The Eco-Techno Spectrum as a Frame for Interdisciplinary Urban Nature Governance Research:

Using 'eco-techno' hybridity of green infrastructure to examine the knowledge systems' challenges of urban nature management

By Marissa Matsler
Cary Institute of Ecosystem Studies

Prepared for delivery at the Workshop on the Ostrom Workshop (WOW6) conference, Indiana University Bloomington, June 19–22, 2019.

Abstract

Green infrastructure (GI) development – or the explicit management of greenspaces to provide services – is increasing in US municipalities. However, despite technical optimism regarding benefits provided by GI, governance challenges create significant barriers to effective GI implementation and maintenance. This stems in part from the contested definition of GI as stakeholders place varied, oft-conflicting demands on the concept. This means GI consists of a mishmash of disparate facilities, from large-scale natural areas (at the wildland interface) to small-scale engineered bioswales (throughout the urban-to-rural gradient), all of which are designed, implemented, and maintained by organizations with different, sometimes conflicting, goals and missions.

To make sense of GI management, I organize this variety along the Eco-Techno Spectrum, arranging facilities according to the proportion of biological components to human-made technological components. On the 'eco' end of the spectrum are remnant forests and floodplains where most components are biological; on the 'techno' end of the spectrum are engineered green roofs and permeable pavement where components are primarily human-made technologies. This spectrum allows for the combination of ecological and engineering data, which are usually siloed.

Importantly, the Eco-Techno Spectrum provides a platform on which to analyze governance concerns. Across the spectrum, GI facilities are subject to different performance metrics, jurisdictions, asset classes, etc. While relatively simple, the Eco-Techno Spectrum is a powerful heuristic because it captures this socio-political diversity and links it to ecological and technical data in a single framework. Here, I show the Eco-Techno Spectrum's utility to an interdisciplinary examination of urban governance through cases in Portland and Baltimore.

Introduction

The U.S. has an infrastructure problem. The American Society of Civil Engineers (ASCE) recently gave infrastructure nationwide a grade of D+, which means,

> infrastructure is in fair to poor condition and mostly below standard…Condition and capacity are of serious concern with strong risk of failure (ASCE 2017).

Infrastructures are unable to withstand the new pressures placed upon them by increasing population densities in urban areas (i.e. overwhelming traffic deteriorating roads, and increased hardscape overwhelming local streams and rivers with erosion and pollution), and changing climatic conditions (i.e. increasing intensity of precipitation (Cooley and Chang 2017) overwhelming sewer systems, and intensifying storms overtopping fail-safe levees and storm walls.)

The problem of infrastructure is simultaneously technological, social, and ecological. While infrastructure design, construction, and maintenance is highly technical, involving a number of engineering experts, these processes are also fundamentally social and ecological. All municipal infrastructures must interact with people and ecosystems on the ground, connecting each residence with centralized energy, water, transportation, and waste removal systems which rely on ecosystems as final sinks for byproducts as well as background conditions in which the systems exist. Real people and other living creatures interact with technologies at the end of these systems (i.e. toilets and facets in homes and businesses), as well as intermediary points (i.e. storm drains, electric substations).

To 'fix' the infrastructure problem in the U.S. then, we must focus not only on the technological challenges of design, construction, and maintenance, but also the social and ecological challenges of the processes. This is ultimately a *knowledge systems* problem: How do we gather evidence about the social, ecological, and technological problems of infrastructure? How is evidence from each of these systems perceived and prioritized within decision-making about infrastructure? Can we better design our knowledge systems to integrate these different problems? Will it lead to better outcomes on the ground?

Here, knowledge systems are defined as the norms, protocols, and procedures used to gather and vet evidence about how the world works and put it to use in municipal decision-making. Knowledge systems analysis therefore consists of examining the institutionalized and taken-for-granted procedures we use to approach the topic of infrastructure, and working to uncover the embedded visions of how the world works within them (Miller, Munoz-Erickson, and Monfreda 2010; Munoz-Erickson 2014).

Why uncover these embedded visions of technical decisions-making? The hot-button political issues of our times are negotiated in a number of different social arenas. Debates about the value of life (human and nonhuman) and the responsibility for nurturing and supporting that life are most visible on the national political stage. It is easy to see in a heightened political climate that those who write our national policies use these policies to reach particular goals, embedding within them their worldviews, understandings of what is right and wrong, what is appropriate, and who is responsible. The way a problem is framed will favor some and disadvantage others, constraining the set of solutions we pursue as a nation moving forward. For example, one way Americans living below the poverty line are framed is as lazy individuals taking advantage of the system (i.e. "welfare queens"); this establishes the idea that welfare is an inappropriate system that should be reduced or removed. However, an alternate framing of these individuals as products of oppression and a financial system that does not provide living-wage jobs may lead to a solution set that includes expanding or growing welfare assistance – and potentially intervening in other connected arenas to improve wages.

While easy to see in national politics, this process is not just happening on the national stage or only in overtly political arenas. Within spaces of seemingly apolitical technical management, negotiations between worldviews are taking place, embedding certain values and epistemologies into the infrastructures that prescribe the actions of our daily lives (Lampland and Star 2009; Ben-Joseph 2005). For example, Ben-Joseph (2005) shows how municipal code dictates the way individuals interact with each other because these codes form the basic structure of the city. Many of the negotiations that end up prescribing these interactions are quite mundane, occurring in bureaucratic spaces where experts frame local problems and design potential solutions. The seemingly straight-forward technical nature of these decisions belies the important co-production of technology and society. Science and technology studies (STS) is one realm of social science that interrogates the winners and losers within society via an examination of the social constructs that we create through social interactions in mundane and taken-for-granted spaces. In particular, STS examines the ways that scientific knowledge (as only one form of knowledge) and technologies (everything from cell phones to tractors (Rasmussen 1968)) co-produce the social structure of our world today (Winner 1986; Jasanoff and Kim 2013; Shapin, Schaffer, and Hobbes 1985).

As urban environmental issues intensify with climate change and increasing population densities in cities worldwide, our collective societal interactions with nature become ever more important to understand. This paper starts with the notion that the way we know nature, or our epistemic orientation towards nonhuman life, matters; that our visions of the world should not be taken for granted and examining these visions can reveal important connections between social and natural systems that may encourage or deter us from our shared goals (Dryzek 1997). As Hull et al. (2002) sum up succinctly, "…differing assumptions about nature constrain people's vision of what environmental conditions can and should exist, thereby constraining the future that can be negotiated" (Hull et al. 2002).

Here, green infrastructure is presented as a site of inquiry used to explore the knowledge systems influencing infrastructure decision-making in the US today. Green infrastructure employs or mimics ecological processes and functions to deliver municipal services, making it an excellent site of intersection between technological, social, and ecological systems. The *eco-techno spectrum* of green infrastructure interventions is developed as a conceptual heuristic to systematically structure an examination of green infrastructure knowledge challenges. This spectrum highlights the different degrees to which ecological entities (i.e. plants, soils, microbes) are incorporated as infrastructural components in green infrastructure facilities; this inclusion presents one of the major knowledge challenges to green infrastructure implementation, namely that it brings ecological knowledge into traditionally engineering-dominated decision-making spaces where it does not easily fit procedures for *defining*, *measuring*, or *valuing* facilities.

Urban Nature Management

Urban nature exists in many forms – everything from remnant woodlands, open fields, and parks, to street trees, grassy medians, and backyards. Each of these contain biological entities interacting to form elaborate food webs and ecosystems that function in the midst of, and in concert with, human culture. Management actions impact the structure and function of urban nature both consciously and indirectly. In some cases, jurisdictions are created specifically to manage a particular form of urban nature. For example, local departments of transportation (DOTs) are tasked with managing grassy medians and roadside ditches within guidelines set by traffic safety regulations and road engineering specifications; and planning departments craft zoning codes that dictate the management of private, commercial, and industrial landscaping features to enhance livability and neighborhood character.

Often, the goals of management differ across the various jurisdictions managing urban nature. Parks and recreation departments, for example, manage urban nature in the form of parks and street trees to provide recreational opportunities to city residents, while water utilities manage urban nature in the form of open reservoirs and restricted forested areas that provide clean water to residents. Traditional systems of city management neatly divide the work of managing nature across different communities of expertise, often adding these spaces onto a more central management responsibility (i.e. DOT's central responsibility is management of roads; management of roadside ditches and grassy medians is an add-on responsibility to that 'hard' infrastructural system.)

Each of these traditional ways of managing urban nature rely on particular definitions, ways of knowing, and theories of management that have grown into distinct silos through time. Increasingly, however, society recognizes the need for more integrated and holistic management of urban development (Gottlieb 2005; Worster 1990; Innes and Booher 2010; Healey 1997). Concepts such as sustainability and urban resilience advocate breaking down silos and increasing interdisciplinary approaches to understanding the city that include the voices and knowledges of citizens, in particular regarding urban nature management (Romolini et al. 2016; Grove et al. 2006; Collins et al. 2011; S. T. A. Pickett, Cadenasso, and Grove 2004; Bocchini et al. 2014; Goldstein 2012; Davoudi et al. 2012).

Green infrastructure is an emerging approach to managing urban nature that crosses bureaucratic and disciplinary silos by integrating natural elements with engineered elements in the design of facilities. In this paper, the term green infrastructure refers to both naturally occurring and engineered vegetated greenspaces that are explicitly managed to provide urban services such as stormwater treatment, flood mitigation, recreation, or clean water provisioning, among other services. This definition of green infrastructure encompasses facilities that include living, biological components, rather than solely the mechanical components that are usually evoked by the term infrastructure[i]. The inclusion of living, ecological entities complicates the management of green infrastructure facilities; for example, engineering-focused jurisdictions, like a department of transportation or a sewer authority, do not traditionally have staff with ecological expertise to appropriately design and maintain the nature in green infrastructure facilities.

The concept of green infrastructure also includes a wide variety of landscape features and technologies – from large coastal wetlands and urban forests to manicured pocket parks and bioswales – any place were biological entities such as plants, soils, and microbes, are designed and managed explicitly to do the work of providing urban services. This large array of different types of green infrastructure facilities also complicates management: ownership of facility types is divvied up by department but the entire spectrum makes up a single infrastructural system. This requires coordination across departments that usually act separately, responding to their own set of institutional drivers.

In the following sections, I will present the growing popularity of green infrastructure as well as expand on the concept's technological-ecological hybridity. A subsequent review of green infrastructure plans will portray the two primary visions of green infrastructure present in the U.S. today.

Growth of green infrastructure

Green infrastructure is increasingly popular. Today, communities of all sizes create and implement green infrastructure plans and policies: a variety of prominent cities have green infrastructure facilities on the ground, including New York City (NYC Environmental Protection 2010), Philadelphia (Philadelphia Water Department 2011), Seattle (City of Seattle 2015), and Chicago ("City of Chicago: Green Stormwater Infrastructure Strategy" 2014); mid-size and small communities are building new demonstration projects and assessing potential social acceptance of green infrastructure with the help of grant-funding from the EPA and other sources, including

Corvallis, OR (EPA 2011), Vancouver, WA, and Coos Bay, OR; across rural and suburban settings, entire counties are implementing green infrastructure networks, including McHenry County in Illinois, Alachua County in Florida, and agricultural land throughout Indiana (WRESTORE 2017).

While it is difficult to quantify the popularity of green infrastructure comprehensively in the world today, the growth in the term's use is undeniable. An exploration of Google searches for the term "green infrastructure" show steady interest in the topic since 2004 (this is as far back as Google Trends data extends); as seen in Figure 1-1 below, Google searches peaked in popularity in 2010. While there are monthly fluctuations in searches, popularity of the search term has remained steady into the present.

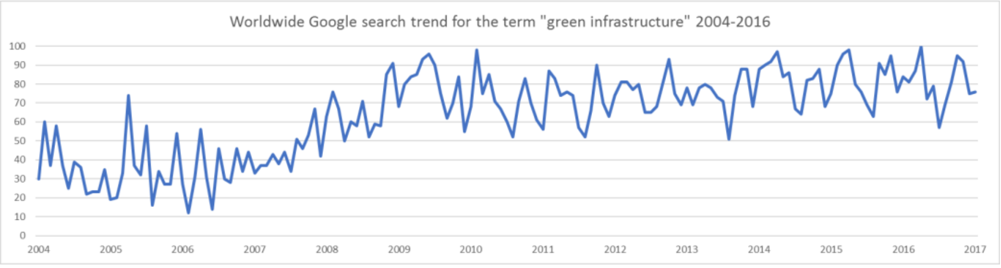

Figure 1-1: Google search trend data for the term "green infrastructure" 2004-2017; Shows the relatively popularity of the term, compared to itself through time; a score of 100 is the time stamp with the most searches for the term relative to all other time stamps

Hybridity

Academic publication records (displayed in Figure 1-2) shed light on a different aspect of green infrastructure popularity. Since 2000, the number of academic publications with the term "green infrastructure" in the title have grown, supporting the earlier discussion of its increasing popularity. The academic database Web of Science reports that the first publication to appear with the term "green infrastructure" in the title was published in 2000. The number of publications with the term in the title remained low, only 1 or 2 each year, until 2008 when an abrupt increase in publications peaked at over 70 in 2015, more than doubling the number of publications in 2014 (just under 30). In December of 2016, when this data was accessed, the number of publications dropped slightly to around 55 publications (see Figure 1-2).

While these increases in the use of the term "green infrastructure" as a topic of academic study generally help show the growth in popularity of the practice, a look at the disciplinary category of these publications is even more revealing, and particularly useful to the exploration of knowledge systems. As seen in Figure 1-3, the interdisciplinary categories of *Environmental Studies* and *Urban Studies*, which tend to combine social, ecological, and economic data, have the highest number of publications with "green infrastructure" in the title – more than half the 243 total publications found by Web of Science. *Civil Engineering* publications with "green infrastructure" in the title, on the other hand, number about 30, which is less than half the number of publications of *Environmental Studies* (over 70); *Ecology*, a more traditional disciplinary group, also has about half the publications of interdisciplinary categories. *Economics* trails the lot with only 4 publications over the 16 year period where the term shows up in publication titles.

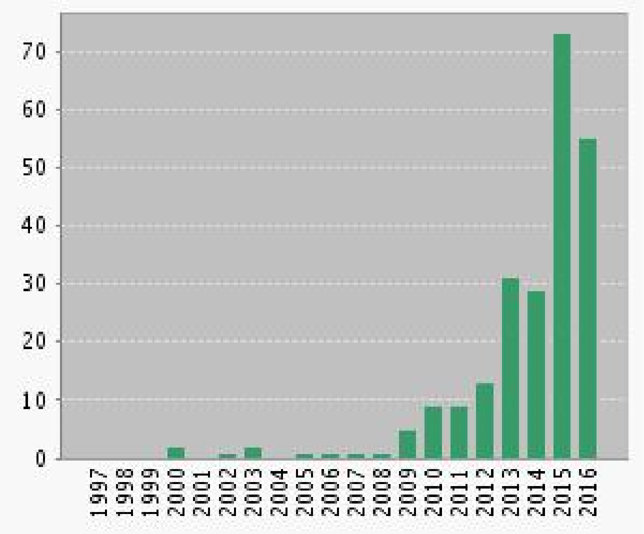

Figure 1-2: Number of academic publications captured by the database Web of Science with the term "green infrastructure" in the title by year (1997-2016)

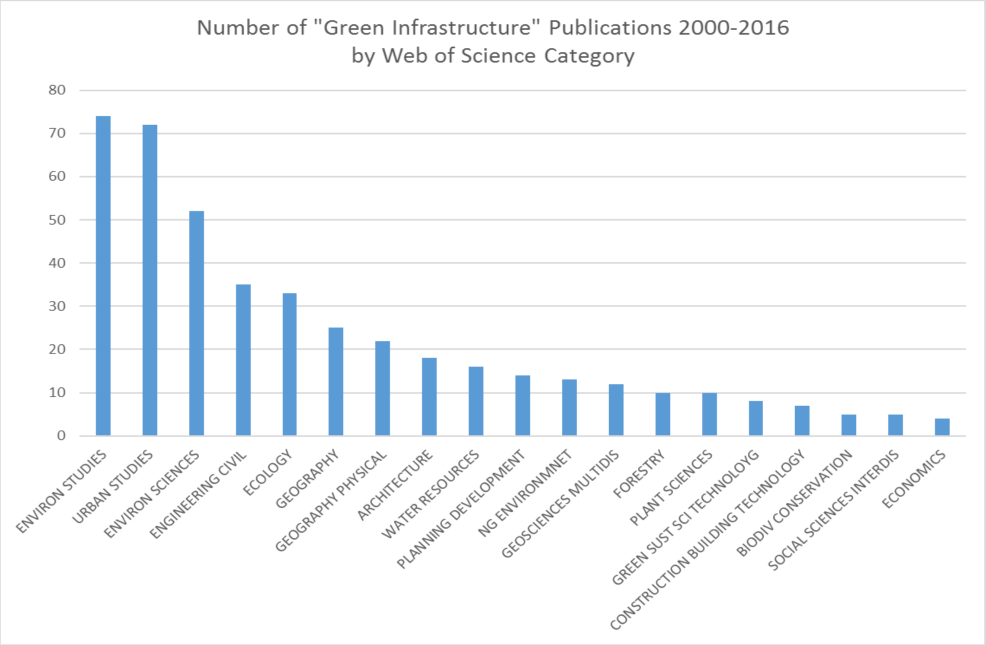

Figure 1-3: Number of publications with the term "green infrastructure" in the title 2000-2016 by Web of Science category

This kind of publication record highlights the *in-between-ness* of green infrastructure. Green infrastructure is not often perceived as pure nature, therefore is not pursued as actively in *Ecology* as it is in interdisciplinary fields. Likewise, the living components of green infrastructure are not often viewed as real infrastructure, making facilities with living components marginal in physical-science-dominated fields like *Civil Engineering*. Finally, the lack of financial mechanisms to subsume green infrastructure under existing valuation techniques or theories makes it incommensurate with *Economics* in general (see Figure 1-3).

The ecological-technological hybridity of green infrastructure also contributes to continued lack of stable classification. Green infrastructure includes both biological, living components (e.g. plants, soils, microbes) and mechanical, physical components (e.g. pipes, concrete, pumps). Each of these component types is the epistemic territory of different professional and academic groups. For example, ecologists and conservation biologists have the “epistemic authority” (Gieryn 1999) to define the structure and function of living, non-human nature in the city. They use specific metrics to define the performance of ecological assemblages: nutrient uptake, community structure, etc. These metrics are quite different in character, scope, and type, however, from those used to define and measure the mechanical and physical components of infrastructure, which are primarily developed and circulated by engineers and physical scientists. Metrics defining infrastructure performance include acre-feet of water retained or pipe capacity and flow rate. Green infrastructure includes both living and mechanical components to do the work of service delivery in the city necessitating the negotiation of these incommensurate epistemologies.

A review of green infrastructure plans can provide a sense of the different visions of urban nature invoked by definitions of differing epistemic authorities of green infrastructure. Recent literature establishes that the definition of green infrastructure is still unsettled internationally (Mell 2013), that the value of green infrastructure is contested (Netusil et al. 2014; Mell et al. 2016), and that social and institutional, rather than technical, uncertainties stand out as primary barriers to wider adoption of green infrastructure programs (Carlet 2015; Young et al. 2014; Thorne et al. 2015). To find a working definition for my own research, I conducted a brief, preliminary review of green infrastructure plans and policies readily available online.

Definitional confusion can be seen playing out in current green infrastructure plans, with a dichotomy of visions emerging. Table 1-1 below displays the two distinct visions of urban nature observed in green infrastructure plans from across the US. While all documents made some reference to nature and natural elements (i.e. greenspaces), some of the plans and policies defined green infrastructure as a natural area conservation strategy and others as a stormwater management technique.

Not all plans adhered completely to one vision or the other, however, there are elements of similarity across the definitions used. For example, the terms "hub and corridor" are used to describe a *green infrastructure as ecological network* vision (see Figure 1-4), while the idea of "mimicking natural processes" is prominent in a *green infrastructure as cheap and sustainable stormwater management* vision. I use the short-hand 'network' and 'stormwater' respectively to refer to these two different visions.

While not the only visions of nature at work in the city (Dryzek 1997), these 'stormwater' and 'network' visions are the two most prominent and influential visions within the current green infrastructure discussion that I have deciphered through extensive literature review, preliminary interviews, and preliminary plan review (Table 1-1). Likewise, the differing ways of knowing nature in the city that form the foundation of these visions are an example of two directly conflicting knowledge systems that can be usefully examined through a knowledge systems analysis frame.

In particular, this dichotomy of visions raises a number of questions: How are these conceptual visions stabilized? Is one vision more influential than the other? Could vision inconsistency be a barrier to the broad uptake of green infrastructure or to any positive outcomes of green infrastructure implementation?

It is important to note that neither of these conceptual visions of green infrastructure is wrong, nor is one necessarily better than the other. I believe that both conceptions are useful to the development of resilience in our cities today; in fact in a minority of the plans, both visions are discussed (as seen in McHenry County's definition in Table 1-1). But underlying this dichotomy is a rub – a tension – between two epistemically and ontologically disconnected views of urban nature that deserves additional consideration. These two visions of urban nature are in fact incommensurate in many contexts, creating potential issues to their realization. For example, in many cases, the creation of small-scale facilities for stormwater management focuses green infrastructure development narrowly on technological solutions that reduce water quantity concerns at the expense of ecological and social co-benefits of greenspaces like access to nature, biodiversity, urban cooling, etc. I argue here that the underlying tension between different views of the role of urban nature creates institutional barriers to the increased implementation and mainstreaming of green infrastructure throughout the US.

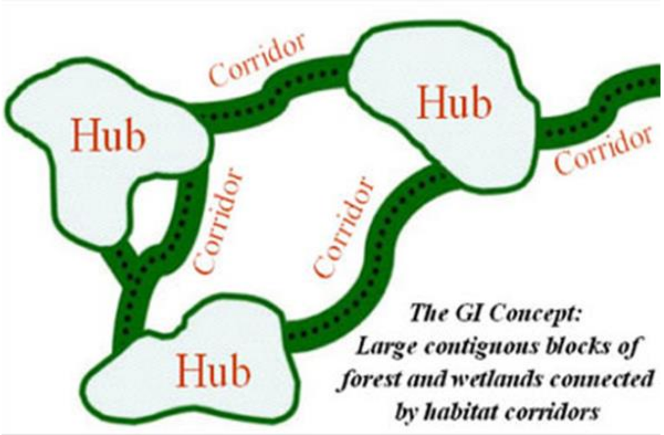

Figure 1-4: The "hub" and "corridor" approach to green infrastructure from the State of Maryland's 1990 Green Infrastructure Plan. This structure represents the principal of greenspace connectivity that is central to the 'network' vision of green infrastructure displayed in Table 1-1.

Table 1-1: This table displays the verbatim definitions of "green infrastructure" from a number of recent green infrastructure plans and policies from across the United States. Each of these definitions frames the problem that green infrastructure is employed to solve in each city/region, and therefore constrains the solution set (i.e. facility types considered) in each case.

Examples of Network Vision

Plan/Policy	Year	Definition
Howard County, MD "Green Infrastructure Network Plan"	2012	"Green Infrastructure is a network of interconnected waterways, wetlands, forests, meadows and other natural areas. Green Infrastructure helps support native plant and animal species, maintain natural ecological processes, sustain air and water resources, and contribute to the health and quality of life for communities. " (p.1)
Kane County, IL "2040 Green Infrastructure Plan"	2013	"Green infrastructure is an interconnected systems of natural areas and open spaces including woodlands, wetlands, trails, and parks, which are protected and managed for the ecological values and functions they provide to people and wildlife." (p. 6)
Saratoga County, NY "Green Infrastructure Plan"	2006	"Green infrastructure is a relatively new concept that recognizes the importance of interconnected natural systems that provide valuable services to us each and every day... Like the highways, water, sewer, and electric lines and other built or "grey" infrastructure, "green" infrastructure is the network of natural landscapes including forests, farmlands, parks and preserves. " (p. 1)
City of Summerville, SC "Green Infrastructure Plan"	2017	"Green infrastructure is identified as the natural assets of an area, including intact forests, tree canopy, wetlands, parks, rivers, and agricultural soils, and how these assets are connected throughout the landscape. " (p. 1)

Example of Combined Network & Stormwater Visions

Plan/Policy	Year	Definition
McHenry County "Green Infrastructure Plan"	2012	"The term green infrastructure has many definitions. Some focus on efforts to manage natural lands for their ecological and recreational value. Others see it as networked lands that support biodiversity and habitats for plant and animal life. Yet, others view the term as a description of the technologies and engineering (e.g. green roofs, vegetated swales, and permeable pavement) that replicate natural water and environmental processes—as opposed to conventional gray infrastructure methods… different sections of this plan highlight the different ways in which GI can be defined and applied, from a regional scale all the way down to individual sites." (p. 7)

Examples of Stormwater Vision

Plan/Policy	Year	Definition
Illinois "Green Infrastructure for Clean Water Act"	2010	"Green infrastructure means any storm water management technique or practice employed with the primary goal of preserving, restoring, or mimicking natural hydrology. Green infrastructure includes, but is not limited to, methods of using soil and vegetation to promote soil percolation, evapotranspiration, and filtration."
Milwaukee, WI "Regional Green Infrastructure Plan (Phase 1)"	2013	"…green infrastructure is one piece of the multi-tiered approach to meeting the [sewerage district]'s 2035 Vision for zero basement backups, zero overflows, and improved water quality." (p.5)
Northeastern Ohio "Project Clean Lake: Green Infrastructure Plan"	2012	"GI is defined in the Consent Decree as "a range of stormwater control measures that use plant/soil systems, permeable pavement, or stormwater harvest and reuse, to store, infiltrate, or evapotranspirate stormwater and reduce flows to the combined sewer system (CSS). Green infrastructure may include, but is not limited to, bioretention and extended detention wetland areas as well as green roofs and cisterns." " (p. 1-1)
City of Mount Rainier, MD "Urban Green Infrastructure Master Plan"	2013	"…presents a set of tools to be utilized when selecting and implementing projects to improve and reduce urban stormwater runoff. " (p. iv)
City of Pittsburgh, PA "Wet Weather Feasibility Study"	2013	"Green infrastructure refers to a variety of strategies designed to mitigate the effects of development on the surrounding environment, typically using smaller, distributed management practices which infiltrate, evapotranspirate, and/or detain stormwater runoff on-site." (p. 9-2)
City of Chicago, IL "Green Stormwater Infrastructure Strategy"	2014	"a term used to refer to strategies for handling storm precipitation where it falls rather than after it has run off into a sewer system." (p. 17)
City of Tucson, AZ "Green Streets Policy"	2013	"Landscape and engineering features that utilize soils and vegetation to manage stormwater for multiple environmental and community benefits. These features…include but are not limited to, curb scuppers, curb depressions, core drills, water harvesting basins, swales, bio-retention basins, berms, check dams, infiltration trenches, and active water harvesting/storage systems." (p. 1)"
Washington, D.C. "Clean Rivers Project: Green Infrastructure Program Plan"	2016	"GI uses plants, trees and other measures to mimic natural processes to control stormwater, resulting in cleaned, cooled and slowed stormwater runoff." (p. ES-1)

Research Motivations

This research is motivated by an intense interest in the different visions of the role of nature in the city, and the influence of these visions on management actions and outcomes on the ground. The long-standing dichotomy between “country” and “city” / “society” and “nature” that permeates the way we know and understand the world around us is challenged by the very notion that there is non-human nature living and thriving by its own rules in our city centers. Many of the historical ideas and frameworks that define “nature” as the opposite of “city” have been dismantled (Wachsmuth 2012; Light 2009; Collins et al. 2011). However, a new understanding of the relationship between nature and society in cities that effectively answers persistent social and ecological problems has been difficult to forge; much of the urban sustainability and urban resilience literature continues to ask: what is the structure and function of cities as socio-nature hybrid spaces (Felson and Pickett 2005; Kaye et al. 2006; Alberti et al. 2003; Collins et al. 2011)? and what are the appropriate ways for humans and urban nature to interact (Goldstein 2012; Davoudi et al. 2012; Gottlieb 2005)?

Infrastructure is an excellent site of inquiry to begin to answer these questions. This is because all infrastructural systems use/require nature in some shape or form and therefore influence the relationship of urban humans to ecosystems. As Edwards (2003) thoroughly describes, infrastructures provide stability in an otherwise dynamic natural systems and change our responses to nature:

> Infrastructures constitute an artificial environment, channeling and/or reproducing those properties of the natural environment that we find most useful and comfortable; providing others that the natural environment cannot; and eliminating features we find dangerous, uncomfortable, or merely inconvenient. In doing so, they simultaneously constitute our experience of the natural environment, as commodity, object of romantic or pastoralist emotions and aesthetic sensibilities, or occasional impediment. They also structure nature as resource, fuel, or "raw material", which must be shaped and processed by technological means to satisfy human ends (Edwards 2003).

While all infrastructural systems must cross epistemic and physical boundaries in their organization and management (Pinch 2010; Star 1999), green infrastructure represents a *new* assemblage of previously disparate groupings and component types which have not been traditionally viewed as ‘infrastructure’ (i.e. plants are not typically understood as water storage and filtration tanks) and therefore do not fit into established silos. The ways in which this new infrastructure is understood, and the job it is conceived to do, are still under negotiation between the various organizations in charge of designing, implementing, and maintaining green infrastructure. This differs from most urban infrastructures that have faded into the background of daily life as “certain, cold, unproblematic, black box[es]” (Latour 1987). For example, society is now familiar with the concept of wastewater treatment plants – we know that when we flush the toilet or wash the dishes the water travels through a managed sewer system that then ‘takes care’ of the waste. The messy political and social decisions of the late 1800s that moved us towards building wastewater treatment plants throughout the US in the late 1940s and 1950s are mostly closed – we don’t question the usefulness of microbes in the cleaning of our wastewater as was once openly contested among chemical and physical science experts (Schneider 2011).

This research, then, takes advantage of green infrastructure as an interdisciplinary site of “infrastructure in the making” (Bowker et al. 2009). I follow Latour’s lead when he writes, "the impossible task of opening the black box is made feasible (if not easy) by moving in time and space until one finds the controversial topic on which scientists and engineers are busy at work” (Latour 1987). Through my own experience in the field of urban sustainable design and stormwater management, I have seen that the definition, measurement, and valuation of urban nature are places where scientists and engineers are in uncertain territory and are actively making decisions about open controversies of ecological fact. Green infrastructure represents a site where I can observe and analyze the production and use of ecological knowledge by different epistemic communities, providing insight into deeply held ontologies of municipal actors that are usually hidden during business-as-usual infrastructure design and implementation processes.

Theoretical Background

This paper engages with the intellectual history of work on the *social construction of nature* and *critical infrastructure studies* to understand green infrastructure planning, implementation, and management in the U.S. today. The concept of *knowledge systems* is utilized to operationalize and bridge a study of these two theoretical approaches to co-production, as shown in Figure 1-6.

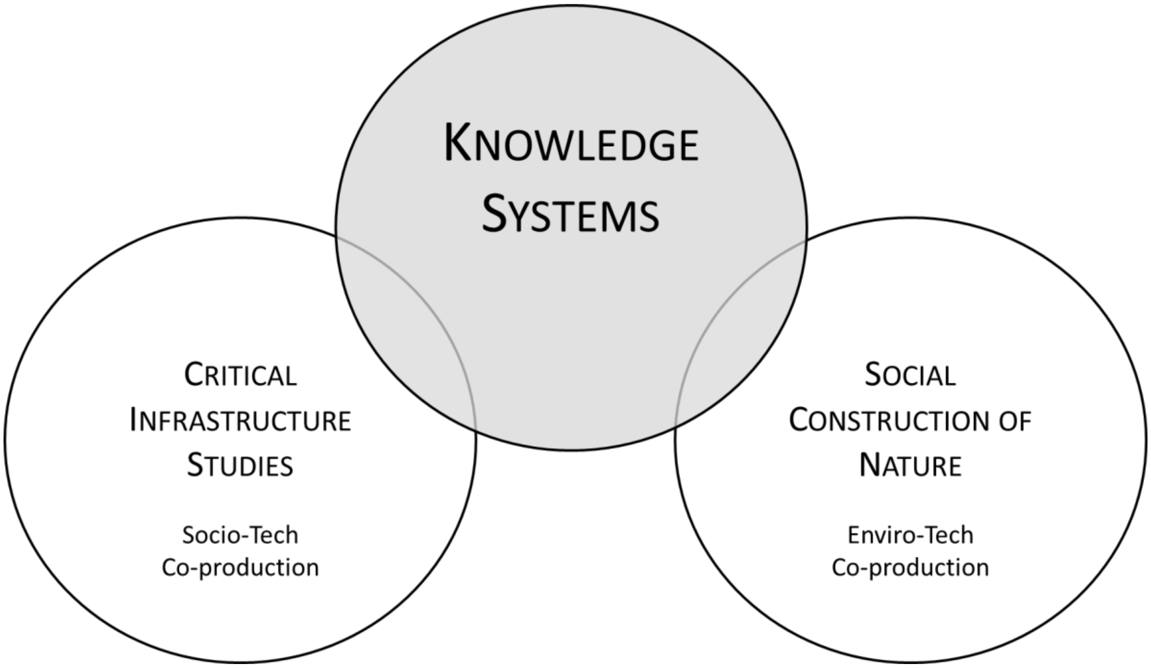

Figure 1-6: Knowledge systems acts as an operationalized bridging concept between theories of Socio-Technical and Enviro-Technical Co-production

A theoretical grounding in knowledge systems begins by recognizing a recent re-visioning of the city as an ecological space, in addition to its traditional understanding as a social space. This shift has changed the ways in which researchers gather data about and explain the processes we see in urban areas (Lave et al. 2014; S. T. Pickett et al. 2001). This, in turn, has changed the *knowledge* available to urban decision-makers, influencing the ways that cities are built and governed in general (Lachmund 2013; Light 2009). In particular, the design, implementation, and maintenance of urban infrastructure is influenced by this ‘ecological turn’; as ecological thinking has increasingly permeated popular thought (Worster 1990), a push to “work with nature” by designing ‘soft’ infrastructural systems has grown, while prior paradigms of “command-and-control” of nature with ‘hard’ infrastructure has become unfavorable and viewed as flawed by many (Greenberg 2012; Kimmelman 2012).

The *knowledge systems* literature can be usefully applied to understand the ways the city is conceptualized by different social groups, and also begin to untangle the influences that different theoretical frameworks (both scientific and otherwise) have on practice and decision-making in the city. Tools from the knowledge systems literature, therefore, can illuminate the knowledge used and produced around the shift from “command-and-control” of nature to a “work with nature” paradigm within cities, and when viewed in tandem with the *critical infrastructure studies* literature can also explore the *consequences* of such a shift on the design, implementation, and maintenance of urban infrastructures; for example, the knowledge systems literature illuminates current and past understandings of the feedback loops between humans and nature in the city, and how urban infrastructures mediate this relationship.

A focus on knowledge is timely. As Knorr-Cetina (1999) asserts, “There is widespread consensus that contemporary Western societies are in one sense or another ruled by knowledge and expertise” (p. 5); therefore, understanding the production, negotiation, and utilization of knowledge claims allows researchers to track power relationships (Lave 2011; Miller, Munoz-Erickson, and Monfreda 2010) and relate knowledge claims to their negotiated material outcomes

(Callon 1999; Lave et al. 2014) in general in the city. A better understanding of these relationships allows us to consciously design our knowledge systems to be more effective and inclusive.

I have also chosen this focus because of the increasing use of knowledge from the natural sciences, and specifically ecology, in designing and governing the city in recent decades (Davoudi 2012; Healey 1997). One aspect of this increase is the growing popularity of describing cities as socio-ecological systems (SES) in both urban ecology (Felson and Pickett 2005; S. T. A. Pickett, Cadenasso, and Grove 2004) and the social sciences (Anderies, Janssen, and Ostrom 2004; McGinnis and Ostrom 2011). To understand the wider impacts of emerging SES knowledge claims, the knowledge production process and its social and material consequences needs to be traced.

Ecological knowledge about the city has only recently begun to be produced; initially the field of ecology focused on ecosystems far from humans. Only areas beyond human influence were considered natural and the appropriate subject matter for ecological inquiry (Kingsland 2005; Light 2009; S. Pickett, Cadenasso, and Meiners 2009). Over time, ecological knowledge of the city has grown in legitimacy. In particular, the application of ecological knowledge about the city to the engineering-dominated field of infrastructure design and implementation has become popular in cities hoping to improve their sustainability.

To examine epistemological knowledge system concerns in infrastructure, it is useful to explore the STS literature around socio-technical systems; STS scholars have worked to outline a number of different system parameters that exist in the feedback loops between technical-material actors and socio-political actors (Winner 1986). While initially focused on the dialectical relationship between technology and society, STS scholars have increasingly focused on the influence of nature as an actor on these mutually articulating factors (Gandy 2002; S. B. Pritchard

2012). This opens a connection between infrastructure studies, environmental history, and urban ecology within the new analytical framework of *socio-ecological-technical systems* or SETS (Redman and Miller 2015; McPhearson et al. 2016). Because, as asserted in the introduction, the infrastructure problems faced in the U.S. are simultaneously social, ecological, and technological, SETS is an excellent conceptual tool to illuminate the social and material consequences of the emergence of green infrastructure development in particular.

In the remainder of this section, I review both the knowledge systems literature and the infrastructure studies literature in an effort to better contextualize this research and point to its theoretical positioning. The literature reviewed here is operationalized in the following conceptual framing section.

Knowledge Systems

The knowledge systems literature explores the production, validation, circulation, consumption (Miller, Munoz-Erickson, and Monfreda 2010), negotiation, translation (Callon 1999), and utilization of knowledge in society. None of these is a discrete step or process; in practice, knowledge systems processes are not linear and often happen simultaneously (Miller, Munoz-Erickson, and Monfreda 2010). Therefore, each will be touched on in the following review of STS scholarship. While the knowledge system concept has varied meanings in the work of different scholars, most agree that “new knowledge claims do not merely appear, fully formulated. Rather they are the product of sometimes long and involved work” (Miller, Munoz-Erickson, and Monfreda 2010).

Expert-driven decision-making processes have become the norm in a variety of social settings in today’s world (Knorr-Cetina 1999). This is especially true of engineering-based infrastructural design, implementation, and maintenance decisions. While a privileging of one type of knowledge (i.e. quantitative, expert, engineering knowledge (Friedmann 1993)) initially brought cities enormous health benefits (e.g. sewer pipes and piped drinking water systems eliminating cholera epidemics in early industrial cities (Tarr 1996)), the use of an abundance of one kind of knowledge, from a select and elite group of people, has not necessarily led to better societal (or material for that matter) outcomes (Scott 1998). Often diverse, experiential, or tacit knowledge claims, can provide the needed contextual information to solve a problem that generalized expert knowledge alone cannot complete (Mukerji 2009).

Before moving forward, a working definition of 'knowledge' itself should be put forward. I borrow the succinct but broad definition put forth by Miller et al. (2010) for use in this paper:

> Knowledge…refers to claims made by actors (who can be individuals or institutions) that either purport to tell us something of a factual character about the world (of potentially varying degrees of certainty) or are taken by actors to tell us something factual about the world (p. 1).

This definition is helpful to my work regarding green infrastructure development because of its explicit focus on decision-making:

> Knowledge refers to an idea or belief that someone, whether an individual or a community, takes to be true, or at least relatively more true than other kinds of statements, and therefore of sufficient character *to guide his, her, or their reasoning or, especially…action* (p. 1, emphasis added).

I would also like to quickly note the primacy of *uncertainty* in science and knowledge systems before moving forward with this review. Because each piece of new knowledge expands known unknowns (i.e. each single piece of knowledge illuminates multiple new questions), in a 'knowledge society', where expert knowledge is produced around the clock, there will be more ignorance (unknowns) and therefore more surprises. "If this is the case, handling ignorance and surprise becomes one of the distinctive features of decision-making in contemporary society"

(Gross 2010, p.1). In infrastructure design and implementation, the emerging production and application of ecological knowledge in the city means a variety of facilities are now built with ecological components whose response to social, political, and other ecological actors in the city is unknown. As Gross (2010) states "new knowledge…allows for new options without delivering secure criteria for how these new options need to be handled" (p. 1). Uncertainty in infrastructure outcomes is important to infrastructure decision-making and it permeates all the concepts discussed below.

Production of Knowledge

Western societies are increasingly described as 'knowledge societies'; consistent with the concept of a 'post-industrial society' this term acknowledges an emerging economic relationship in which knowledge is "a productive force replacing capital, labor, and natural resources as the central value- and wealth-creating factor…fundamentally changing the nature of production systems" (Knorr-Cetina 1999). This makes knowledge an increasingly important phenomenon to trace within modern societies, as it has increasingly more impact on decision-making processes and material systems of our world (Miller, Munoz-Erickson, and Monfreda 2010; Ozawa 1991).

In particular, *scientific knowledge*[ii] dominates the ways in which we collectively understand and interpret the world around us (Ozawa 1991). This necessitates the work of a variety of experts to collect, integrate, and interpret scientific data for us (Bocking 2004). As Knorr-Cetina (1999) describes, knowledge societies "run on expert processes and expert systems…are epitomized by science" (p.1). I follow the lead of scholars who have worked to improve the social, political, and ecological relationships of our world by de-mystifying and examining epistemological orientations that become "structured into all areas of social life" (Knorr-Cetina, 1999, p. 1) from expert knowledge production.

While popularly considered objective – happening somewhere ‘out there’ away from politics – science is in fact entangled deeply within social and political processes and concerns (Jasanoff 2004). As Gieryn (1999) notes, science actually has a wide “reservoir of meanings” (p. 21) and people selectively use what meanings they want to when it is useful to them. Knorr-Cetina recognizes this overlap between politics, expertise, science, and society and asserts that

> in a knowledge society, exclusive definitions of expert settings and social settings – and their respective cultures – are theoretically no longer adequate; this is why the study of knowledge settings becomes a goal in the attempt to understand not only science and expertise but also the type of society that runs on knowledge and expertise (p.8).

Urban infrastructure is often considered to be made up a number of “certain, cold, unproblematic, black box[es]” (Latour, 1987, p.4); but by utilizing the tools of STS scholars and focusing on the ‘epistemic machineries’ (Knorr-Cetina) of emerging green infrastructure development, I can observe knowledge systems negotiations in real time, providing insight into deeply held knowledge claims that are hidden during business-as-usual infrastructure design and implementation.

Co-production of Knowledge

> Rather than forwarding a compartmentalized view of urban nature, a relational perspective recognizes the indelible connectedness of urban residents with their material surroundings. Such a perspective is helpful to understand how the contemporary conditions of cities came into being and how they can be reworked into more desirable configurations. (Karvonen 2011, p. ix)

The concept of co-production is central to the exploration of knowledge systems. Jasanoff (2004) describes co-production as "shorthand for the proposition that the ways in which we know and represent the world (both nature and society) are inseparable from the ways in which we choose to live in it" (p.2). From this standpoint, knowledge creation is entangled both materially and ideologically, one inseparable from the other, and constantly evolving. Knowledge is not something pure that is waiting out there for humans to find it (like Plato's Forms); but it is instead constantly produced and re-formed through human social and political processes, as well as through ecological and physical processes.

The idea of co-production is therefore a direct challenge to common conceptions of scientific knowledge as "…a transcendent mirror of reality" (Jasonoff 2004, p.3). From a positivist viewpoint, the scientist strives to distill information about the world into a few underlying fundamental and unchanging laws (Cartwright 1999). An important assertion of this viewpoint is that the scientist, via scientific methods, can produce an objective image/description of the world. The quantitative nature of much scientific expression solidifies the notion that scientific knowledge is objective (T. Porter 1994; T. M. Porter 1996); we hear this culturally reinforced in our daily lives through colloquial expressions like 'numbers don't lie.' However, the very act of making decisions about *what* to measure and *how* to measure it in scientific research studies entangles the quantitative scientific knowledge creation process with ideology, politics, and culture (Jasanoff 2004; T. Porter 1994; Scott 1998).

In particular, co-production is implicated in the practices of state-making and governance: "…co-production offers new ways of thinking about power, highlighting the often invisible role of knowledges, expertise, technical practices and material objects in shaping, sustaining, subverting or transforming relations of authority" (Jasanoff, 2004, p. 4). By examining which pieces of knowledge are used and which are thrown out of a decision-making process, or observing how and which specific topics are considered by scientists, can shed light on *who* is influencing knowledge creation. Flyvbjerg (1998) posits that Francis Bacon's famous idiom "knowledge is power" is not uni-directional; power is also knowledge, due to the control that the powerful have over what knowledge is counted as relevant and pertinent in the world: "Power procures the knowledge which supports its purposes, while it ignores or suppresses that knowledge which does not serve it" (p. 319). Therefore, tracking the knowledge production and utilization process allows a researcher to study power relations within state-making at the same time; "the findings [of knowledge co-production research can] help to clarify how power originates, where it gets lodged, who wields it, and by what means, and with what effect within the complex networks of contemporary societies" (Jasanoff 2004).

In the end, co-production is a crucial analytical tool for understanding the feedback loops between knowledge production and use. As Jasanoff (2004) says, “our methods of understanding and manipulating the world curve back and reorder our collective experience along unforeseen pathways..." (p.13). In other words, the way that we understand the world, the definitions and conceptual frameworks we use, influence our day-to-day social and material experience in the world; therefore, if we change the ways that we conceive of the world around us, we can change our socio-material experience of reality.

Infrastructure

What is infrastructure?

> Analytically, infrastructure appears only as a relational property, not as a thing stripped of use. (Star & Ruhleder 1996, p. 113)

A standard dictionary definition points to the most common understanding of an infrastructural system: “the basic equipment and structures (such as roads and bridges) that are needed for a country, region, or organization to function properly” (Merriam-Webster 2014). What is left out of this predominant, dictionary definition which emphasizes infrastructure as a *physical* network of pipes, cables, asphalt, etc., is that infrastructures also consist of overlapping *socio-*

political networks; embedded within an infrastructure’s physical components are a vast array of values and knowledge types (Star 1999; Winner 1986). The STS literature therefore employs an extended definition of infrastructures for the purposes of understanding the complex interactions between social and technical factors.

There are two popular ways that the socio-technical relationship within infrastructures, and technologies in general, is viewed. One is technological instrumentalism and the other is technological determinism (Rowland and Passoth 2014; Winner 1986). First the technological instrumentalist view: "…technologies carry no intrinsic meanings. Their meanings are always to be found amongst social groups who interact with the technology and share a meaning of the technology" (Pinch 2010, p. 79). In this way, politics work *through* technology (Rowland and Passoth 2014), but the technology itself is not an actor; consequences are wholly reducible to characteristics of social actors. Next, the technological determinist view: Winner (1986) asserts, "if the experience of modern society shows us anything…it is that technologies are not merely aids to human activity, but also powerful forces acting to reshape that activity and its meaning." (Winner 1986). In this view, politics are *in* technology itself (Rowland and Passoth 2014); technology has a ‘life of its own’ and becomes a nonhuman actor separate from human and social actions. Both views essentialize and reduce the complexity of socio-technical relationships to either a social or a technical phenomenon; therefore, STS scholars actively work to blend these two perspectives of the world, showing how technologies are neither completely reducible to social or technological determinants but are instead co-producing:

> …social and technical causes and effects are bound up together in ways that are more complex than either the instrumentalist or determinist views can encompass. As a consequence, the emergence of new forms of technology cannot be attributed to a single, simple cause, whether the pure human will or some inherent technological imperative" (Kirkman, 2008, p. 237).

I will use Pinch (2010) to provide an example of the balance between socially and technologically reductionist views of infrastructure in STS research. Pinch's (2010) case study involves the building of an eruv around his hometown. An eruv is an invisible wall that can built around a house, neighborhood, or town using wires and poles that has great significance for Orthodox Jews (i.e. it designates an area as temple-like allowing people to behave differently on the Sabbath within its boundary); but an eruv would just look like a series of telephone poles to anyone else. Pinch notes that, even in its invisibility, the eruv *does* require material elements - namely the phone poles constructed in a specific way as to satisfy the doctrine (the wire must be perfectly aligned over the tops of the poles, etc). Even though the eruv is mostly symbolic, holding very special meaning for a specific social group, it is has real consequences in the material world; namely it costs a money and time.

The example of the eruv displays that the "deep insight of recent social studies of technology is to show that signification and materiality always form an interaction process" (Pinch 2010). This is exquisitely powerful to the examination of infrastructure; it allows the researcher to describe both the impact of physical structures on social life as well as outline the impacts of social and political actions on the physical structure of our world. STS scholars show that technologies are an actor in the meaning-making process involved in the development knowledge systems. As Pinch (2010) says, "…technologies and their meanings do not exist detached from the rest of society, its institutions, culture and the vast assemblages of technologies and humans we have already built" (p.80). He illustrates this point through a case study of a proposal to build an eruv around a neighborhood in Ithaca. The proposal sparked open public debate regarding the separation between church and state, economic responsibility, and even what legally constituted a “sign.” National laws, economics, local social stratification all came into play in these public debates about what was essentially an invisible wall.

Beyond the general balance between technological determinist and technological instrumentalist views, infrastructures require additional layers of analysis because of their position as connections between technologies and social groups. Larkin (2013) goes as far as saying that infrastructure is distinct from technology generally because it is inherently a *system*: "What distinguishes infrastructures from technologies is that they are objects that create the grounds on which other objects operate, and when they do so they operate as systems" (Larkin 2013). The large networks that these systems represent make defining the actual object under study in infrastructure research difficult.

> Given the ever-proliferating networks that can be mobilized to understand infrastructure, we are reminded that discussing an infrastructure is a categorical act. It is a moment of tearing into those heterogeneous networks to define which aspect of which network is to be discussed and which parts will be ignored (Larkin 2013).

Adding Nature to the mix

> STS as a whole has been primarily concerned with science and technology while issues related to nature and the environmental assumed a secondary position. Nature is consequently - and quite ironically - naturalized. A necessary correction would be to, rather than reject it as a hollow concept, add it again to the arsenal of machineries that are studied by STS: that is what enviro-technical analysis is aiming at. (Pritchard 2011; Rowland and Passoth 2014)

While the STS recognition of the hybridity of society and technology is very useful, it often neglects another critical actor: nature. Recognizing nature as an actor moves the discussion from Kirkman’s “sociotechnical ensembles” to socio-ecological-technical systems (SETS). The emergent concept of infrastructures as SETS complicates the picture of infrastructures as shaping, and being shaped by, society with the addition of *ecological actors*. Plants, animals, fungi, and microbes all play a role in infrastructural service delivery, either by design (for example, bacteria in a wastewater treatment plant) or unintentionally (for example, scum growing on the inside of pipes). This means that all urban infrastructural systems interact with ecology – the degree to which city managers and engineers explicitly define this relationship varies spatially and temporally. This suggests that differential definitions, or the use of different kinds (Hacking), influences the functionality of these systems in addressing social and ecological parameters.

While the use of living ecological components (i.e. microbes, trees, vegetation, etc.) in infrastructural design has been present throughout the history of urban development, the specific configuration of the human-ecology interaction has changed throughout this time. The relationship is constantly reimagined as human needs and ecological/geological systems evolve. As the concept of the Sustainable City continues to emerge in the 21st century, it is increasingly important to define the enrollment of nature in the creation of infrastructure. Recognizing the past definitions of the human-nature relationship materialized in infrastructure facilities becomes critical data in the quest to reveal the political, social, and ecological consequences of these changing relationships (Schneider 2011).

STS scholars have explored the hybridity of nature and technology though a number of different frameworks. Pritchard's (2011; 2012) approach focuses on the social construction of nature. While acknowledging that, "...nonhuman nature may be profoundly mediated and constructed, both literally and metaphorically", she admits that "it is not wholly reducible to culture" (Pritchard 2011); Pritchard argues that what is important to track is how nature can be evoked within strategic political arguments by specific groups of humans for particular ends.

Pritchard (2012) uses the term 'envirotechnical system' – defined as "the historically and culturally specific configurations of intertwined 'ecological' and 'technological' systems, which may be composed of artifacts, practices, people, and ecologies" (p.19) – to define a set of technological and natural systems used by politicians within a specific governance context referred to as an "envirotechnical regime." Regimes in this case are prescriptive, made up of "the institutions, people, ideologies, technologies, and landscapes that together define, justify, build, and maintain a particular envirotechnical system as normative" (p.23). In Pritchard's work,

> …various groups and ambiguous agencies did what STS scholars claim we are doing all the time: we are not just building technologies into an otherwise pure and unaltered nature, but are engaged in enviro-technical modifications; we are not holding nature and technology apart, but are continuously binding and stitching them together (Rowland and Passoth 2014).

When considering green infrastructure knowledge systems, this 'stitching together' begins to interact with various standards. Policy-makers begin to ask, can we count a tree as a technological asset? Is an engineered green street facility natural, meaning that it can be included in an ecosystem services management plan? While we continually intertwine human-made and ecological components of the city, these two categories increasingly 'rub up' against incompatible preexisting standards (Bowker and Star 1999); a new kind must be 'made and modeled' (Hacking 1999) for green infrastructure to allow for the creation of new categories with new standards (Lampland and Star 2009).

The description of power relations in Pritchard's work is also closely tied to the concept of co-production of knowledge and state power (Jasanoff 2004). The concept of linked technical and environmental spheres articulated under the control of political power is important to the study of urban infrastructure, and highlights the importance of contextualization. Examination of the emergence of new norms, protocols, and practices within infrastructure design at the local level is predicated on the concept that context matters, and that local implementation of generic knowledge creates unique and emergent knowledge systems that can change the efficacy of best management practice (BMP) facilities socially, ecologically, and technologically.

Because infrastructures are, by definition, built to provide on-going services or processes rather than end-point products, they are ideal artifacts to use to describe SETS as *systems* in particular. As Star mentions, infrastructure does not exist outside of the concept of use, it "appears only as a relational property, not as a thing stripped of use." For example, bioswales push the limits of the traditional viewpoint of nature as raw material; they are built to explicitly take advantage of *process* in nature: water filtration and storage in soil. Therefore, it is easy to see this infrastructural facility as more than just an end point, or a technology that we feed raw materials from nature. It is a visual and explicit hybrid of the natural and the technological. With this starting point, a study of infrastructure can focus on process without having to black-box one side or the other.

Another framing of this topic dismisses a discussion of hybridity all together and analyzes the direct acknowledgement of nature as infrastructure itself: "Nature is…in some sense the ultimate infrastructure" (Edwards 2003, p.196). This recognition of nature as infrastructure is somewhat new. In the past, "infrastructure implies artifice, nature typically signifies its absence" (Carse 2012). Carse (2012) describes an example of how this idea is changing explaining how the natural landscape around the Panama Canal has increasingly become viewed as a water-provisioning infrastructural system. Without the water stored in the soils of the surrounding landscape, the Panama Canal would not have enough water to fill the locks that transport tankers and boats, making nature a key water management infrastructure system.

Also, because of the ambiguity of what infrastructure actually is, it can be stretched to encompass nature as well as technology. "The concept of infrastructure does not delimit a priori which - or even what kind of - components are needed to achieve a desired objective" (Carse 2012). Therefore, nature becomes much like a technology in STS research: "As nature becomes infrastructure through work, human politics and values are inscribed on the landscape, much as they are embedded in arrangement of steel and concrete" (Carse 2012).

Lastly, one of the most important aspects of the STS lens is that technical and ecological system components are viewed as actors, rather than static background conditions. In this framework, infrastructures can be revealed as important mediators of the human relationship with nature:

> Infrastructures constitute an artificial environment, channeling and/or reproducing those properties of the natural environment that we find most useful and comfortable; providing others that the natural environment cannot; and eliminating features we find dangerous, uncomfortable, or merely inconvenient. In doing so, they simultaneously constitute our experience of the natural environment, as commodity, object of romantic or pastoralist emotions and aesthetics sensibilities, or occasional impediment. They also structure nature as resource, fuel, or "raw material," which must be shaped and processed by technological means to satisfy human ends. *Thus to construct infrastructures is simultaneously to construct a particular kind of nature, a Nature as Other to society and technology* (Edwards 2003, p. 189).

All of these STS interpretations lead to a greater understanding of the emergence green infrastructure design and implementation; however, it is important to keep in mind that “studies of infrastructure tend to privilege the technological even if they qualify it by defining urban spaces as hybrid systems of humans and machines bundled together through infrastructural networks" (Larkin 2013, p. 339).

Invisibility

Basic etymology highlights the overwhelming background-ness of infrastructure. Through employing the Latin prefix ‘infra-’, meaning below or underneath, ‘infrastructure’ is an antonym of ‘superstructure’ (Merriam-Webster 2014). While superstructures are overt, visible, and often seen as powerful, infrastructure is primarily hidden, taken-for-granted, and seen as mundane; it is “something that other things ‘run on’, things that are substrate to events and movements” but that aren’t events or movements themselves (Lampland and Star 2009). This is because most people interact directly with the output end of infrastructures; they notice the goods and services provided by infrastructural systems because that is what they need and want (Edwards 2003). The ways in which infrastructure provide those goods and services are for the most part invisible to the user. Take for example, an electric outlet. In my house, I use outlets everyday to run a variety of appliances: my coffee maker, the bedside lamp, my dishwasher, my cell phone charger. Electric outlets allow me to go about the activities of my day, but I rarely think about the outlets or the electricity they provide to run the appliances in my life; instead, I think about that first sip of coffee that wakes me up in the morning, the ability to see my book when I read in bed, my clean dishes to make dinner, and calling my mom in the middle of the day. This is closely related to the concept that infrastructures only appear relationally: “Analytically, infrastructure appears only as a relational property, not as a thing stripped of use" (Star & Ruhleder 1996, p. 113).

The daily invisibility of infrastructure is an oft repeated insight of the STS literature (Larkin 2013). However, it is important to be nuanced in the discussion of invisibility. As Star (1999) mentions, “one person’s infrastructure is another’s topic, or difficulty” (p.380). A tangible example of this is the stairs leading to the front door of a building; for most people it is simply taken-for-granted transportation infrastructure, but for a person in a wheelchair it represents a real barrier to use. Depending on a variety of demographic factors, infrastructures can be either background systems or front and center problems (Larkin 2013).

This nuanced description of invisibility also illuminates the relationship between invisibility and pluralism. Bowker and Star (1999) argue that for information to be perceived, it “*must* reside in more than one context” (p. 290). This is because “we know what something is by contrast with what it is not" (Bowker and Star 1999). To communicate knowledge, therefore, there must be multiple interpretations at work:

> A radical statement of this would be that information is only information when there are multiple interpretations. One person's noise may be another's signal or two people may agree to attend to something, but it is the tension between contexts that actually creates representation….This multiplicity is primary, not accidental nor incidental" (Bowker and Star 1999, p. 291).

In other words, you never need to create a representation of something that everyone else already understands and views in the same way. However, in the pluralistic world in which we live, there are multiple viewpoints of the same objects and processes that need to be translated, shared, and communicated in order for understanding and action to take place.

A corollary theme to the invisibility of man-made infrastructures, is the deeper invisibility of earth systems from daily life. Primarily, the purpose of infrastructure systems is to deliver life-support services in a more steady fashion than ecosystems would if left unaltered (Edwards 2003). In our day-to-day lives, as discussed above, we primarily interact with the human-crafted technical hardware and software of infrastructural systems – facets, roads, electrical sockets, grocery carts. But in the background of these systems are ecological systems – water filtering through the soil and plants, microbes fixing nitrogen in farm fields, plants and animals dying and slowly becoming formations of coal and gas (Millennium Ecosystem Assessment 2005). Most people rarely, if ever, engage with this part of infrastructure directly. These processes are messy, seasonal, too slow or too fast, contrasting ordered urban infrastructural systems (Edwards 2003).

Infrastructure therefore alters the city-dwellers' vision of the life-support network provided by ecosystems; one of the problematic pieces of this vision is the distributed and distant feedback loops that do not allow individuals to directly see their interactions with nature. Instead of messiness and evolving ecosystems, they see a consistent service delivery (Edwards 2003). This influences the production of knowledge about infrastructure through time, therefore changing the kinds of knowledge available for application in the city. For example, as users continue to expect reliable clean water in their pipes, ever-more-complicated mechanical water treatment has been added to the system (Melosi 2008; Tarr 1996). As Edwards (2003) asserts, "[infrastructures'] capacities permit us…to approach nature as a consumable good, something to be experienced (or not) as and when we wish" (p. 189).

The messy work done by natural actors, or ecosystem components of infrastructure, has been minimized or re-branded as part of mechanical systems throughout the industrial era (microbes in wastewater treatment are an excellent example of this as described by (Schneider 2011)). This has meant that the role of nature in the city has been underplayed and made less visible through time (notable exceptions have been in park design where social and moral improvements have been attributed to natural systems (Gandy 2002; Lachmund 2013)). As the perceived role of nature in water infrastructure design and maintenance decreased, the attention to ecological elements of the system likewise waned. In this way, we have come to measure and categorize water infrastructure as a human-made technology, rather than as a natural ecosystem (Schneider 2011); this categorization, or kind-making (Hacking), has influenced the development of scientific and tacit knowledge about water in the city, determining the ways that we measure and therefore value water infrastructure (Edwards, Gandy).

Both the network and stormwater visions of green infrastructure work to change this invisibility of ecology in infrastructure and the city in general. The ecosystem services framework has been developed as a way to categorize the benefits humans receive from nature (Millennium Ecosystem Assessment 2005). There are wide-ranging benefits included in the framework, from provision of clean air and clean water (via natural cycles of filtration through biotic and abiotic ecological components) to spiritual rejuvenation and sense of place (inspired by interactions with intact forests, wetlands, lakes, etc.) (Millennium Ecosystem Assessment 2005). These new categories valorize the contributions of natural systems while silencing the work of man-made systems which is opposite to the way that the categories are currently perceived (popularly and in municipal government). These new service categories are on track to become new standards for urban nature and green infrastructure in the city. As reviewed thus far, research into these changing categories can shed light on the power of knowledge systems in the city (Jasanoff 2004).

Conceptual Framing

The 'Eco-Techno' Spectrum of Green Infrastructure Interventions

The idea of green infrastructure today comes with a significant amount of conceptual baggage from the differing worldviews that invoke the term to accomplish different goals. As described above, different stakeholders hold different ideas about both what green infrastructure is and what it should do. These differing visions are contested in cities attempting to build low-cost and sustainable infrastructures. For example, green infrastructure options were originally dismissed by engineers in Pittsburgh when completing a new stormwater management plan; the knowledge claims regarding green infrastructure's effectiveness, which are mostly regarding ecological benefits, were not relevant or salient to their knowledge system which focused on the engineering problem of reducing water quantity in the sewer system. Non-profit and community groups in marginalized areas of the city however, envisioned the many benefits green infrastructure could provide, from social cohesion to reduction of urban heat island effects, contesting the all-grey-infrastructure CSO plan in the city and demanding revisions that included green infrastructure (Finewood 2016).

To better understand green infrastructure, and its potential outcomes, we must better understand the ways that differing definitions and visions of green infrastructure are being evoked and negotiated in cities today. How are the different conceptualizations of green infrastructure combining or competing, and what socio-natures do they produce on the ground? To do this, a connection between disparate facilities and the siloed institutions that manage them must be made. Therefore, I developed the *eco-techno spectrum* (displayed in Figure 1-7) to connect the large variety of green infrastructure interventions currently in use in the United States in a single framework. This framework exposes three important knowledge system challenges (described in more detail in the following section) emerging in US cities today.

The eco-techno spectrum highlights the different degrees to which a green infrastructure facility includes biological entities, or living 'stuff' (including plants, microbes, etc) as a designed component of the facility. This living stuff is the 'eco' part of 'eco-techo' shorthand. There is more ecology on the left-hand side of the spectrum and more physical-mechanical technology on right-hand, or 'techno', side of the spectrum.

As discussed in the introduction, a wide variety of facility types are included in municipal green infrastructure programs and plans (Mell 2013), spanning from small-scale, highly engineered facilities like bioswales and green roofs (as seen in New York City's plan (NYC Environmental Protection 2010)) to larger-scale parks, natural areas, urban wetlands and floodplains (as seen in Philadelphia's *Green City, Clean Waters* Plan (Philadelphia Water Department 2011)). And in between these two extremes are urban agriculture facilities, smaller and more developed parks, and greenbelts, as well as street tree networks and urban tree canopies (as seen in Portland's Watershed Management Plan and Baltimore's Green Pattern Book). The primary distinguishing characteristic of green infrastructure across this variety is the *explicit* use (or mimicry) of ecological processes to provide utility services; biological elements are integrated to differing degrees with grey technological components to provide these services, making green infrastructure facilities *ecological-technological hybrids.*

Others scholars have presented similar spectrums to examine aspects of green infrastructure, including Mell's (2013) use of Davies' "grey-green continuum" which highlights the distinctions between facilities that are 'visually green' (i.e. parks, grass) and those that are considered green because they are 'sustainable' (i.e. bike paths, LEED buildings); and the Royal Society's (2014) rejection of an infrastructure binary (i.e. as either 'grey' or 'green') through recognizing a "hybrid" category of resilient infrastructure options that exists between "ecosystem-based" and "engineering" options (see also Grimm et al. (2016)).

The eco-techno spectrum, therefore, follows the lead of Mell (2013), the Royal Society (2014), and other scholars (Grimm et al. 2016) that display the usefulness of continuums in exposing the nuances of green infrastructure programs. However, the eco-techno spectrum differs from these other research projects by specifically highlighting facilities that *use living organisms* in their design and service delivery, therefore directly engaging with both non-human nature and technology (Redman and Miller 2015). Because of this cross-epistemological framing, the eco-techno spectrum is well suited to explore the connections (and disconnects) between various knowledge systems.

While a relatively simple ordering of green infrastructure facility types, the eco-techno spectrum is a powerful tool because it captures the diversity of technologies, jurisdictions, scales, and ecosystems that make up green infrastructure in current municipal programs. Heterogeneity of components, scales, and jurisdictions is not unique to green infrastructure, as nearly all infrastructural systems must cross epistemic and physical boundaries in their organization and management (Pinch 2010; Star 1999). However, green infrastructure represents a *new* assemblage of previously disparate groupings and component types which have not been traditionally viewed as 'infrastructure' (i.e. plants are not typically viewed as water storage and filtration 'tanks'). The well-established kinds (Hacking 1999), categories (Bowker and Star 1999), and standards (Lampland and Star 2009) that have developed over time in municipal management to deal with cross-boundary issues of grey infrastructure are not germane to managing the ecological processes and biological entities of green infrastructure. In fact, in most instances biological components and their ecological properties are invisible to the epistemic communities designing, constructing, and maintaining them.

Figure 1-7: The eco-techno spectrum displays the varying ecological-technological hybridity of green infrastructure facilities. On the left-hand side of the spectrum ecological and biological components make up more of the facility, whereas on the right-hand side technological, mechanical components make up more of the facility. This spectrum is used as heuristic to organize insights regarding current green infrastructure knowledge challenges across a practice-oriented spectrum of facilities.

I use the eco-techno spectrum to link insights regarding knowledge systems' negotiations and changes in on-the-ground case studies back to the different facility types that different knowledge competitions and combinations encourage and discourage. Below I describe three important knowledge system challenges that are exposed by the eco-techno spectrum.

Emergent Knowledge System Challenges

Definitional Challenges

The hybrid biological/mechanical make-up of green infrastructure facilities do not fit neatly into the jurisdiction of any one municipal department or agency. The divergent goals and missions of these managing authorities has led to *differing definitions* of green infrastructure facilities and components across, and even within, cities. Therefore, the development of cohesive city-wide green infrastructure strategies (including development of facility design, implementation, and maintenance standards that work with existing land-use plans) is not straightforward; it requires the negotiation and reconciliation of multiple nascent knowledge practices and work-arounds found across cities and across city bureaus and departments.

Definitional challenges stem from ontological tensions within green infrastructure development; in particular the categorization of what is *natural* and what is *human*. This observation builds off a robust literature that explores the social construction of ‘nature’ and ‘ecology’ as something separate from humans (Katz 1997; Cronon 1992; Worster 1990): “What is considered natural and what constitutes nature changes historically and culturally…[O]ur view of nature has more to do with the society we live in than with an objective ‘nature’; in other words, nature is a social construct.” (Hartmann 1998)

Few contemporary urban concepts expose this ontological tension between the natural and the human better than green infrastructure. While the specific definition of green infrastructure varies from place to place (Mell 2013), green infrastructure is generally understood as networked green spaces that provide ecosystem services (Millennium Ecosystem Assessment 2005) to human populations and provide contiguous habitat for non-human nature. Depending on the institution, however, the services and facilities included in the definition of "green infrastructure" can be quite different. For example, Benedict and McMahon's (2006) highly cited definition of green infrastructure stresses the importance of conservation of natural areas:

> …green infrastructure is…an interconnected network of green space that *conserves natural ecosystem values and functions* and provides associated benefits to human populations. (Benedict and McMahon 2006, p. 5)

These authors and those that cite them (primarily environmental non-profits and ecologists) claim that the primary service provided by green infrastructure is natural ecosystem function and protection, while the benefits to human populations are secondary. From this perspective, green infrastructure is described as a win-win land-use solution that helps both humans and the environment, but with an explicit focus on environmental gains. To these groups, green infrastructure represents preserved/conserved/restored *nature*.

Regulatory institutions like the U.S. EPA, instead, focus on the stormwater management benefits of green infrastructure systems and are often agnostic to the natural character of facilities, allowing engineering solutions to be a major component of the concept:

> Green infrastructure is a cost-effective, resilient approach to *managing wet weather impacts* that provides many community benefits… At the neighborhood or site scale, *stormwater management systems that mimic nature* soak up and store water. (EPA 2015)

Cost-effectiveness and resilience in addressing regulatory compliance issues are upfront in definitions from institutions like these, with habitat benefits a happy secondary outcome. Facilities within this framing *mimic* the functions natural systems offer with engineering/grey solutions, rather than creating facilities through restoration or conservation of ecosystems. This win-win land-use solution emphasizes technology over the environment. To these groups, green infrastructure is *human*.

Measurement Challenges

Green infrastructure facilities rely on multi-faceted ecological functions that result from the combination of biological actors, instead of narrowly-defined and precisely measured physical functions that result from well-understood mechanical combinations of grey infrastructure components. In many cases, the combination of ecological entities in facilities is novel (Hobbs, Higgs, and Harris 2009; Kaye et al. 2006), meaning current ecological theory may not apply to the size and composition of the community assembled in a green infrastructure facility. This reliance on new and unpredictable ecological structure and function makes it difficult to *measure or predict* the performance of green infrastructure facilities, complicating estimates of total service delivery.

This challenge stems primarily from an epistemological tension within green infrastructure development. Different epistemic communities measure services in different, sometimes conflicting, ways (Haas 1992). Essentially, “an epistemic community is a network of professionals with recognized expertise and competence in a particular domain and an authoritative claim to policy-relevant knowledge within that domain or issue-area” (Haas 1992). For example, engineers represent an epistemic community which has strong “authoritative claim” over the knowledge relevant to infrastructure performance, and the services that a particular infrastructure is meant to provide.

Knowledge systems analysis is particularly important to apply to the discretionary utilization of ecological knowledge claims within green infrastructure technologies because of the *hybrid epistemologies* (Wilson 2009; Burnham, Ma, and Zhang 2016) that must be formed to design, build, and manage these facilities. Hybrid knowledge practices allow the particularities of the green knowledge systems (i.e. their engagement with ecological structure and function) to ‘fit’ in a traditional grey knowledge system. These new practices present challenges to existing institutional structures and their knowledge systems, and create new barriers to specific ecosystem services (i.e. the focus on water quantity management puts the emphasis on amplifying this function at the expense of other important benefits like nutrient cycling, recreation, and air filtration, among many others.) As Bowker and Star (1999) put it, "each standard and each category" – a knowledge practice or epistemology in this case – "valorizes some point of view and silences another. This in not inherently a bad thing - indeed it is inescapable. But it *is* an ethical choice, and as such is dangerous - not bad, but dangerous" (p. 5-6). We need to be explicit about what and who is being silenced by current green infrastructure knowledge systems to better understand and predict facility performance on-the-ground.

Valuation Challenges

Current infrastructure valuation and asset management in cities is based on the cost and maintenance of mechanical components of traditional grey infrastructure, including pipes, pumps, wells, and mechanical filtration systems. Biological entities are *not easily valued with existing techniques*, making green infrastructure facilities difficult to integrate into business-as-usual asset management and financialization at the municipal, state, and federal level.

Valuation is as a specific case of both the challenges described above: financial entities do not categorize biological components as infrastructure, and have limited ways to measure biological components even if they want to categorize them as infrastructure. I draw out valuation as a separate challenge because valuation emerged as a major decision-making point within green infrastructure planning throughout case study work. The City of Portland is openly struggling with valuation of green infrastructure; and many other cities are asking Portland how they include green infrastructure in asset management, indicating that they struggle with similar issues. This makes valuation (monetary and otherwise) an excellent exposed decision-making process that can be used to explore the other two challenges (explored in detail in Chapter 3).

Conclusion

While most urban infrastructures have faded into the background of daily life as "certain, cold, unproblematic, black box[es]" (Latour 1987), the three knowledge systems challenges described here expose green infrastructure as a knowledge system 'in the making'; unlike now well-established ecological-technological hybrid infrastructures, like wastewater treatment plants (Schneider 2011), the messy political decisions of definition and measurement are openly contested. By studying green infrastructure, then, I follow Latour's lead: "The impossible task of opening the black box is made feasible (if not easy) by moving in time and space until one finds the controversial topic on which scientists and engineers are busy at work" (Latour 1987). Measurement, definition, and valuation of urban nature is where scientists and engineers are in uncertain territory and are actively making decisions about open controversies of ecological fact. It is where I can observe and analyze the production and use of ecological knowledge by different epistemic communities, providing insight into deeply held ontologies of municipal actors that are usually hidden during business-as-usual infrastructure design and implementation processes.

In summary, all three of these green infrastructure challenges display the usefulness of knowledge systems analysis as an analytical tool for understanding the feedback loops between social and material reality. As Jasanoff (2004) says, "our methods of understanding and manipulating the world curve back and reorder our collective experience along unforeseen pathways..." (p.13). Knowledge systems analysis begins to expose and characterize these pathways so they can be designed more openly and more sustainably.

References

Alberti, Marina, J.M. Marzluff, Gordon Bradley, Clare M. Ryan, Eric Schlenberger, and Craig Zumbrunnen. 2003. “Integrating Humans into Ecology: Opportunities and Challenges for Studying Urban Ecosystems.” *BioScience* 53 (12): 1169–79.

Anderies, John M., Marco A. Janssen, and Elinor Ostrom. 2004. “A Framework to Analyze the Robustness of Social-Ecological Systems from an Institutional Perspective.” *Ecology and Society* 9 (1): 18.

ASCE. 2017. “Infrastructure Report Card: A Comprehensive Assessment of America’s Infrastructure.”

Benedict, Mark A., and Edward McMahon. 2006. *Green Infrastructure: Linking Landscapes and Communities*. Washington, DC: Island Press.

Ben-Joseph, Eran. 2005. *The Code of the City: Standards and the Hidden Language of Place Making*. Urban and Industrial Environments. Cambridge, Mass: MIT Press.

Bocchini, Paolo, Dan M. Frangopol, Thomas Ummenhofer, and Tim Zinke. 2014. “Resilience and Sustainability of Civil Infrastructure: Toward a Unified Approach.” *Journal of Infrastructure Systems* 20 (2): 04014004. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000177.

Bocking, Stephen. 2004. *Nature’s Experts: Science, Politics, and the Environment*. New Brunswick, N.J: Rutgers University Press.

Bowker, Geoffrey C., Karen Baker, Florence Millerand, and David Ribes. 2009. “Toward Information Infrastructure Studies: Ways of Knowing in a Networked Environment.” In *International Handbook of Internet Research*, edited by Jeremy Hunsinger, Lisbeth Klastrup, and Matthew Allen, 97–117. Dordrecht: Springer Netherlands. http://link.springer.com/10.1007/978-1-4020-9789-8_5.

Bowker, Geoffrey C., and Susan Leigh Star. 1999. *Sorting Things out: Classification and Its Consequences*. Inside Technology. Cambridge, Mass: MIT Press.

Burnham, Morey, Zhao Ma, and Baoqing Zhang. 2016. “Making Sense of Climate Change: Hybrid Epistemologies, Socio-Natural Assemblages and Smallholder Knowledge: Making Sense of Climate Change.” *Area* 48 (1): 18–26. https://doi.org/10.1111/area.12150.

Callon, Michel. 1999. “Some Elements of a Sociology of Translation: Domestication of the Scallops and the Fishermen of St. Brieuc Bay.” In *The Science Studies Reader*, edited by Biagioli. New York: Ratledge.

Carlet, Fanny. 2015. “Understanding Attitudes toward Adoption of Green Infrastructure: A Case Study of US Municipal Officials.” *Environmental Science & Policy* 51 (August): 65–76. https://doi.org/10.1016/j.envsci.2015.03.007.

Carse, A. 2012. “Nature as Infrastructure: Making and Managing the Panama Canal Watershed.” *Social Studies of Science* 42 (4): 539–63. https://doi.org/10.1177/0306312712440166.

Cartwright, Nancy. 1999. *The Dappled World: A Study of the Boundaries of Science*. Cambridge, UK : New York, NY: Cambridge University Press.

"City of Chicago: Green Stormwater Infrastructure Strategy." 2014. Chicago: Department of Water Management.

City of Seattle. 2015. "Green Stormwater Infrastructure in Seattle: Implementation Strategy 2015-2020." Seattle, WA: City of Seattle.

Collins, Scott L, Stephen R Carpenter, Scott M Swinton, Daniel E Orenstein, Daniel L Childers, Ted L Gragson, Nancy B Grimm, et al. 2011. "An Integrated Conceptual Framework for Long-Term Social–Ecological Research." *Frontiers in Ecology and the Environment* 9 (6): 351–57. https://doi.org/10.1890/100068.

Cooley, Alexis, and Heejun Chang. 2017. "Precipitation Intensity Trend Detection Using Hourly and Daily Observations in Portland, Oregon." *Climate* 5 (1): 10. https://doi.org/10.3390/cli5010010.

Cronon, William. 1992. "A Place for Stories: Nature, History, and Narrative." *The Journal of American History*, 1347–1376.

Davoudi, Simin. 2012. "The Legacy of Positivism and the Emergence of Interpretive Tradition in Spatial Planning." *Regional Studies* 46 (4): 429–41. https://doi.org/10.1080/00343404.2011.618120.

Davoudi, Simin, Keith Shaw, L. Jamila Haider, Allyson E. Quinlan, Garry D. Peterson, Cathy Wilkinson, Hartmut Fünfgeld, Darryn McEvoy, Libby Porter, and Simin Davoudi. 2012. "Resilience: A Bridging Concept or a Dead End? 'Reframing' Resilience: Challenges for Planning Theory and Practice Interacting Traps: Resilience Assessment of a Pasture Management System in Northern Afghanistan Urban Resilience: What Does It Mean in Planning Practice? Resilience as a Useful Concept for Climate Change Adaptation? The Politics of Resilience for Planning: A Cautionary Note: Edited by Simin Davoudi and Libby Porter." *Planning Theory & Practice* 13 (2): 299–333. https://doi.org/10.1080/14649357.2012.677124.

Dryzek, John S. 1997. *The Politics of the Earth: Environmental Discourses*. Oxford ; New York: Oxford University Press.

Edwards, Paul N. 2003. "Infrastructure and Modernity: Force, Time, and Social Organization in the History of Sociotechnical Systems." In *Modernity and Technology*, edited by Thomas J. Misa, Philip. Brey, and Andrew Fennberg, 185–225. MIT Press.

EPA. 2011. "Urban Waters Small Grants: City of Corvalis." Overviews and Factsheets. US EPA. 2011. https://www.epa.gov/urbanwaters/urban-waters-small-grants.

———. 2015. "What Is Green Infrastructure?" United States Environmental Protection Agency. December 2015. http://www2.epa.gov/green-infrastructure/what-green-infrastructure.

Felson, Alexander J., and Steward T. A. Pickett. 2005. "Designed Experiments: New Approaches to Studying Urban Ecosystems." *Frontiers in Ecology and the Environment* 3 (10): 549. https://doi.org/10.2307/3868611.

Finewood, Michael H. 2016. "Green Infrastructure, Grey Epistemologies, and the Urban Political Ecology of Pittsburgh's Water Governance: Pittsburgh's Water Governance." *Antipode* 48 (4): 1000–1021. https://doi.org/10.1111/anti.12238.

Flyvbjerg, Bent. 1998. *Rationality and Power: Democracy in Practice*. Morality and Society. Chicago: University of Chicago Press.

Friedmann, John. 1993. "Toward a Non-Euclidian Mode of Planning." *Journal of the American Planning Association* 59 (4): 482–85. https://doi.org/10.1080/01944369308975902.

Gandy, Matthew. 2002. *Concrete and Clay: Reworking Nature in New York City*. Urban and Industrial Environments. Cambridge, Mass: MIT Press.

Gieryn, Thomas F. 1999. *Cultural Boundaries of Science: Credibility on the Line*. Chicago: University of Chicago Press.

Goldstein, Bruce Evan, ed. 2012. *Collaborative Resilience: Moving through Crisis to Opportunity*. Cambridge, Mass: MIT Press.

Gottlieb, Robert. 2005. *Forcing the Spring: The Transformation of the American Environmental Movement*. Rev. and updated ed. Washington, DC: Island Press.

Greenberg, P. 2012. "An Oyster in the Storm." *New York Times*, October 29, 2012. http://www.nytimes.com/2012/10/30/opinion/an-oyster-in-the-storm.html.

Grimm, Nancy, Elizabeth M. Cook, Rebecca L. Hale, and David M. Iwaniec. 2016. "Chapter 14: A Broader Framing of Ecosystem Services in Cities." In *The Routledge Handbook of Urbanization and Global Environmental Change*, edited by Karen Ching-Yee Seto, William Solecki, and Corrie Griffith, 1 Edition. New York: Routledge, Taylor & Francis Group.

Gross, Mattias. 2010. *Ignorance and Surprise: Science, Society, and Ecological Design*. MIT Press.

Grove, J. M., A. R. Troy, J. P. M. O'Neil-Dunne, W. R. Burch, M. L. Cadenasso, and S. T. A. Pickett. 2006. "Characterization of Households and Its Implications for the Vegetation of Urban Ecosystems." *Ecosystems* 9 (June): 578–97. https://doi.org/10.1007/s10021-006-0116-z.

Haas, Peter. 1992. "Epistemic Communities and International Policy Coordination." *International Organization* 46 (1): 1–35.

Hacking, Ian. 1999. "Kind-Making: The Case of Child Abuse." In *The Social Construction of What?* Harvard University Press.

Hartmann, Franz. 1998. "Towards a Social Ecological Politics of Sustainability." In *Political Ecology Global and Local*. London; New York: Routledge. http://site.ebrary.com/id/10100171.

Healey, Patsy. 1997. *Collaborative Planning: Shaping Places in Fragmented Societies*. Vancouver: UBC Press.

Hobbs, Richard J., Eric Higgs, and James A. Harris. 2009. "Novel Ecosystems: Implications for Conservation and Restoration." *Trends in Ecology & Evolution* 24 (11): 599–605. https://doi.org/10.1016/j.tree.2009.05.012.

Hull, R. Bruce, David P. Robertson, David Richert, Erin Seekamp, Gregory J. Buhyoff, and others. 2002. "Assumptions about Ecological Scale and Nature Knowing Best Hiding in Environmental Decisions." *Conservation Ecology* 6 (2): 12.

Innes, Judith Eleanor, and David E. Booher. 2010. *Planning with Complexity: An Introduction to Collaborative Rationality for Public Policy*. Milton Park, Abingdon, Oxon ; New York, NY: Routledge.

Jasanoff, Sheila, ed. 2004. *States of Knowledge: The Co-Production of Science and Social Order*. International Library of Sociology. London ; New York: Routledge.

Jasanoff, Sheila, and Sang-Hyun Kim. 2013. "Sociotechnical Imaginaries and National Energy Policies." *Science as Culture* 22 (2): 189–96. https://doi.org/10.1080/09505431.2013.786990.

Karvonen, Andrew. 2011. *Politics of Urban Runoff: Nature, Technology, and the Sustainable City*. Urban and Industrial Environments. Cambridge, Mass: MIT Press.

Katz, Eric. 1997. *Nature as Subject: Human Obligation and Natural Community*. Studies in Social, Political, and Legal Philosophy. Lanham: Rowman & Littlefield.

Kaye, J, P Groffman, N Grimm, L Baker, and R Pouyat. 2006. "A Distinct Urban Biogeochemistry?" *Trends in Ecology & Evolution* 21 (April): 192–99. https://doi.org/10.1016/j.tree.2005.12.006.

Kimmelman, M. 2012. "Vetoing Business as Usual After the Storm." *New York Times*, November 19, 2012. http://www.nytimes.com/2012/11/20/arts/design/changes-needed-after-hurricane-sandy-include-politics.html?pagewanted=all.

Kingsland, Sharon E. 2005. *The Evolution of American Ecology, 1890-2000*. Baltimore: Johns Hopkins University Press.

Knorr-Cetina, K. 1999. *Epistemic Cultures: How the Sciences Make Knowledge*. Cambridge, Mass: Harvard University Press.

Lachmund, Jens. 2013. *Greening Berlin: The Co-Production of Science, Politics, and Urban Nature*. Inside Technology. Cambridge, Mass: MIT Press.

Lampland, Martha, and Susan Leigh Star, eds. 2009. *Standards and Their Stories: How Quantifying, Classifying, and Formalizing Practices Shape Everyday Life*. Ithaca: Cornell University Press.

Larkin, Brian. 2013. "The Politics and Poetics of Infrastructure." *Annual Review of Anthropology* 42 (1): 327–43. https://doi.org/10.1146/annurev-anthro-092412-155522.

Latour, Bruno. 1987. *Science in Action: How to Follow Scientists and Engineers through Society*. Cambridge, Mass.: Harvard University Press.

Lave, Rebecca. 2011. "Circulating Knowledge, Constructing Expertise." In *Knowing Nature: Conversations at the Intersection of Political Ecology and Science Studies*, edited by Mara Goldman, Paul Nadasdy, and Matt Turner. The University of Chicago Press.

Lave, Rebecca, Matthew W. Wilson, Elizabeth S. Barron, Christine Biermann, Mark A. Carey, Chris S. Duvall, Leigh Johnson, et al. 2014. "Intervention: Critical Physical Geography." *The Canadian Geographer / Le Géographe Canadien* 58 (1): 1–10. https://doi.org/10.1111/cag.12061.

Light, Jennifer S. 2009. *The Nature of Cities: Ecological Visions and the American Urban Professions, 1920-1960*. Baltimore: Johns Hopkins University Press.

McGinnis, Michael, and Elinor Ostrom. 2011. "SES Framework: Initial Changes and Continuing Challenges." In *Bloomington, IN: Workshop in Political Theory and Policy Analysis, Department of Political Science, and Schoolof Public and Environmental Affairs, Indiana University*. http://www.iub.edu/~workshop/publications/materials/W11-6_McGinnisEO.pdf.

McPhearson, Timon, Steward T. A. Pickett, Nancy B. Grimm, Jari Niemelä, Marina Alberti, Thomas Elmqvist, Christiane Weber, Dagmar Haase, Jürgen Breuste, and Salman Qureshi. 2016. "Advancing Urban Ecology toward a Science of Cities." *BioScience* 66 (3): 198–212. https://doi.org/10.1093/biosci/biw002.

Mell, Ian C. 2013. "Can You Tell a Green Field from a Cold Steel Rail? Examining the 'Green' of Green Infrastructure Development." *Local Environment* 18 (2): 152–66. https://doi.org/10.1080/13549839.2012.719019.

Mell, Ian C., John Henneberry, Sigrid Hehl-Lange, and Berna Keskin. 2016. "To Green or Not to Green: Establishing the Economic Value of Green Infrastructure Investments in The Wicker, Sheffield." *Urban Forestry & Urban Greening* 18 (August): 257–67. https://doi.org/10.1016/j.ufug.2016.06.015.

Melosi, Martin V. 2008. *The Sanitary City: Environmental Services in Urban America from Colonial Times to the Present*. Abridged ed. History of the Urban Environment. Pittsburgh, Pa: the University of Pittsburgh Press.

Merriam-Webster. 2017. “Definition of INFRASTRUCTURE.” 2017. https://www.merriam-webster.com/dictionary/infrastructure.

Millennium Ecosystem Assessment. 2005. “Ecosystems and Human Wellbeing Synthesis.” Synthesis.

Miller, Clark A, Tischa Munoz-Erickson, and Chad Monfreda. 2010. “Knowledge Systems Analysis: A Report for the Advancing Conservation in a Social Context Project.” #10-05. CSPO Arizona State University.

Mukerji, Chandra. 2009. *Impossible Engineering: Technology and Territoriality on the Canal Du Midi*. Princeton Studies in Cultural Sociology. Princeton, N.J: Princeton University Press.

Munoz-Erickson, Tischa. 2014. “Co-Productiom of Knowledge-Action Systems in Urban Sustainable Governance: The KASA Approach.” *Environmental Science & Policy* 37: 182–91.

Netusil, Noelwah R., Zachary Levin, Vivek Shandas, and Ted Hart. 2014. “Valuing Green Infrastructure in Portland, Oregon.” *Landscape and Urban Planning* 124 (April): 14–21. https://doi.org/10.1016/j.landurbplan.2014.01.002.

NYC Environmental Protection. 2010. “NYC Green Infrastructure Plan: Executive Summary.” http://www.nyc.gov/html/dep/pdf/green_infrastructure/NYCGreenInfrastructurePlan_ExecutiveSummary.pdf.

Ozawa, Connie P. 1991. *Recasting Science: Consensual Procedures in Public Policy Making*. Boulder: Westview Press.

Philadelphia Water Department. 2011. “Green City, Clean Waters: The City of Philadelphia’s Program for Combined Sewer Overflow Control Program Summary.” http://www.phillywatersheds.org/doc/GCCW_AmendedJune2011_LOWRES-web.pdf.

Pickett, S.T.A., M.L. Cadenasso, and J.M. Grove. 2004. “Resilient Cities: Meaning, Models, and Metaphor for Integrating the Ecological, Socio-Economic, and Planning Realms.” *Landscape and Urban Planning* 69 (4): 369–84. https://doi.org/10.1016/j.landurbplan.2003.10.035.

Pickett, STA1ã, M. L. Cadenasso, and S. J. Meiners. 2009. “Ever since Clements: From Succession to Vegetation Dynamics and Understanding to Intervention*.” *Applied Vegetation Science* 12 (1): 9–21.

Pickett, Steward TA, M. L. Cadenasso, J. M. Grove, C. H. Nilon, R. V. Pouyat, W. C. Zipperer, and R. Costanza. 2001. “Urban Ecological Systems: Linking Terrestrial Ecological, Physical, and Socioeconomic Components of Metropolitan Areas.” *Annual Review of Ecology and Systematics*, 127–157.

Pinch, T. 2010. “On Making Infrastructure Visible: Putting the Non-Humans to Rights.” *Cambridge Journal of Economics* 34 (1): 77–89. https://doi.org/10.1093/cje/bep044.

Porter, Theodore. 1994. “Making Things Quantitative.” *Science in Context* 7 (3): 389–407.

Porter, Theodore M. 1996. *Trust in Numbers: The Pursuit of Objectivity in Science and Public Life*. Princeton, N.J.: Princeton University Press.

Pritchard, S. B. 2012. “An Envirotechnical Disaster: Nature, Technology, and Politics at Fukushima.” *Environmental History* 17 (2): 219–43. https://doi.org/10.1093/envhis/ems021.

Pritchard, Sara B. 2011. *Confluence: The Nature of Technology and the Remaking of the Rhône*. Harvard Historical Studies 172. Cambridge, Mass: Harvard University Press.

Rasmussen, Wayne D. 1968. "Advances in American Agriculture: The Mechanical Tomato Harvester as a Case Study." *Technology and Culture* 9 (4): 531. https://doi.org/10.2307/3101894.

Redman, Charles L., and Thaddeus R. Miller. 2015. "The Technosphere and Earth Stewardship." In *Earth Stewardship: Linking Ecology and Ethics in Theory and Practice*, edited by Ricardo Rozzi, F. Stuart Chapin III, J. Baird Callicott, S.T.A. Pickett, Mary E. Power, Juan J. Armesto, and Roy H. May Jr., 269–79. Cham: Springer International Publishing. http://dx.doi.org/10.1007/978-3-319-12133-8_17.

Romolini, Michele, J. Morgan Grove, Curtis L. Ventriss, Christopher J. Koliba, and Daniel H. Krymkowski. 2016. "Toward an Understanding of Citywide Urban Environmental Governance: An Examination of Stewardship Networks in Baltimore and Seattle." *Environmental Management* 58 (2): 254–67. https://doi.org/10.1007/s00267-016-0704-4.

Rowland, N. J., and J.-H. Passoth. 2014. "Infrastructure and the State in Science and Technology Studies." *Social Studies of Science*, June. https://doi.org/10.1177/0306312714537566.

Royal Society (Great Britain). 2014. *Resilience to Extreme Weather*.

Schneider, Daniel. 2011. *Hybrid Nature: Sewage Treatment and the Contradictions of the Industrial Ecosystem*. Urban and Industrial Environments. Cambridge, Mass: MIT Press.

Scott, James C. 1998. *Seeing like a State: How Certain Schemes to Improve the Human Condition Have Failed*. Yale Agrarian Studies. New Haven: Yale University Press.

Shapin, Steven, Simon Schaffer, and Thomas Hobbes. 1985. *Leviathan and the Air-Pump: Hobbes, Boyle, and the Experimental Life : Including a Translation of Thomas Hobbes, Dialogus Physicus de Natura Aeris by Simon Schaffer*. Princeton, N.J.: Princeton University Press.

Star, S. L. 1999. "The Ethnography of Infrastructure." *American Behavioral Scientist* 43 (3): 377–91. https://doi.org/10.1177/00027649921955326.

Tarr, Joel A. 1996. *The Search for the Ultimate Sink: Urban Pollution in Historical Perspective*. 1st ed. Technology and the Environment. Akron, Ohio: University of Akron Press.

Thorne, C.R., E.C. Lawson, C. Ozawa, S.L. Hamlin, and L.A. Smith. 2015. "Overcoming Uncertainty and Barriers to Adoption of Blue-Green Infrastructure for Urban Flood Risk Management: Uncertainties and Barriers to Adoption of BGI." *Journal of Flood Risk Management*, December, n/a-n/a. https://doi.org/10.1111/jfr3.12218.

Wachsmuth, David. 2012. "Three Ecologies: Urban Metabolism and the Society-Nature Opposition." *The Sociological Quarterly* 53 (4): 506–523.

Wilson, Matthew W. 2009. "Cyborg Geographies: Towards Hybrid Epistemologies." *Gender, Place & Culture* 16 (5): 499–516. https://doi.org/10.1080/09663690903148390.

Winner, Langdon. 1986. *The Whale and the Reactor: A Search for Limits in an Age of High Technology*. Chicago: University of Chicago Press.

Worster, Donald. 1990. "The Ecology of Order and Chaos." *Environmental History Review* 14 (1/2): 1. https://doi.org/10.2307/3984623.

"Wrestore | Watershed REstoration Using Spatio-Temporal Optimization of REsources." 2017. 2017. http://wrestore.iupui.edu/.

Young, Robert, Julie Zanders, Katherine Lieberknecht, and Elizabeth Fassman-Beck. 2014. "A Comprehensive Typology for Mainstreaming Urban Green Infrastructure." *Journal of Hydrology* 519 (November): 2571–83. https://doi.org/10.1016/j.jhydrol.2014.05.048.

---

[i] “Infra- means "below;" so the infrastructure is the "underlying structure" of a country and its economy, the fixed installations that it needs in order to function. These include roads, bridges, dams, the water and sewer systems, railways and subways, airports, and harbors. These are generally government-built and publicly owned. Some people also speak about such things as the intellectual infrastructure or the infrastructure of science research, but the meaning of such notions can be extremely vague.” (Merriam-Webster 2017)

[ii] While definitions of ‘scientific’ range from highly specific to vague, Hacking's (1999) wide definition serves the purposes of this paper best; he states that science is “…what passes as science, what models itself on the methods of established and successful science, what claims to discover objective truth about the world and its inhabitants, what claims to give explanations, to make falsifiable conjectures, to increase our power to predict, control, and improve” (p. 130).