resident
Suggested use-process	Designed to be completed through and community-based facilitated discussion process with key municipal officials and staff. Participation and dialoguing about local flood vulnerability, how well existing planning addresses flood hazards, and ways to improve resilience
	After completing the checklist, review responses in each section to identify areas in which your community is doing well and areas where improvements can be made Using checklist results and recommended next steps in Appendix A as guidance, identify specific actions and strategies your community would like to undertake to enhance local flood resilience. Results are time sensitive – consider revisiting the Checklist as social and environmental conditions change and as new data become available.
Use-Cases	
Primary Use-Case	Saco, Maine with the Southern Maine Planning and Development Commission
Purpose/Plans/Goals	For Maine's coastal communities to evaluate vulnerability to flood hazards and increase resilience.
Timeline/Stage of use	Spring 2017
Interactions with knowledge-producers	Two 2.5 hour workshops and a summary report provided at the end of the checklist process with recommendations on next steps and potential action items.
Use process	Facilitator led community through the checklist and provided recommendations after.
Explicit added value	SLR chapter in comprehensive plan – policies, strategies, goals were taken directly from the finished checklist report and are being integrated into policy now which will be updated in local regulations.
	Improving online GIS portal so flood hazard data is easier to access.
	Identified actions they had taken that could count towards CRS
Implicit added value	Brought multiple people from different departments who do not normally work together in on a project.
Other knowledge systems used	None identified.
Written documentation	Added SLR chapter to Comprehensive Plan with the policies, strategies, goals developed at Checklist workshops and from Checklist recommendations http://cms.revize.com/revize/saco/Comp%20Plan/Sec%207%20Sea%20Level%20Rise%20120517.pdf, last accessed 06/18/2018

Table 12. Continued.

Secondary Use-Case(s)	
Use-Case #2	South Portland, Maine
Purpose/plans/Goals	For Maine's coastal communities to evaluate vulnerability to flood hazards and increase resilience.
Timeline/Stage of use	Summer 2018
Interactions with knowledge-producers	Two 2.5-hour workshops and a summary report provided at the end of the checklist process with recommendations on next steps and potential action items.
Use process	Facilitator led community through the checklist and provided recommendations after.
Explicit added value	Using process to update floodplain ordinance, regulate housing to align with new FEMA floodplain maps that they will adopt early
	Putting action steps into climate adaptation and action plan
	Identified CRS action steps as they are planning to join CRS
	Provided clarity and action steps for applying to a grant
Implicit added value	Increased overall understanding of resilience
	Provided some perceived legitimacy for the sustainability department
	Participants reported that they learned more about SLR
	Brought diverse group of participants together who do not normally work together across projects.
Other knowledge systems used	SLR introduction at the beginning of the workshop that used different knowledge systems to visualize SLR changes
Measurable actions taken	Still in the planning phases (workshop was completed June 2018).
Use-case #3	Swan's Island (with facilitation by the Hancock County Planning Commission)
	Planned to initiate in fall 2018
Use-case #4	Town of Orland (with facilitation by the Hancock County Planning Commission)
	Planned to initiate in fall 2018

**Some text in Table 12 may be taken directly from Maine Checklist documents and is considered data.*

Discussion: Analyzing the KSE framework

The application of the KSE framework to the Urban-CAT and the Maine Checklist provides insights into advancing the evaluation of knowledge systems. We discuss three main insights next.

Accounting for context and communicating with knowledge system users

First, these applications reinforce the importance of thoroughly considering the contextual details of a knowledge system and the processes of its production, dissemination, and use (Miller et al., 2010; Muñoz-Erickson et al., 2017). For example, an evaluation of the Maine Checklist that would not have communicated with producers and users would have made the incorrect assumption that alignment to the FEMA-NFIP Community Rating System is an important factor attracting communities to use the Maine Checklist. Contrarily, it was revealed during interviews that the Community Rating System is somewhat controversial in Maine. Funders of the Maine Checklist also incorrectly perceived that linking to the Community Rating System would be important and emphasized it in the original Maine Checklist project description. Alternatively, many communities in Maine do not pursue the Community Rating System, and likely would have avoided the Maine Checklist if it was too focused on the CRS, which was recognized by the Maine Checklist producer, and was also identified during KSE framework discussions.

Second, talking to knowledge system users also revealed insights into how some users interpret the information provided within a knowledge system. For example, a few Urban-CAT users noted that using Urban-CAT helped them reduce subjectivity in the decision-making process. This interpretation likely stems from the way knowledge systems, in general, are often disseminated into decision-making processes, even though, at best, a knowledge system might displace subjectivity, but likely does not reduce it (Muñoz-Erickson et al., 2017). Care should be taken to detail the uncertainties and subjectivities within a knowledge system (Moss, 2016), and to note that the use of a knowledge system does not provide an avenue away from necessary decision-making tasks. For example, the Urban-CAT assessment of social vulnerability should not provide a justification to avoid necessary communication with citizens. The idea that Urban-CAT could reduce subjectivity was only brought up by its users indicating that facilitation and supporting documentation detailing the development, subjectivity, and uncertainty (or confidence) in a knowledge system would help improve user interpretation.

Additionally, the value-added identified in both KSE framework applications was predominately identified through producer and user discussions, which raises concerns about action identification methodologies that do not involve communication with decision-makers. Resilience building efforts like changing tree species recommendations or increased collaboration across city departments do not always fit into a budgetary line-item on a Comprehensive Annual Financial Report. Communicating with knowledge system producers and users is an essential part of understanding the multiple nuances, feedbacks, and outcomes of the use of knowledge for decision-making. Additionally, since enhancing resilience is as much a process as a set of actions (Vogel et al., 2007), methods to identify progress that rely solely on actions stated in reports are potentially missing resilience-building efforts that are not readily measured or outlined in a report.

Three approaches to using the KSE framework

The KSE framework is potentially applicable to knowledge system producers and users, as well as large-scale assessment processes focused on evaluating knowledge systems, like the U.S. National Climate Assessment. A decision-support chapter was included within the latest U.S. National Climate Assessment, but an evaluation process for knowledge systems has yet to be identified or used (Moss et al., 2014; Moss, 2016). The KSE framework represents a useful starting point for large-scale evaluation of knowledge systems, however it would be a time-intensive endeavor. We recommend that large-scale evaluation processes consider saving time by simplifying the KSE framework for knowledge systems that have not been used beyond the primary use-case. This would provide some standardized information on all knowledge systems but would focus efforts on knowledge systems that display the potential to scale-up beyond primary-use cases.

Additionally, knowledge system producers could use the KSE framework while planning, developing, and producing knowledge systems. Specifically, knowledge system producers could start by identifying the purpose and goals within the Element Overview, then consider the analytical bounds of the knowledge system by filling out the Scalar Assessment, and theoretical definitions and considerations within the Resilience Assessment. Then, the KSE framework could be continually revisited, provided to new knowledge system producers and users as the project expands, and used to provide continuity throughout knowledge system documents. The Use Assessment would help knowledge system producers think beyond the primary use-case and consider what kind of implementation plan or supporting documentation might be necessary to realistically support secondary use-cases.

Also, knowledge system users could reference the KSE framework to consider which knowledge systems to use. This may be a lengthy process, but the KSE framework organizes elements of knowledge systems to consider before using knowledge systems, and some users may find that useful. Specifically, boundary workers, agriculture extension agents, or planners at RPOs who recommend knowledge systems regularly may find the KSE framework useful to evaluate the knowledge systems they recommend.

Additionally, the KSE framework could provide guidance to knowledge system users to help them identify and ask questions relevant to their decision-making process that knowledge systems and knowledge systems producers may not have explicitly stated. Using the KSE framework in this way could potentially increase the agency of knowledge system users.

Considering implementation and facilitation strategies as aspects of knowledge systems production

Surprisingly, the Maine Checklist KSE revealed the lengths that a single knowledge system producer can take to make a knowledge system both useful and used. The degree to which the Maine Checklist knowledge system producer went to develop and institutionalize an implementation process is something that is not widely discussed in knowledge system production or dissemination literature. Specifically, she changed the focus of the project from a scorecard to a process-based checklist to be completed during a workshop; she iterated multiple times with numerous city personnel and RPO staff about what would be most useful to decision-makers; she communicated with producers of similar knowledge systems about what they did and also about what they would do differently; she trained facilitators to give the checklist within an already established and trusted organization (the RPOs); she set up a process for the facilitator to provide context-specific recommendations after each workshop; and she now works at a Maine RPO and oversees the implementation of the Maine Checklist workshops. Her methods to facilitate and institutionalize the use of the Maine Checklist are not widely discussed elements of most research-focused knowledge systems development processes.

This unanticipated finding related to the implementation of the Maine Checklist reinforces the importance of analyzing the broad conceptualization of knowledge systems collectively. The development of knowledge systems for urban resilience is a broad pursuit that brings together numerous disciplines, professional backgrounds, expertise, values, and communication styles (Meerow et al., 2016; Moss, 2016). Surely, by working towards the same goal from different vantage points and analyzing the many approaches taken to achieve that same goal, many useful insights can be identified, and eventually, implemented to make knowledge systems for urban resilience more effective. To the extent that knowledge systems are created to help decision-makers build resilience and make more effective decisions, knowledge system producers are tasked to consider untraditional research tasks beyond engaging stakeholders including learning how knowledge is best communicated, how assumptions and subjectivities within knowledge systems are effectively detailed, and how to effectively implement knowledge systems into decision-making processes after they have been created.

Alternatively, boundary organizations and other entities engage in this work, and it should not be left up to an individual knowledge systems producer to figure everything out about the knowledge production, dissemination, and use process. Yet, the *build it and they will come* mantra of climate information for decision-making is a fallacy (Dilling and Lemos, 2011; Feldman and Ingram, 2009; Woodruff and Stults, 2016). These realities emphasize the need for knowledge systems producers to collaborate and work in diverse groups with actors that have numerous areas of expertise beyond that of the science behind the information within a knowledge system, not to do everything themselves.

Overall the KSE framework organizes information on many facets of knowledge systems and could help knowledge system producers address potential gaps within their knowledge system, highlight methodologies or subjectivities to articulate to users, and consider important aspects of the knowledge systems development process.

Conclusions

If it is the priority of research institutions and funding agencies to add value to urban resilience efforts, then it is imperative to analyze knowledge systems for urban resilience and reflect on their development, use, and standard practices. Cities continue to lead resilience efforts in the U.S., while state and national levels avoid prescriptive policies or regulations (Arnott et al., 2016; Bierbaum et al., 2013; Bulkeley, 2010). Without national guidance on adaptation, urban resilience efforts, like the knowledge systems built for them, are piecemeal and disparately scattered across the U.S. Knowledge systems for urban resilience producers can work towards providing some clarity, congruity, and reflexivity within urban resilience efforts through reflection of the knowledge systems production, dissemination, and use processes. This reflexivity needs to consider the elements of a knowledge system as well as how the knowledge system is communicated and used in decision-making processes. The KSE framework provides a foundation for pursuing knowledge systems evaluation. However, this framework requires commitment by knowledge system producers and funders alike to think reflexively about what elements of knowledge systems for urban resilience are done well, and more importantly, what needs attention and improvement.

CONCLUSION

Climate changes combine with environmental changes, outdated infrastructure and energy systems, an aging and increasing population, and increasing population density along vulnerable coastlines and in other vulnerable geographies (i.e. wildfire prone areas, below glacial lakes held together by melting dams[4], where droughts and heat waves are common and increasing) to create losses and damages primarily experienced at the local level (Mimura et al., 2014; Nordgren et al., 2016; Porter et al., 2015). To what extent systems respond to losses and damages with holistic adaptations (i.e. adaptation efforts that consider related systems and do not displace negative consequences onto other systems, sectors, places, or people) (Ernst and Preston, 2017) remains to be seen. In general, the institutions that govern and manage urban, energy, and water systems are highly adapted to current (and sometimes past) conditions (Libecap, 2010), and accept certain unnecessary losses and damages that create new, and reinforce existing, inequalities (Burkettt, 2008; Leichenko et al., 2010; O'Brien and Leichenko, 2000; Weichselgartner and Kelman, 2015). Efforts focused on "bouncing-back" or a return to "previous conditions" reproduce unequal and unjust realities for some stakeholders, and are unsustainable for some existing systems (Weichselgartner and Kelman, 2015). Alternatively, new adaptation pathways can exploit existing or create new injustices, inequalities, or constraints for individuals, groups, or related systems (Barnett and O'Neill, 2010).

Adapting to new conditions effectively across systems without displacing negative consequences onto other people, places, or systems is difficult, but not impossible. However, many potential solutions that are effective across systems deviate from well-worn paths of dependence, many of which have been traced for decades, and sometimes centuries (Libecap, 2010; Preston, 2013). Additionally, stepping out of one dependence pathway commonly means stepping onto another (de Bremond et al., 2014). In contrast, many effective adaptation strategies are flexible, dynamic, and are generally more nuanced than large-scale infrastructure and technological fixes that create new dependence pathways (Pittock, 2011). For example, the Wonthaggi desalination plant in Melbourne, Australia was expensive, created path dependence, and only considered the water system; whereas

[4] A glacial outburst like this is called a jökulhlaup and can cause flash flooding and mudslides downstream from the jökulhlaup.

multiple flexible and cheaper alternatives could have been combined to create adaptation actions that were more effective across systems (Barnett and O'Neill, 2010). Rather than a few large-scale solutions, successful coupled systems adaptation often looks more like a nuanced suite of multiple changes that, when combined, transform systems.

The findings within this dissertation provide insights related to the effectiveness of current climate change adaptation efforts, and the knowledge systems that support these efforts. Adaptation efforts continue to increase, largely in response to previously experienced impacts (Klein et al., 2014; Mimura et al., 2014), and despite a lack of other change-inducing elements like widespread economic pressures or explicit policies, regulations, or financial support for adaptation (Adger et al., 2005; de Bremond et al., 2014; Nordgren et al., 2016; O'Neill and Handmer, 2012; Porter et al., 2015; Preston, 2013). Limitations of existing climate knowledge systems inhibit their effectiveness and influence on adaptation decision-making processes. Specifically, knowledge systems for adaptation align with predominate sector-specific framings of adaptation that lead to ineffective adaptation outcomes; climate knowledge system producers face constraints which, in turn, create new or exacerbate existing adaptation decision-making constraints; and knowledge systems for urban resilience and adaptation lack evaluation and validation, limiting the extent to which knowledge systems can evolve and become more effective.

This dissertation takes a step towards moving past knowledge system constraints on adaptation decision-making by identifying and analyzing these constraints and developing a framework to analyze knowledge systems. Future research should focus on 1) identifying generalized constraints to climate knowledge systems production processes beyond national contexts (Porter and Dessai, 2017; Skelton et al., 2017); 2) evaluating knowledge systems for adaptation to reflect on their configurations, development, use, and common practices (Miller et al., 2010; Moss, 2016; Muñoz-Erickson et al., 2017); 3) analyzing adaptation actions taken and how they are determined; 4) identifying and testing methods to assess costs, benefits, and impacts of adaptation implementation in consideration of coupled systems (Porter et al., 2015; Preston et al., 2015c), and 5) identifying adaptation decision-making processes and assessing the driving factors that influence adaptation actions, and their consideration of coupled systems.

This dissertation also identified specific ways knowledge systems for adaptation can be improved. Specifically, rigorous and increased reflexivity of the knowledge production process has the potential to improve knowledge systems for adaptation; coupled systems, tradeoffs, and co-beneficial opportunities need consideration or acknowledgement within knowledge systems to avoid negative consequences and missed co-benefits; and knowledge-producing institutions should adapt their frameworks, incentives, plans, and strategies to support the development of actionable information for adaptation decision-making processes.

Creating knowledge systems for adaptation that are reflexive, consider coupled systems, and detail elements that commonly encourage urban, energy, and water system decision-makers to make changes (policies, regulations, costs, benefits, system operability) is likely to enable more effective adaptation actions in well-resourced locales (Hughes, 2015) with motivated actors (Porter et al., 2015), particularly if a recent large-scale event has been partially attributed to climate change (i.e. Hurricane Sandy or Harvey) (Mimura et al., 2014). However, knowledge systems are not drivers of widespread adaptation actions. Reflexive and holistic knowledge systems for adaptation decision-making processes must also be combined with policy, regulations, and capital to ensure that climate change adaptation actions are widespread and effective across systems.

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APPENDICES

APPENDIX A: Further details on identifying the Maine Flood Resilience Checklist as a second urban resilience knowledge system

Choosing a web-resource to search for knowledge systems

We searched two other knowledge system databases in addition to the Climate Adaptation Knowledge Exchange (CAKEx). We searched the U.S. Climate Resilience Toolkit which returned 62 results after applying a filter to identify "Take action" as the resilience step. The U.S. Climate Resilience Toolkit could not be filtered to focus on a local or urban scale, and had broken links on a few of the initial results tested. The Adaptation Clearinghouse returned 34 results after filters were applied (local as the jurisdictional focus, data and tools as the category, and ["resilience" AND "adaptation" AND "urban"] as search terms). The Adaptation Clearinghouse returned numerous results that could be uploaded by anyone, whereas the CAKEx inclusions process involves vetting knowledge systems before inclusion into the knowledge exchange. These resources could be included in further analyses, but CAKEx provided the most complete, tangible results for testing the framework.

Steps completed to search for knowledge systems using CAKEx conducted on May 1, 2018

1. We went to: http://www.cakex.org/resources/type/tool. This action returned only tools present in the exchange and returns 171 results.
2. We filtered results by "scale of project" and chose "Community/Local" which returns 17 results. Next, we viewed the associated entry for each knowledge system and took out tools that did not specify contact information, did not specify that they were free, and were not based in the U.S. The Climate Smart Cities knowledge system did not have an entry webpage, so that tool was also not included.
3. Five knowledge systems were identified for as potential cases: Adaptation Workbook, Surging Seas, Maine Flood Resilience Checklist, Populations at Risk, and Stormtools.
4. After a cursory overview of each knowledge system, the Maine Flood Resilience Checklist was identified as a secondary test case because it most clearly aligned to planning for urban areas and building resilience.

Table 13 CAKEx search results.

CAKEx Knowledge Systems Identified	Contact information, cost, U.S. based
Green Infrastructure Toolkit	Not specified as free
Adaptation Workbook	**Contact information, cost, U.S. based**
Surging Seas	**Contact information, cost, U.S. based**
Naturally Resilient Communities	Not specified as free
Climate Smart Cities	Page not found
Maine Flood Resilience Checklist	**Contact information, cost, U.S. based**
Urban Adaptation Support Tool	Not U.S. based
The Umbrella	Not specified as free
STAR Communities Climate Change Guide	Not specified as free
Preparing for Climate Change: A Guidebook for Local, Regional	Not specified as free
Populations at risk	**Contact information, cost, U.S. based**
Local Government Climate Change Adaptation Toolkit	Not specified as free
Coastal Hazard Wheel	Not U.S. based
Climate Convenings Toolkit	No contact information
Local Climate Analysis Tool	No contact information, not specified as free
RABIT: Resilience Assessment Benchmarking and Impact Toolkit	Not U.S. based, not locally focused
Stormtools	**Contact information, cost, U.S. based**

APPENDIX B: Knowledge system evaluation (KSE) framework templates

Table 14 KSE framework: Element Overview Template.

KSE Elements	Description of each element
Typology	*Type of knowledge system (e.g. data-based or process-based)*
Description	*Description of the knowledge system*
Purpose	*Stated purpose*
Definition of resilience	*Stated definition of resilience*
Risks assessed	*Stated risks assessed*
Intended Users	*Stated intended users*
Intended Use	*Stated intended sue*
Links to additional	*Links to additional resources in knowledge system*
Stated value-added	*Stated value-added to decision-making processes*
Development	*Development process*
Implementation	*Implementation processes*
Method(s) for tracking use and actions taken	*Any method to track use and actions taken after use of the knowledge system*
Links to existing policies, regulations, frameworks	*Any policies, regulations, frameworks that are aligned with the knowledge system*
Citation	*Citation of the knowledge system*
Availability	*Where the knowledge system can be accessed*
Methodologies used during knowledge system production and/or dissemination	
Weighting methodology	*Were scale or indicator weighting methodologies used? Which*
Methods used to develop	*Were methods to develop indicators used? Which ones?*
Methods used to detail	*Were methods used to detail uncertainty or confidence? Which*
Interdependency	*Are indicators causally related?*
Imbalance	*Is one theme over- or under-emphasized?*
Scale mismatch	*Is data being used at an inappropriate scale?*

Italicized text details the information that populates the cell.

Table 15 KSE framework: Scalar Assessment Template.

Scalar Typology	Scales included	Levels included
Spatial	*Detail the scales present within the knowledge system.*	*Detail the levels present within the knowledge system.*
Temporal		
Jurisdictional		
Biophysical		
Economic		
Institutional		
Management		
Risk		
Ethical		
Developmental		
Networks		
Knowledge		
Social		

Italicized text details the information that populates the cell.

Table 16 KSE framework: Resilience Assessment Template.

Resilience Assessment Template		
Resilience	**Adaptive Capacity**	*Is adaptive capacity considered?*
	Bounce-Back Capacity	*Is bounce back capacity considered?*
	Vulnerability	*Is vulnerability considered in the short-term?*
Robustness	**Predictability**	*Does the system use projections and/or consider or use future scenarios?*
	Scalability	*Is the system usable and available across geographical and governance scales?*
	Validation	*Has the system been validated against real world data and knowledge?*

Italicized text details the information that populates the cell.

Table 17 KSE framework: Use Assessment Template

Use-cases and Actions	***Name of the knowledge system***
Suggested participants	*Suggested participants to effectively use the knowledge system.*
Suggested use-process	*Suggested process to effectively use the knowledge system.*
Primary Use-Case	*Specific case the knowledge system was developed for.*
Purpose/goals	*Summary of the intentions for use of the knowledge system.*
Timeline/Stage of use	*Timeline of development, stage of development and/or use.*
Interactions with knowledge system producers	*Type and amount of interactions with knowledge system producers.*
Use process	*The way(s) users engage(d) with the knowledge system.*
Explicit added value	*Tangible actions taken that have resulted in changes to policies or plans; daily activities; different goals, strategies, or actions; or recommendations.*
Implicit added value	*Other value-added because of using the knowledge system (e.g. increased communication between departments, brought together participants that do not typically communicate, realized that a website was no longer active, learned about sea-level rise, understand resilience better).*
Other knowledge systems used	*Lists any additional knowledge systems used throughout the decision-making process.*
Written documentation	*Identify any documentation of use or of actions taken after use.*
Secondary Use-Case(s)	*Use the same inputs as the primary use-case*

Italicized text details the information that populates the cell.

APPENDIX C: The Urban-Climate Adaptation Tool Knowledge System Evaluation framework

Note that some text used to populate the KSE framework is taken directly from Urban-CAT documents and is considered data for the KSE framework.

Table 18 KSE Element Overview: The Urban-CAT

Elements	Urban-CAT
Typology	Data-based
Description	Map-based, non-regulatory, scenario planning tool focused on stormwater management
Purpose	Assess urban vulnerability to climate change
	Identify optimal conditions for green infrastructure placement
Definition of resilience	Measure of eight components (Berkes and Ross, 2013) – climate, social, community, capital, economic, institutional, infrastructure, ecological
Risks assessed	Flooding (extreme precipitation)
	Extreme temperature
	Calculate vulnerability based on resilience components (climate, social, community, capital, economic, institutional, infrastructure, ecological)
Intended Users	City decision-makers focused on stormwater management and green infrastructure placement
Intended Use	Designed to inform strategic emplacement of green infrastructure to alleviate urban flooding and costly stormwater management projects
	No specific process for how/when to use
Links to additional resources	No links to additional resources
Stated value-added	Evaluate climate change impacts on urban infrastructure
	Identify/prioritize adaptation options for minimizing impacts
	Explore the potential benefits of the adaptation options under different scenarios related to urban growth and infrastructure evolution
	Facilitate communication among urban policy decision-makers
	Promote science-driven policies and regulations for updating urban infrastructure
	Help to quickly identify, adapt for, and mitigate emerging environmental problems
	Provide guidance for planning judicious urban development
	Assess urban resilience using a system of indicators
	Monitor and evaluate the effectiveness of selected adaptation actions in reducing risk
	Characterize the complex Knoxville urban landscape and its water infrastructure
	Identify areas vulnerable to flooding, discriminate system exposure, sensitivity, and stress

Table 18. Continued.

Funding/Implementation plans, links to policies, regulations, frameworks, knowledge systems	
Development	In response to the US President's [Obama] call to leverage open government data resources to build tools that will make America's communities more resilient to climate change
	2014-2016, Sponsored by the Computational Sciences and Engineering Division, Climate and Environmental Sciences Division from a Lab Directed Research and Development Grant
Implementation	Implemented with the city of Knoxville, TN during development, no current implementation plans
	Partnering with the Engineering for Climate Extremes Partnership to explore expansion to other cities and applications.
Method(s) for tracking use and actions taken	None
Additional resources provided	None
Links to existing policies, regulations, frameworks, knowledge systems	Related to U.S. EPA Clean Water Act focus on green infrastructure placement in cities
Citation	Omitaomu, Olufemi A, Parish, Esther S, and Nugent, Philip J. A Decision Analysis Tool for Climate Impacts, Adaptations, and Vulnerabilities. United States: N. p., 2016. Web.
Availability	https://urbancat.extranet.ornl.gov/
Methodologies used during knowledge system production and/or dissemination	
Weighting methodology	Scales are of equal weight and not proportioned
Methods used to develop indicators	None identified.
Methods used to detail uncertainty/confidence	None identified.
Interdependency Are indicators causally related?	Some socio-economic, capital and community indicators are casually related.
Imbalance, Is one theme over- or under-emphasized?	Not currently.
Scale mismatch, Is data being used at an inappropriate scale?	No.

Table 19 KSE Scalar Assessment: The Urban-CAT

Scalar Typology	Scales included	Levels included
Spatial	Included, but varies across indicators	Parcels – neighborhoods - census tract – watershed basins - City of Knoxville, Knox County Population, climate, plant hardiness at 30 m square cells Economic, Risk scales by census tract
Temporal	Included within climate, population, plant hardiness zones	Population – 2010 – 2030 – 2050 Climate and Plant Hardiness Historic (1980-2005) – Projected (2025-2050) for: climate (min, max, average temperature and precipitation) Plant hardiness zones
Jurisdictional	Not considered	City of Knoxville – Knox County
Biophysical	Included	Soil hydrology: poorly – well – excessively drained soil (spatial scale) Geology: claystone, limestone, dolostone Climate min, max, average temperature and precipitation for 1980-2005 and 2025-2050 Plant hardiness numbered range from 0-8
Economic	Included	Household socioeconomic status (spatial spectrum by census tract low-high)
Institutional	Not considered	
Management	Not considered	Green infrastructure suitability (spatial) – permeable pavers – bioretention basins – micro bioretention basins – managed vegetated areas – rainwater harvesting
Risk	Included as a consideration of social vulnerability	Vulnerable – Not vulnerable spectrum (composite of below indicators) Transportation access Socioeconomic status Household composition Minority status
Ethical	Not considered	
Developmental	Not considered	
Networks	Not considered	
Knowledge	Not considered	
Social	Not considered	

Table 20 KSE Resilience Assessment: The Urban-CAT

KSE Resilience Assessment summarized from the scale-based resilience assessments below		
Resilience component(s) considered	**Adaptive capacity**	Not considered, 0
	Bounce-back capacity	Not considered, 0
	Vulnerability	Main resilience consideration, 1
Robustness	**Scalability**	Scalable throughout the U.S., but some climate data was derived specifically for this knowledge system (East Tennessee extent).
	Predictability	Most scales are trailing.
		Climate and population projections are leading.
	Validation	Widely accepted system inputs, but has not been validated
	Other concerns	Institutional scale was mentioned in literature and definition of resilience, but not included in the knowledge system.

Table 21 KSE Use Assessment: The Urban-CAT

Use-cases and Actions	**Urban-CAT**
Suggested participants	No suggested participants
Suggested use-process	No suggested use process
Primary Use-Case	City of Knoxville, Tennessee decision-makers (sustainability manager, stormwater engineers, GIS analysts, urban planners)
Purpose/plans/Goals	Intended to use a straightforward, fast methodology (Urban-CAT) to highlight best areas for GI placement so that when development was initiated and stormwater management needed to be built the city could have potential sites available to work with rather than diverting to other costlier or less ideal locations.
Timeline/Stage of use	Two-year development process.
Interactions with knowledge-producers	Met about 4-5 times.
Use process	Used tool together at meetings, now is accessible online – urban forester uses it regularly
Explicit added value	Used drought analysis for hazard mitigation plan – more precise estimates than other data, going to the city council in a few months
	Changing recommendations for which trees to plant based on new USDA plant hardiness zones
Implicit added value	Brought together multiple departments that do not typically communicate much and increased collaborations with ORNL
	Better understand how other departments make decisions
	Ability to see the region, watershed, parcel and multiple factors together
	Can aggregate multiple factors together rather than take a subjective approach
Other knowledge systems used	None explicitly identified.
Written documentation	Collaboration is mentioned with ORNL, stated that it is in the "evaluation phase" http://knoxvilletn.gov/UserFiles/Servers/Server_109478/File/Sustainability/Sustainability%20Work%20Plan%202017.pdf, last accessed 06/16/2018
Secondary Use-Case(s)	None as of 06/23/2018

Section-based KSE Resilience Assessments

These three assessments are combined to create the overall KSE Resilience Assessment in the table above.

Table 22 Resilience Assessment Section 1: Social, Community, Capital, Economic, and Institutional sections for the Urban-CAT

Urban-CAT Resilience Assessment of the Social, Community, Capital, Economic, and Institutional sections which uses the Social Vulnerability Index used by the U.S. Center for Disease Control (Flanagan et al., 2011; CDC, 2016) and LandSCAN and LandCAST data		
Description	15 variables, organized by 4 themes (Socioeconomic, Household composition/disability, Minority status/language, housing/transportation) using data from the 2008-2012 Census American Community Survey + Population Change using data from LandScan and LandCast	
Input type(s)	Raster data	
Relevance to Resilience	**Adaptive Capacity**	NA (not available)
	Bounce-Back Capacity	NA
	Vulnerability	1
Robustness	**Predictability**	All census data is trailing (2008-2012) LandCast data is leading – 2030 and 2050
	Scalability	1, Available and transferable across the United States at the urban scale or larger, applicable to many different contexts.
	Validation	Widely accepted, accuracy has not been validated

Table 23 Resilience Assessment Section 2: Ecological and Infrastructure sections for the Urban-CAT

Urban-CAT Resilience Assessment of the Ecological and Infrastructure Sections		
Description	Produced data on impaired streams, tree canopy, calculated slope, FEMA flood zones	
Input type(s)	Raster data	
Relevance to Resilience	**Adaptive Capacity**	NA (not available), 0
	Bounce-Back Capacity	NA, 0
	Vulnerability	1
Robustness	**Predictability**	All indicators are trailing
	Scalability	1, Available and transferrable across the U.S. at the urban scale or larger. Particularly relevant for stormwater management, forestry
	Validation	FEMA data and slope inputs are widely accepted, produced inputs are provided by city and regional personnel and are not necessarily validated

Table 24 Resilience Assessment Section 3: Climate section for the Urban-CAT

Urban-CAT Resilience Assessment of the Climate Section		
Description	Downscaled and bias-corrected climate data produced by ORNL	
Input type(s)	Raster data	
Relevance to resilience	**Adaptive Capacity**	NA (not available) 0
	Bounce-Back Capacity	NA, 0
	Vulnerability	1, Projected climate extremes are calculated
Robustness	**Predictability**	Historic climate data are trailing indicators
		Projected climate data and climate extremes are leading indicators
	Scalability	0.5*, Developed specifically for this project, potentially available for other cities in East Tennessee. **Scalable, if it were developed.*
	Validation	Downscaled and bias-corrected data developed for Urban-CAT, has not been validated

Table 25 The Urban-CAT – Data Overview

Data Overview of Scales included in the Urban-CAT			
Overview: scales are populated with information that is arranged by indicators (multiple data source inputs categorized) or variables (a single data-sourced input). Input, Type/Format, and Source are defined			
Scale	**Primary Input**	**Secondary Input**	**Additional details**
Ecological	Impaired Streams	TDEC 303d listed "impaired" streams in 2014	Plan East Tennessee-derived
	TreeCanopy	% Tree cover (2013-2015) – Tree canopy <40% is highlighted as "risk canopy" (trailing)	Knoxville-derived
	Slope	Calculated	Map algebra
	100-year Flood Zone 500-year Flood Zone	2013 FEMA data (trailing) (1% and .2% annual chance of flooding) 30mgrid	FEMA
Climate	Climate history	1960-2005 temperature and precipitation	Oak Ridge National Laboratory (ORNL)-derived
	Climate projections	2010-2050 temperature and precipitation	ORNL-derived
Social, economic, capital, community	Social Vulnerability Index (2008-2012 census)	% below poverty	Census American Community Survey (ACS) 2008-2012 variables
		% civilian unemployed	
		Inverse per capita income	
		% persons no high school diploma	
	Population	Population change	LandSCAN/LandCAST
		Population density increase	
	Household composition/disability	Persons over 65+% 17 or younger	Census American Community Survey (ACS) 2008-2012 variables
		% persons older than 5 with disability	
		% male or female householder	
		no spouse present, with children under 1	
	Minority status	% minority	
		% persons over 5 years who speak English less than well	
	Housing and transportation	% multi-unit structure	
		% mobile homes	
		Crowding	
		No vehicle available	
		% persons in group quarters	
Infrastructure	Impervious areas	Highly impervious areas	LandUse/LandChange maps from ORNL, no source specified
	Sewer pipe layouts	Sewer pipe layouts	Knoxville-derived
Institutional	No data/indicators identified		

Sources used to complete the Urban-CAT KSE framework

Urban-CAT is available to view and test here, registration is required https://urbancat.extranet.ornl.gov/map, last accessed, July 6, 2018

1. Project Summary, Urban Climate Adaptation Tool, https://udi.ornl.gov/content/urban-climate-adaptation-tool-urban-cat, Last Accessed 05/03/2018
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10. Developing a Climate-Induced Social Vulnerability Index for Urban Areas: A Case Study of East Tennessee, https://info.ornl.gov/sites/publications/Files/Pub75836.pdf

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1. City of Knoxville Comprehensive Annual Financial Reports, 05/07/2018

a. 2015 http://www.knoxvilletn.gov/UserFiles/Servers/Server_109478/File/Finance/CAFR/CAFR_fy2015.pdf
b. 2016 http://www.knoxvilletn.gov/UserFiles/Servers/Server_109478/File/Finance/CAFR/CAFR_fy2016.pdf
c. 2017 http://www.knoxvilletn.gov/UserFiles/Servers/Server_109478/File/Finance/CAFR/CAFR_fy2017.pdf

2. Urban Forestry Department website and documents, http://www.knoxvilletn.gov/cms/One.aspx?portalId=109562&pageId=206873, 05/14/2018
3. Stormwater Engineering Department website and documents, http://www.knoxvilletn.gov/cms/One.aspx?portalId=109562&pageId=195088, 05/14/2018
4. Sustainability Department website and documents, http://www.knoxvilletn.gov/cms/One.aspx?portalId=109562&pageId=195088, 05/14/2018

APPENDIX D: The Maine Flood Resilience Checklist Knowledge System Evaluation framework

Note that some text used to populate the KSE framework is taken directly from Maine Flood Resilience Checklist (the Maine Checklist) documents and is considered data for the KSE framework.

Table 26 KSE Element Overview: The Maine Checklist

Elements	The Maine Checklist
Typology	Process-based facilitation-support tool
Description	Text-based, non-regulatory self-assessment facilitative planning checklist focused on flooding
	Questions are organized by five scales and increase in complexity
Purpose	Integrated framework to guide communities through examining local flood risk, assessing vulnerability, identifying strategies, and planning for action to increasing resilience
	Evaluate how well positioned communities are to prepare for, respond to, recover from flooding events and SLR
Definition of resilience	The ability of a community to adapt to changing conditions, withstand disruption, and rapidly recover from emergencies
Risks assessed	Existing/potential future flood hazards
	Hurricane and storm surge inundation
	SLR
Intended Users	Communities in coastal Maine
Intended Use	Designed to be completed through a community-based, facilitated discussion process in which key municipal staff and decision-makers participate in a dialogue about local flood vulnerability, how well existing plans, policies, and actions address flood hazards, and ways to enhance resilience
	Specific and detailed facilitation process to use
Links to additional resources	Numerous links to existing resources (53) throughout the checklist process and development
Stated value-added	Prepare for increasing flood hazards and SLR
	Build and operationalize resilience
	Reduce vulnerability
	Evaluate preparedness, improve understanding for existing and future flood hazards
	Examine local flood risk
	Assess vulnerability and resilience of existing natural, built, and social environments
	Engage a diverse group of decision-makers about flood preparedness
	Enhance information sharing across municipal departments
	Integrate flood resilience into existing plans and policies
	Identify ways to reduce flood insurance costs by earning points through FEMA’s NFIP CRS
	Identify specific opportunities and actions to enhance community flood resilience
Funding/Implementation plans, links to policies, regulations, frameworks, knowledge systems	
Development	National Oceanographic and Atmospheric Administration (NOAA) Office for Coastal Management funded through a contract with Tridec Technologies and created by a 2015-2017 NOAA Coastal Management Fellow

Table 26. Continued.

Implementation	Island Institute Technical Assistance Fund provided grants for communities to go through the checklist process ($500-6000)
	Maine Regional Planning Commission helps communities go through the checklist facilitation process
Method(s) for tracking use and actions taken	Checklist downloads are tracked (256 since August 17, 2017 as of 07/06/2018)
	Asks communities to share completed checklist with the Maine Geological Survey and/or Municipal Planning Assistance Program
	Participant list with date, facilitator, and participants is provided to track progress and participation over time
	Five question evaluation form for every participant
	Wants to track influence but is not formalized.
Additional resources provided	53 resources provided. Some are organized by scale in the checklist, additional ones are listed at the end. Located at different places to approach at different times or focused on specific scales and analyses.
Links to existing policies, regulations, frameworks, knowledge systems	Process highlights steps to earning points in the National Food Insurance Program's Community Rating System (FEMA), reducing flood insurance costs
	Regional Planning Organization staff have been trained to help communities complete the Checklist and facilitate the discussion process.
Citation	Sherwin, Abbie, 2017, Maine Flood Resilience Checklist; A self-assessment tool for Maine's coastal communities to evaluate vulnerability to flood hazards and increase resilience: Maine Geological Survey, Open-File Report 17-15, report 44 p.. *Maine Geological Survey Publications*. 521. http://digitalmaine.com/mgs_publications/521
Availability	http://digitalmaine.com/cgi/viewcontent.cgi?article=1520&context=mgs_publications
Methodologies used during knowledge system production and/or dissemination	
Weighting methodology	Scales are not weighted.
Methods used to develop indicators	Interviews with producers of previous similar knowledge systems about what they would do differently and lessons learned. Built off a resilience definition that includes the five scales considered.
Methods used to detail uncertainty/confidence	Since no data is included in the knowledge system, uncertainty and confidence methods are not used. However, many knowledge systems are linked and there is no discussion of uncertainty or confidence related to applying them to decision-making.
Interdependency Are indicators causally related?	No.
Imbalance, Is one theme over- or under-emphasized?	Not currently.
Scale mismatch, Is data being used at an inappropriate scale?	No.

Table 27 KSE Scalar Assessment: The Maine Checklist

Scalar Typology	Scales included	Levels included
Spatial	Not included	
Temporal	Included, but undefined	Long term—short term
Jurisdictional	Included	School/Business community - City departments (Land-use planning, hazard mitigation, emergency management) – City – State of Maine – MEMA – FEMA (NFIP-CRS)*
Biophysical	Not included	
Economic	Not included	
Institutional	Not included	
Management	Not included	
Risk	Included	Not prepared – preparations in process – prepared Not threatened – threatened and a plan is in place – abandonment plan Coastal Hazards: Vulnerable to potential future hazards – Very vulnerable to existing hazards Coastal/nuisance flooding – storm surge – sea level rise – coastal erosion/shoreline change
Ethical	Not included	
Developmental	Not included	
Networks	Not included	
Knowledge	Not included	
Social	Not included	

**Maine does not have counties, so they were not included*

Table 28 KSE Resilience Assessment: The Maine Checklist

KSE Resilience Assessment summarized from the scale-based resilience assessments below		
Resilience component(s) considered	**Adaptive capacity**	Considered throughout the knowledge system
	Bounce-back capacity	Considered throughout the knowledge system
	Vulnerability	Considered throughout the knowledge system
Robustness	**Scalability**	Most transferable to other coastal city, county, regional planning entities within the U.S. Critical infrastructure and facilities, community planning, and social and economic vulnerability scales are transferable beyond coastal geographies.
	Predictability	Not predictable. Many questions are based on the status of something.
		Much consideration for future conditions, but not predictable.
	Validation	Determined by the quality of the information provided by the participants. Not explicitly validated.
	Other concerns	Many knowledge systems are linked throughout, without qualifying how data from each one could be used or interpreted.

Table 29 KSE Use Assessment: The Maine Checklist

Use-cases and Actions	**The Maine Checklist**
Suggested participants	Planning staff, Municipal administrator, Code enforcement office, Floodplain manager, Emergency manager, Public works official, Economic development staff, Municipal engineer, Waterfront coordinator/harbormaster, Elected officials, Public safety officials, Conservation commission representative, Chamber of commerce representative, Neighborhood association representative, Local leader/resident
Suggested use-process	Designed to be completed through and community-based facilitated discussion process with key municipal officials and staff. Participation and dialoguing about local flood vulnerability, how well existing planning addresses flood hazards, and ways to improve resilience
	After completing the checklist, review responses in each section to identify areas in which your community is doing well and areas where improvements can be made Using checklist results and recommended next steps in Appendix A as guidance, identify specific actions and strategies your community would like to undertake to enhance local flood resilience. Results are time sensitive – consider revisiting the Checklist as social and environmental conditions change and as new data become available.
Use-Cases	
Primary Use-Case	Saco, Maine with the Southern Maine Planning and Development Commission
Purpose/Plans/Goals	For Maine's coastal communities to evaluate vulnerability to flood hazards and increase resilience.
Timeline/Stage of use	Spring 2017
Interactions with knowledge-producers	Two 2.5 hour workshops and a summary report provided at the end of the checklist process with recommendations on next steps and potential action items.
Use process	Facilitator led community through the checklist and provided recommendations after.
Explicit added value	SLR chapter in comprehensive plan – policies, strategies, goals were taken directly from the finished checklist report and are being integrated into policy now which will be updated in local regulations.
	Improving online GIS portal so flood hazard data is easier to access.
	Identified actions they had taken that could count towards CRS
Implicit added value	Brought multiple people from different departments who do not normally work together in on a project.
Other knowledge systems used	None identified.
Written documentation	Added SLR chapter to Comprehensive Plan with the policies, strategies, goals developed at Checklist workshops and from Checklist recommendations http://cms.revize.com/revize/saco/Comp%20Plan/Sec%207%20Sea%20Level%20Rise%20120517.pdf, last accessed 06/18/2018

Table 29. Continued.

Secondary Use-Case(s)	
Use-Case #2	South Portland, Maine
Purpose/plans/Goals	For Maine's coastal communities to evaluate vulnerability to flood hazards and increase resilience.
Timeline/Stage of use	Summer 2018
Interactions with knowledge-producers	Two 2.5-hour workshops and a summary report provided at the end of the checklist process with recommendations on next steps and potential action items.
Use process	Facilitator led community through the checklist and provided recommendations after.
Explicit added value	Using process to update floodplain ordinance, regulate housing to align with new FEMA floodplain maps that they will adopt early
	Putting action steps into climate adaptation and action plan
	Identified CRS action steps as they are planning to join CRS
	Provided clarity and action steps for applying to a grant
Implicit added value	Increased overall understanding of resilience
	Provided some perceived legitimacy for the sustainability department
	Participants reported that they learned more about SLR
	Brought diverse group of participants together who do not normally work together across projects.
Other knowledge systems used	SLR introduction at the beginning of the workshop that used different knowledge systems to visualize SLR changes
Measurable actions taken	Still in the planning phases (workshop was completed June 2018).
Use-case #3	Swan's Island (with facilitation by the Hancock County Planning Commission)
	Planned to initiate in fall 2018
Use-case #4	Town of Orland (with facilitation by the Hancock County Planning Commission)
	Planned to initiate in fall 2018

The Maine Checklist Resilience Assessments by section.

These five assessments are combined to create the overall Maine Checklist KSE Resilience Assessment in the above table.

Table 30 Resilience Assessment Section 1: Risk and Vulnerability section of the Maine Checklist

The Maine Checklist Resilience Assessment of Risk and Vulnerability sections		
Description	Assessing risk and vulnerability is a critical first step to understand and address possible impacts to people, property, and natural resources. Assesses general risk and vulnerability from existing and potential future flood hazards so priorities can be established, and progress may be measured.	
Input types	Links to eight resources for assessing and visualizing various flood inundation scenarios and local impacts. A ten-question checklist with yes/no questions, some options provided and the opportunity to write notes as necessary.	
Relevance to Resilience	**Adaptive Capacity**	0.2, 2/10 (considered in 2 of 10 questions asked)
	Bounce-back capacity	Not considered
	Vulnerability	0.9, 9/10
Robustness	**Predictability**	Includes both trailing and leading considerations, more emphasis on trailing considerations, with numerous notes to consider potential future impacts
	Scalability	0.5, Potentially applicable at the county or regional scale, not as applicable at larger scales *(NOTE: Maine does not have counties).* Most applicable to coastal areas that experience or potentially will experience, flood hazards and sea level rise
	Validation	Determined by the quality of the information provided by the participants. Not explicitly validated.

Table 31 Resilience Assessment Section 2: Critical Infrastructure and Facilities section of the Maine Checklist

The Maine Checklist Resilience Assessment of the Critical infrastructure/facilities section		
Description	Step by step process to identify critical infrastructure and facilities for a community and to develop a plan to ensure that critical assess are operational and accessible during flood conditions to protect the health, safety, and wellbeing of community members.	
Input types	Suggests five resources to identify, map and assess operation and maintenance of critical infrastructure. 12 yes or no questions with supporting information to assess critical infrastructure facilities for a community and identify next steps and priorities	
Relevance to Resilience	**Adaptive Capacity**	0.9, 11/12
	Bounce-back capacity	0.7, 8/12
	Vulnerability	0.9, 11/12
Robustness	**Predictability**	All questions have some trailing elements to them. 1/3 of the questions consider leading information
	Scalability	1, Applicable across governance levels and contexts, geographic locations, and transferable to other cities
	Validation	Determined by the quality of the information provided by the participants. Not explicitly validated.

Table 32 Resilience Assessment Section 3: Community Planning section of the Maine Checklist

The Maine Checklist Resilience Assessment of Community Planning		
Description	Section incorporates information about community planning, emergency preparedness, and natural resource management to highlight the interconnectedness of land use planning, hazard mitigation, and emergency management and emphasize the importance of integrating those sectors within communities to enhance resilience	
Input types	Highlights three plans to use as resources (Comprehensive, Hazard Mitigation, and Emergency Response Plans) and Land use zoning regulations and ordinances. 33 yes or no questions about a city's status of community planning	
Relevance to Resilience	**Adaptive Capacity**	0.64, 21/33
	Bounce-back capacity	0.64, 21/33
	Vulnerability	0.64, 21/33
Robustness	**Predictability**	Includes both trailing and leading considerations, more emphasis on trailing considerations, with numerous notes to consider potential future impacts
	Scalability	0.5, Potentially applicable at the county or regional scale, not as applicable at larger scales *(NOTE: Maine does not have counties).* Spatially transferable, any geographic location could use this scale. Mostly contextually transferable, but some questions and information is specific to Maine (i.e. state of Maine programs) and Maine's home-rule governance structure
	Validation	Determined by the quality of the information provided by the participants. Not explicitly validated.

Table 33 Resilience Assessment Section 4: Risk and Vulnerability section of the Maine Checklist

The Maine Checklist Resilience Assessment: Social and Economic Vulnerability (Economic and Social Scale)		
Description	Checklist to assess social and economic vulnerability so that strategies and actions can be developed to protect those populations form flood hazards and for building resilience.	
Input types	Links to our resources to consult that a community likely already has or has access to (community tax maps, economic development plans, U.S. Census data, list/map of culturally and historically significant resources. A 16-question checklist with yes/no questions, some options provided and the opportunity to write notes as necessary.	
Relevance to Resilience	**Adaptive Capacity**	0.4, 6/16
	Bounce-back capacity	0.4, 6/16
	Vulnerability	0.8, 13/16
Robustness	**Predictability**	Includes both trailing and leading considerations, more emphasis on trailing considerations, with numerous notes to consider potential future impacts
	Scalability	0.5, Potentially applicable at the county or regional scale, not as applicable at larger scales *(NOTE: Maine does not have counties).* Applicable across geographic locations and communities, especially coastal communities
	Validation	Determined by the quality of the information provided by the participants. Not explicitly validated.

Table 34 Resilience Assessment Section 5: Natural Environment section of the Maine Checklist

The Maine Checklist Resilience Assessment: Natural Environment (Biophysical Scale)		
Description	Checklist to assess a community's natural environment and systems to consider potential impacts including sea level rise, flood impacts, and other coastal hazards to identify plans, policies, and strategies in place and to prioritize to protect the natural environment now and into the future.	
Input types	Links to six resources to assess the current and projected future state of the natural environment of the community. An 11-question checklist with yes/no questions, some options provided and the opportunity to write notes as necessary.	
Relevance to Resilience	**Adaptive Capacity**	0.3, 3/11
	Bounce-back capacity	0.4, 4/11
	Vulnerability	0.9, 10/11
Robustness	**Predictability**	Includes both trailing and leading considerations, more emphasis on trailing considerations, with numerous notes to consider potential future impacts
	Scalability	0.5, Potentially applicable at the county or regional scale, not as applicable at larger scales. *(NOTE: Maine does not have counties).* 0.1, Only transferable to other coastal areas and communities
	Validation	Determined by the quality of the information provided by the participants. Not explicitly validated.

Sources used to populate the Maine Flood Resilience Checklist KSE framework

The Maine Flood Resilience Checklist is accessible here http://digitalmaine.com/mgs_publications/521/, last accessed July 6, 2018

A Google search on 05/17/2018 for "Maine Flood Resilience Checklist" returned 18 results

No GoogleScholar Search Results as of 05/17/2018.

1. Maine Flood Resilience Checklist, CAKEx overview, http://www.cakex.org/tools/maine-flood-resilience-checklist, last accessed 05/17/2018, Page created 8/18/2017 and updated 09/01/2018
1. Main Flood Resilience Checklist Overview http://www.maine.gov/dacf/mgs/hazards/coastal/MaineFloodResilienceChecklistOverview.pdf, last accessed 05/17/2018
2. NOAA, Office of Coastal Management, Coastal Management Fellowship, Project Summaries by Year https://coast.noaa.gov/fellowship/15_fellows.html, Last Accessed 05/17/2018
3. Event for "Climate Vulnerability Assessment Tools: A Hands-On Workshop – multiple dates, free, at Bowdoin College by the Casco Bay Estuary Partnership https://www.eventbrite.com/e/climate-vulnerability-assessment-tools-a-hands-on-workshop-tickets-44883217913, last accessed 05/17/2018
4. Webpage from maine.gov on coastal hazards, http://www.maine.gov/dacf/mgs/hazards/coastal/index.shtml#floodchecklist, last accessed 05/17/2018
5. Maine Flood Resilience Fact Sheet Checklist http://www.maine.gov/dacf/mgs/hazards/coastal/MaineFloodResilienceChecklistOverview.pdf, last accessed 05/18/2018
6. Northeast Climate Science Center Newsletter, September 29, 2017 – Highlighted as a resource, but no extra information, just a link to the CAKEx website, https://necsc.umass.edu/news/ne-csc-newsletter-73, last accessed 05/17/2018.
7. PowerPoint for a presentation at the 2018 Beaches Conference, "Tools to be Equipped for Change: from Raising Awareness to Adaptation Practices slides 21-31,

https://www.seagrant.umaine.edu/files/project/mbc/2017/2017-mbc-slr-tools-change.pdf, last accessed 05/17/2018

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2. How Resilient is Your Town to Floods?, Jim Fisher, October 26, 2017, Maine Association of Planners – dedicated to enhancing the practice of community planning. https://www.meplan.org/articles/5368224, last accessed 05/17/2018
3. Washington County Council of Governments, Helping communities plan for their future in Downeast Maine, http://www.wccog.net/municipal-climate-adaptation-guidance.htm, last accessed 05/17/2018 – listed as a resource for communities
4. Assessing Flood Risk in the Lamprey Watershed, http://100yearfloods.org/resources/, last accessed 05/17/2018
5. Event for the Mid-Maine Chamber of Commerce, https://midmainechamber.com/cms/events/workshop-rising-water-adapting-maine-communities/, last accessed 05/17/2018
6. Island Institute, Climate Impacts Page, http://www.islandinstitute.org/program/climate-impacts, last accessed 05/18/2018
7. Discussed at the November 28, 2017 event: Staying above high water: helping prepare Maine's coastal communities for coastal flooding and sea level rise, http://www.islandinstitute.org/sea-level-rise-symposium, http://www.islandinstitute.org/sites/default/files/Lee%20Jay%20Feldman_Flood%20Resiliency%20Presentation.pdf, last accessed 05/18/2018
8. Potential Use-Case Vinalhaven, Maine https://www.townofvinalhaven.org/sea-level-rise-committee
    a. https://www.townofvinalhaven.org/sites/vinalhavenme/files/uploads/adaptationoptionsmemo.pdf

VITA

Kathleen Marie Ernst (Kassie) grew up in the rural, 1500-person town of Whitehall, Wisconsin where she graduated from high school in 2004. She is the middle child of three sisters with retired public-school teachers for parents, one who is currently Whitehall's mayor. Kassie attended the University of Wisconsin from 2004 to 2008 and earned Bachelor of Arts degrees in Geography and Sociology while working for the MultiCultural Student Coalition and facilitating InterCultural Dialogues. Kassie distinctly remembers talking to her undergraduate mentor, Dr. Harvey Jacobs about wanting to study climate change adaptation planning for cities – Harvey smiled and said that he was too old to do those kinds of things. She then worked at National Parks in Kentucky (where she met her partner, Sasha) and Alaska before earning her Master's in Geography with a Minor in Environmental Policy and Management from the University of Tennessee in 2012, studying with Dr. Micheline van Riemsdijk.

Kassie became a student in the Bredesen Center Interdisciplinary Program for Graduate Research and Education at the University of Tennessee in August of 2014 studying environment and climate sciences with Dr. Benjamin Preston and Dr. Budhendra Bhaduri. She has conducted research in Tennessee, Alaska, northern Australia, and most recently in Sweden as a United States Department of State Fulbright Scholar. Kassie gave birth to twins, Selah Magnolia and Leon Sullivan on July 28, 2015, a whole other kind of overwhelming educational endeavor.

After finishing her doctorate, Kassie will become a National Academies of Sciences, Engineering, and Medicine Gulf Research Program Science-Policy Fellow for the National Oceanic and Atmospheric Administration RESTORE Science Program. She remains committed to helping planners and managers make more just and effective decisions across systems in consideration of future changes and hopes to honor that commitment throughout her career. In her spare time, Kassie enjoys running slowly, checking things off lists, traveling with her partner Sasha, visiting her friends and family, and chasing her three-year-old twins Selah and Leo.