The Green Experiment: Cities, Green Stormwater Infrastructure, and Sustainability

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Abstract: Green infrastructure is a unique combination of economic, social, and environmental goals and benefits that requires an adaptable framework for planning, implementing, and evaluating. In this study, we propose an experimental framework for policy, implementation, and subsequent evaluation of green stormwater infrastructure within the context of sociotechnical systems and urban experimentation. Sociotechnical systems describe the interaction of complex systems with quantitative and qualitative impacts. Urban experimentation—traditionally referencing climate change programs and their impacts—is a process of evaluating city programs as if in a laboratory setting with hypotheses and evaluated results. We combine these two concepts into a singular framework creating a policy feedback cycle (PFC) for green infrastructure to evaluate municipal green infrastructure plans as an experimental process within the context of a sociotechnical system. After proposing and discussing the PFC, we utilize the tool to research and evaluate the green infrastructure programs of 27 municipalities across the United States. Results indicate that green infrastructure plans should incorporate community involvement and communication, evaluation based on project motivation, and an iterative process for knowledge production. We suggest knowledge brokers as a key resource in connecting the evaluation stage of the feedback cycle to the policy phase. We identify three important needs for green infrastructure experimentation: (i) a fluid definition of green infrastructure in policy; (ii) maintenance and evaluation components of a green infrastructure plan; and (iii) communication of the plan to the community.

Keywords: green infrastructure; urban water policy; urban experiments; sociotechnical systems

1. Introduction

Cities are not static; they are constantly in a state of flux [1]. Within the past decade, global citizenship shifted from a predominantly rural population to a majority of the Earth's citizens living in urban environments [2]. Accompanying this shift in population is a growing struggle for cities to meet sustainability expectations as put forth by the United Nations in *Local Agenda 21* [3]. Cities sit at a confluence of technology, resource consumption, population, culture, and economics, placing them in a unique position to tackle sustainability concerns. Sustainability agendas in cities are part of sociotechnical transitions, and require long-term policy consideration [4]. Water in the urban environment has transitioned through several states throughout its history: (i) water supply city; (ii) sewered city; (iii) drained city; (iv) waterways city; (v) water cycle city; and, finally, (vi) a water sensitive city [5]. The final state of transition—the water sensitive city—is part of a larger sociotechnical

landscape shift towards sustainable urban development. The current shift to sustainable development is a major objective and driving force for urban planning and policy [6]. One of these sustainability agendas occurs due to large amounts of impervious areas associated with cities, creating persistent stormwater concerns. Practices in the 20th century created a sociotechnical regime of a gray stormwater system with gutters, pipes, and concrete spillways to collect and remove stormwater as quickly as possible from the city [7]. This practice is often not a sustainable solution, leading to combined sewer overflows, basement flooding, and polluted runoff. A transition from a gray stormwater system to an integrated green–gray hybrid system is required to move towards the goal of urban stormwater sustainability.

These types of sociotechnical transitions can be enabled through a multilevel perspective: from the niche, to the regime, to the landscape [8]. These three levels of a sociotechnical approach to transitions have been discussed in many forums [8–14]. Niches are the often small collectives where radical innovations sometimes form and attempt to become widespread [8]. A sociotechnical landscape is the broader societal fabric that provides the foundation for potential change [4]. In contrast, sociotechnical regimes are the locations in which research and policy intersect and react [4]. Sociotechnical transition theorists originally investigated niches as the most important unit of analysis due to their role in innovation [14–16]; however, research has begun focusing on the sociotechnical regime. Regimes are the existing sociotechnical pattern throughout society, and generally evolve at a slow or static rate [14]. Regimes are critical components, as they define the exchanges within a sociotechnical system [16]. In the case of the urban environment, the broader sociotechnical landscape is moving from traditional 20th century planning and engineering principles to a sustainable design framework. Green infrastructure is one artifact that arose out of the niches and is in the process of transitioning the stormwater management regime in line with the broader urban landscape of sustainability-focused design. Urban experimentation is a means to facilitate the transition from niche development and between regimes [15,17].

Bulkeley and Broto [18] define urban experiments as intentional interventions within the sociotechnical fabric of the city to respond to issues of sustainability. While this definition was originally given within the context of climate change mitigation, we generalize the definition for applicability to any sociotechnical intervention within a city, including green infrastructure. Urban experiments allow for the scaling of technological and engineering innovation from an individual project to the city-level [19,20], which is necessary to create a sustainable integrated green–gray stormwater infrastructure system. These experiments are a form of governance helping to steer change [18], inform wider policies to facilitate further sociotechnical transition [4], and make distant sustainability targets into realistic and achievable actions [21]. Urban experiments involve practice, policy, engineering, governance, and theory [22], and are sites of social learning [23].

In this study, we argue that a sociotechnical regime change is necessary in stormwater management, and an iterative, experimental approach is required for this regime change. The regime of gray infrastructure systems is rooted in the 20th century, and requires advancement through long-term policy towards a sustainable future. We propose urban experimentation as the means to promote the sociotechnical system of green infrastructure and a regime shift in stormwater management. Our study provides an engineering perspective on urban experimentation as a tool for the promotion of sustainable green infrastructure. We evaluate the green infrastructure plans of 27 cities across the United States to analyze their use of urban experimentation principles. Our study culminates in a discussion about the experimentality of green infrastructure (or the suitability of green infrastructure as an experiment), and its merits in promoting a sustainable approach to managing stormwater.

2. Background

2.1. Sustainability Policy

Cities are often the focus for sustainability, as urban initiatives and efforts determine the relative success of the quest for sustainability [24]. Sustainability in the urban environment is both a process and a goal [25]. Time horizons for sustainability transitions require both short and long term action [4]. The varying time horizons for sustainability require an adaptive policy framework that is a part of the system and directly influence the functioning of the system [26,27]. Voß et al. [4] proposed long-term policy as a framework to promote sustainability in cities. Long-term policy for sustainability is embedded in the sociopolitical and sociotechnical processes it seeks to influence [28], and requires an integrated learning between stakeholders and policymakers [29]. Sustainability goals have an important role in the governance of cities as they strive to address sustainability challenges [30]. Additionally, the governance of sustainability unites cities in a common set of challenges [4], allowing for comparative sustainability studies. Along with long-term policies, these challenges create opportunities for short term experiments to complement sustainability initiatives and facilitate transitions toward a sustainable future [4].

2.2. Green Infrastructure

One aspect of urban sustainability comes in the form of managing stormwater runoff—an increasingly challenging issue with the rising amount of impervious area in dense urban environments. Increased political, social, and environmental pressures force planners and engineers to help mitigate the number and severity of basement floodings or combined sewer overflows and improve receiving water quality. Handling both sewage and stormwater flows, combined sewer systems (CSS) are prevalent throughout many older municipalities in the United States [31]. These systems carry large risks for overflow, and high costs to municipal governments for full remediation. Essentially, large rainfall events can cause CSSs to overflow, discharging untreated sewage and stormwater into receiving waterbodies. The U.S. Environmental Protection Agency (EPA) regulates combined sewer overflows (CSOs) under the authority of the Clean Water Act (CWA). In 2004, the EPA issued a report to Congress on the widespread nature of CSOs, citing 746 communities in the United States that use CSSs [31]. The literal greening of the urban environment with vegetation (in the form of green infrastructure) provides opportunities for both reducing urban runoff volume and improving its quality.

Green infrastructure has multiple definitions within a common understanding of the system. Benedict and McMahon [32] define green infrastructure as "an interconnected network of green space that conserves natural ecosystem values and functions". Our paper narrows this definition to focus on a stormwater perspective of green infrastructure. A 2007 Memorandum by the EPA provides a definition of green stormwater infrastructure as approaches that infiltrate, evapotranspire, or reuse water as opposed to traditional hardscape conveyance (gray) infrastructure [33]. Expanding on these definitions, green infrastructure is stormwater infrastructure that utilizes natural processes such as infiltration to reduce, slow down, and clean runoff (e.g., green roofs, bioswales, rain gardens, and permeable pavement) [34]. Gray infrastructure—as opposed to its green counterpart—is the traditional means of engineering that utilizes concrete pipes and centralized treatment to remove stormwater as quickly as possible. Studies across the country have shown that expanding sewer services via green infrastructure is economically preferred and provides environmental benefits [35,36].

In addition to water quality and quantity improvements, green infrastructure provides multiple benefits outside of these physical benefits. Through increased amounts of green spaces, green infrastructure provides social benefits to promote a sense of community, public health, and mental health [37–41]. The economic benefits of green infrastructure include increased property values and lower costs compared to comparable gray infrastructure expansion [42–44]. Environmental and ecological benefits include improved air quality and reduced urban heat island effects [45–47].

Additionally, there is a link between various forms of green infrastructure and energy savings [48,49]. It is important to consider both the qualitative and quantitative aspects of these spaces in any green infrastructure assessment [37,50,51].

The combination of the environmental, social, and economic benefits of green infrastructure requires an integrative approach to planning, implementation, and evaluation within the context of a sociotechnical system. Additionally, due to green infrastructure's ecological benefits, the system may also be considered a socio-ecological system providing ecological resilience benefits (e.g., [52,53]). However, we choose to focus on the sociotechnical nature of green infrastructure. Green infrastructure strategies are not a one-size-fits-all approach [54,55], and ad hoc interventions are no longer sufficient to promote a coordinated city-wide strategy for sustainability transitions [56]. There is a vast range of choices for sustainable green initiatives that requires an extensive array of case studies rooted in an experimental framework for comparison and evaluation [1]. Additionally, these green infrastructure strategies require long-term and short-term evaluation strategies to utilize the infrastructure as a means to support sustainable development [57]. Therefore, we propose an evaluation and implementation framework for green infrastructure using sociotechnical systems theory, requiring an urban experimental framework for the advancement of stormwater sustainability.

2.3. Sociotechnical Systems and Transitions

Before a discussion about sociotechnical transitions and their implications in sustainability, it is necessary to define terms. Sociotechnical systems have a long-standing history dating back to work in coal mines after World War II [58]. The phrase "sociotechnical system" was coined by Emery [59] to describe systems that have complex interactions between both human and non-human components (mainly machines). Badham et al. [60] define five key characteristics for sociotechnical systems: (i) have interdependent parts; (ii) experience stress from the external environment and have goals within that environment; (iii) have separate but interconnected social and technical subsystems; (iv) require decision-making to achieve goals; and (v) have performance based on optimizing social and technical subsystems. These five characteristics—while originally applied to industrial engineering and industrial psychology practices—have intentionally vague characteristics, allowing the applicability of the framework for many different systems, including green infrastructure.

Lawhon and Murphy [16] describe science, technology, economics, ecology, and political science as the foundation of sociotechnical transition theory based on multiple works [14,61–68]. The literature of sociotechnical transitions often focuses on the replacement of artifacts to achieve sustainability [69–72]. With increasing pressure on cities and their infrastructure due to flood risk, temperature rise, and other social and economic factors, cities have turned to various artifacts as a means to change course and promote sustainable practices. In this sense, artifacts are features embedded in society such as green infrastructure, new underground pipe infrastructure, etc. These artifacts or features provide the basis for the evaluation of a sociotechnical system; however, focusing only on artifacts limits the scope and the range of actors in play within a sociotechnical system. The full sociotechnical system must be considered.

Cities provide premier opportunities for sociotechnical transitions such as those regarding piped water systems in Europe or the electrical grid in New York City, described by Geels [8]. Additionally, sociotechnical transition case studies have evaluated the green building economy or ecovillages, providing insights into the changing trends of the green economy around the United States and England [73,74]. Cities can play three roles in sociotechnological transitions: primary actors, locations, or seedbeds for early phases of transitions, or limited roles [8]. These transitions can come in the form of four different types of regime changes (described in Hodson and Marvin [75]), with purposive transitions being the suggested norm for city-level sustainability progress. These studies of transitions are particularly important to geographers when addressing concerns of sustainability and why certain unsustainable developmental practices are constraining a region, city, or community [16].

2.4. Urban Experiments

The urban environment is a relatively new area for the application and assessment of sociotechnical transitions [75,76]. However, cities are increasingly using experimentation as a form of governance to generate a sustainable urban environment [77]. Urban experiments attempt to change material arrangements, cultures, norms, and conventions, and in the process, create a new political space [18,78]. Experimentation attempts to rework social and technical networks through multiple stakeholders and iterations over time [22,79]. When discussing sustainability transitions at the urban level, there are often existing regimes in place, including infrastructure, social practices, and economic investment that pose challenges to progressive change. Experimentation in an urban laboratory provides a means to overcome these existing regime challenges and advance a city's infrastructure and social interactions with sustainability goals [15,80].

Current urban experimentation studies have a broad range of focus, which includes climate change mitigation strategies like those in the United Kingdom, Germany, and India [81–83], low carbon experimentation [84,85], and smart urbanism [86,87]. The politics of creating these urban experiments to promote change facilitates questions of wider transformation [22]. The sociotechnical nature of urban experiments enables them as an adaptable framework. We present green infrastructure as a sociotechnical system that satisfies criteria of an urban experiment through its explicit break from the norm of gray infrastructure and through its requirement of new forms of governance, maintenance, and citizen participation.

3. Developing an Experimental Framework

Voß et al. [4] stated that future efforts in sociotechnical transition management should include a design of procedures for experimentation. While we do not attempt to provide a green infrastructure construction plan for all cities, we instead define a policy procedural framework for green infrastructure that is unified under similar governance challenges [88]. Green infrastructure construction, type, and size, on the other hand, depend on a large number of factors that vary by region and policy goals [55]. Literature reveals six requirements for the development of an experimentation framework for sociotechnical transitions:

1. Problem-oriented framework [89]
2. Flexible and adaptive [4]
3. Definitive system boundaries with controlled data collection [81]
4. Social learning/Capture interest of non-scientists [4,90]
5. Recursive/Implement experimental results [4,90]
6. Link between knowledge production and practices [91]

A meaningful assessment of sustainable development—including green infrastructure approaches—requires placement in a problem-oriented framework [89]. Framing green infrastructure as an experiment in sustainability provides this necessary framework. The associated policy for green infrastructure experimentation is an open-ended process, promoting sociotechnical transitions that require flexible and adaptive strategies to cope with the ever-changing sustainability landscape [4]. In the creation of an urban experimental framework, it is important to completely define system boundaries for controlled experimentation, data collection, and evaluation [81]. Stakeholders and their engagement in the learning process are essential to the propagation of the sociotechnical transition [4,90]. The experimental framework requires an iterative and recursive function that utilizes the results of implemented solutions and links policy, production, and practices [4,90,91].

Urban experiments are sites of knowledge production that—when combined with a continuous feedback loop—create a recursive process of learning and data collection [21]. Pennell et al. [92] and Hildén [93] describe this process as a policy feedback cycle (PFC). This cyclical and recursive process aligns with the continuous feedback loop of experimentation in an urban environment [94,95]. Therefore, a PFC provides a suitable foundational framework for green infrastructure experimentation; see Figure 1.
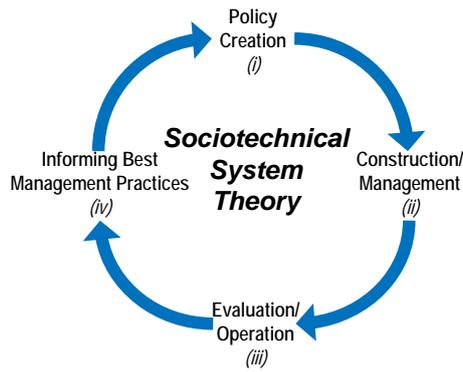
Figure 1. A generalized policy feedback cycle lies within a sociotechnical perspective, and is inherently an experimental framework (modified from Pennell et al. [92]).

The PFC as an experimental framework (Figure 1) consists of four stages: (i) policy creation; (ii) construction/management; (iii) evaluation/operation; and (iv) informing best management practices. Using the six requirements for urban experiments described above, we expand on the framework for the PFC and further describe each of the four stages. Additionally, we describe key stakeholders within the sociotechnical system, including a knowledge broker to facilitate information transfer between experimental results and policy production [91,92]. Additionally, city governments—while in a prominent role—are not the only actors in the sociotechnical experimental framework. Other actors, such as private entities, non-profit organizations, and members of society play key roles in the development and success of a green infrastructure experimental framework [78]. Therefore, we expand the basic PFC in Figure 2.
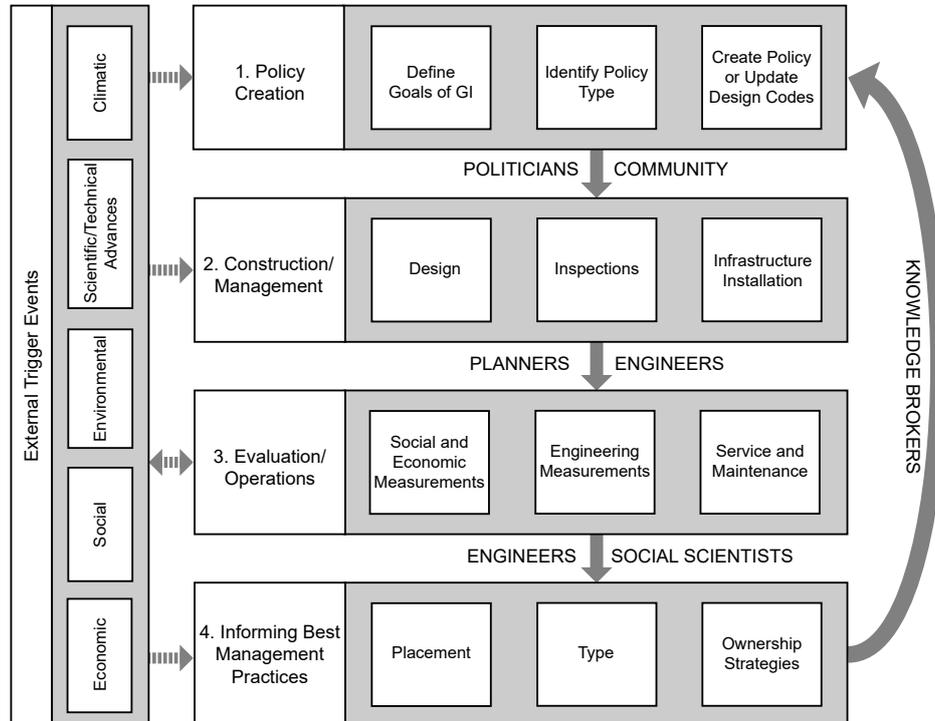
Figure 2. The sociotechnical system of the green infrastructure (GI) policy feedback cycle creates an experimental framework for decision-making. Each of the four main stages of the cycle includes important decisions or subtasks. Subtasks further describe the stage, but also provide the means to analyze the effectiveness of each stage through experimentation. Along the left side of the diagram are external trigger events that might interact with each of the four stages of the cycle.

3.1. Stages of the Policy Feedback Cycle

Urban experiments seek to produce and test knowledge and provide evidence to inform future interventions [96]. The policy feedback cycle (PFC) provides an opportunity to enunciate the distinct processes involved in the urban experimentation of green infrastructure. For ease of display and discussion, each stage of the PFC is presented independently of one another in a logical sequence. However, it is important to note that some overlap of the distinct stages is likely within different municipalities, based on the organizational structure and infrastructure management system. For example, there might be slight overlap between the two stages *construction/management* and *evaluation/operations*; yet, it is still important that the sociotechnical system analyze the stages separately for clarity.

The first stage of the PFC is *policy creation*, driven either through external trigger factors or as a refinement of previous policy based on a transfer of information via a knowledge broker or multiple knowledge brokers (Section 3.2). The first of three components is defining the goals of the policy, where the system benchmarks for the experiment are declared with respect to green infrastructure implementation. Goals can be any combination of hydrologic measurements, environmental concerns, or social factors based on the motivation or external trigger of the green infrastructure policy. Second, the policymaker should determine the type of policy as either public ownership, regulation, mandates, or incentives [97]. Finally, the subsequent construction and management stage receives the updated policy or design code.

The second stage—*construction and management*—is the implementation or execution of the preceding policy through execution of design codes, incentives, or municipality-driven upgrades. This stage includes the design, inspection, and the physical building of infrastructure. The construction and management stage—not the evaluation stage—includes inspections, often mandated explicitly by policy or design codes. Conversely, the operations and evaluation stage is often in response to inspections of existing built infrastructure. Additionally, different management agencies within an organizational structure perform inspections and operations [98].

The third stage—*evaluation and operations*—evaluates system effectiveness, including routine operations and maintenance that are essential for the continued use and performance of the green infrastructure system. Maintenance is a learning process central to the work of urban experimentation [56]. The gathering and evaluation of engineering, social, and economic measurements are equally important. Experiments require a restructuring of flows, resources, power, and materials for the maintenance of infrastructure systems [56]. A variety of measurements and information gathering ensures the consideration of all three pillars of sustainability (environment, economy, society) for decision making in the final stage of the PFC.

Fourth, the *informing best management practices* stage of the cycle includes data synthesis and decision-making based on the previously collected and evaluated data. Decisions include making informed conclusions on the placement, type, and ownership strategies of green infrastructure. Ownership strategies pertain to both lessons learned from the operational side of the green infrastructure and the effectiveness of public versus privately implemented green infrastructure systems. Knowledge brokers communicate these decisions to the policy creation stage of the cycle, where the iterative process will ideally begin again [92].

3.2. Key Stakeholders

Sociotechnical systems are shaped by a broad audience of stakeholders, including engineers, policymakers, business interests, non-governmental organizations, and consumers [14]. Pope et al. [99] discuss stakeholders as an integral part of evaluation for sustainability. The policymakers are involved in the first step of the cycle— making the policy decisions and listening to the information following the evaluation of infrastructure. Engineers are involved in both the construction/management and the evaluation/operations steps of the process. Social scientists and urban planners participate in the evaluation and construction stages, respectively. Community involvement is a part of the

policy creation stage, with opportunities for greater involvement throughout other stages of the PFC. To complete the cycle and create a recursive experiment, there is a need to link knowledge creation in the fourth stage of the cycle to the first stage—policy creation [91]. Pennell et al. [92] proposed the term "knowledge broker" as the intermediary between the experts evaluating the infrastructure and the policymakers making decisions. Knowledge brokers are involved on the back end of the evaluation process and entirely on the informing step of the cycle, with a working knowledge at all process stages. Implementing all steps of this feedback cycle with the participation of each stakeholder is essential in the creation and implementation of green infrastructure policy and systems in terms of sociotechnical systems. The role of knowledge brokers in municipalities' green infrastructure programs offers opportunities for universities, research organizations, non-profits, and others to play a major role in shaping and evaluating green infrastructure systems.

3.3. External Trigger Events

Often, external events—either in the form of disasters (natural or anthropogenic), rare climatic occurrences, new technologies, slow drivers (such as climate change), or a greater understanding of the environment—prompt policy decisions. Walsh et al. [100] describe these occurrences as "wildcard events" (specifically referring to disaster events), and discuss their importance in terms of prompting change from the norm and advancing systems for improvement. The transition literature describes these external events as landscape factors from a multi-level perspective [10]. These external trigger events, landscape factors, or wildcard events can be signs of the shortcomings of the existing gray infrastructure regime. For instance, two major driving forces cited for prompting green infrastructure measures in Chicago, IL, to mitigate stormwater runoff are combined sewer overflows and basement flooding [101]. Environmental trigger events include handling increased water volume demands and other water quality issues (e.g., CSOs). Social trigger events can come from communities or the public seeking and prompting change. Climatic trigger events are floods or long-term climate change. A dashed arrow in Figure 2 indicates the relation of external trigger events to the PFC. A double-headed arrow is included for the evaluation and operations phase of the feedback cycle to indicate potential evaluations leading to new technologies or scientific advances, which can in turn become external trigger events.

4. Methodology

The proposed PFC for green infrastructure provides opportunities to evaluate the green infrastructure experiment in cities across the United States. While the design of green infrastructure is also an experiment, we focus on the experimental nature of green infrastructure as a concept and means to further a regime change in stormwater management. The framework reduces to eight key questions that we apply to 27 cities across the United States; see Figure 3. We selected these cities based on their size and geographical spread across the United States. The answers to these questions provide the basis for comparing and evaluating green infrastructure in cities.

- Does the city have a green infrastructure plan?
- What motivates the city to adopt such a plan?
- Is the plan physically implemented by the city (i.e., public vs. private construction)?
- What green infrastructure installations are included in the plan?
- Is there a maintenance plan/budget?
- Are there plans for evaluation of the built infrastructure performance? Does the plan have a success point?
- Are there opportunities to revise the plan following evaluation?
- Who are the key players in the plans (e.g., departments, knowledge brokers, etc.)?

We answered these questions for each of the 27 cities in the study through analysis of published documents on city websites. The 27 cities have a total population of 31.5 million people, nearly 10% of the 2015 U.S. population. The median city population is 662,000, with a maximum city population of

8.5 million and a minimum population of 180,000. The cities range spatially across the United States and encompass multiple climate zones. More cities are included in the eastern half of the country due to the population distribution in the United States.
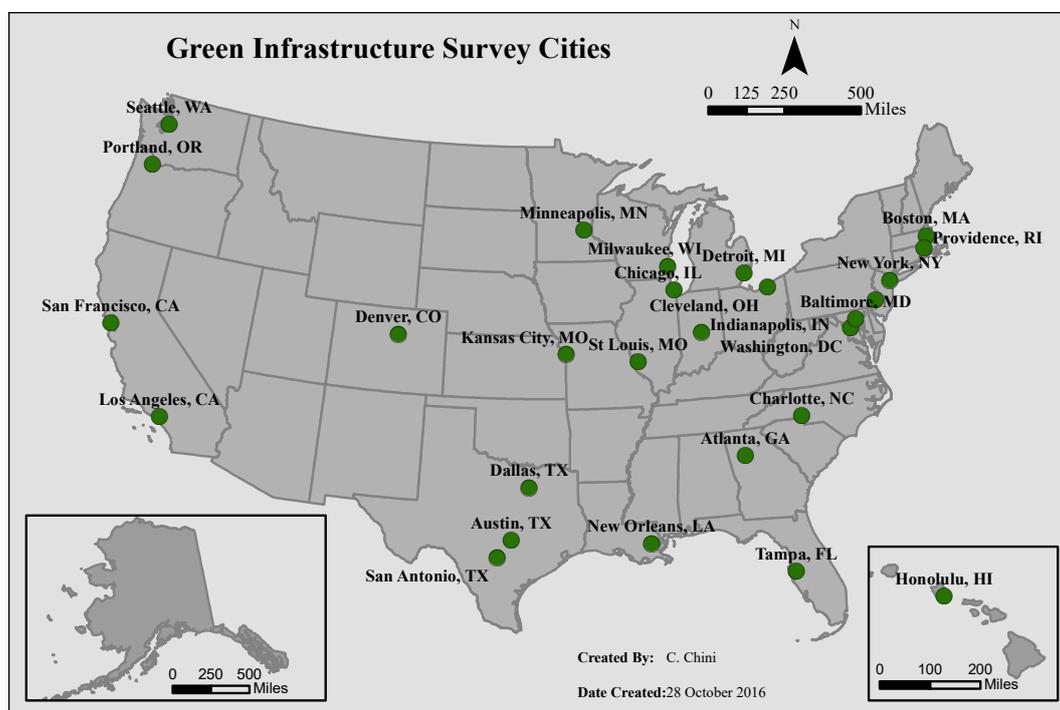
Figure 3. We evaluated 27 cities across the United States with relation to the policy feedback cycle and experimental framework.

We utilize this method of data collection from websites in lieu of submitting formal questionnaires to evaluate the public accessibility of green infrastructure information. While this approach relies on publicly available and published resources, it creates a standard platform for comparing results. We recognize the limitations of this methodology and the benefits of formal questionnaires or surveys; however, the sociotechnical nature of green infrastructure requires stakeholder involvement and communication of the plan to the public. Therefore, if any green infrastructure plans are not readily available to the public, we conclude that no plan is currently implemented in that city. The answers to the above questions provided several important insights to the current status of green infrastructure as an urban experiment.

5. Comparative Urban Analyses

Of the 27-city study, 21 cities have a specific green infrastructure plan, three have a less formalized plan, and three do not have a plan. It is equally important to identify both the stakeholders of the experiment [18,20] and what the motivations of the experiment are (why they are experimenting) [96]. During our investigation of municipal green infrastructure plans, we collected information on motivations beyond water management. Many cities cited climate change as a purpose for their green infrastructure plan; others cited, for example, increased tree canopy (i.e., reduced heat island effect, improved air quality, etc.). There was a wide variety of motivations for the implementation of green infrastructure, even if a city did not have a formal plan. Table 1 displays the breakdown of each city's green infrastructure motivations, categorized into four broad areas: water quality, economic, environmental, and social. These sections help to highlight both the range of benefits that green infrastructure provides and the holistic approach policies are able to take to endorse its implementation. Cities that understand the sociotechnical advantages of green infrastructure list

diverse motivations behind their plans, and subsequently record a higher number of check marks in the table. The cities of Portland, OR, Washington, DC, and San Francisco, CA demonstrated the largest number of motivations. Conversely, cities that lacked a formalized publicly-available green infrastructure plan (San Antonio, TX, Providence, RI, and Tampa, FL) each operate a municipal separate storm sewer system (MS4) and were among the cities that contained the fewest amount of motivations for disconnected green infrastructure projects within the city. Despite the absence of a formalized plan, however, these cities understood some of the benefits that green infrastructure offers.

Table 1. Motivations for implementing green infrastructure vary in cities across the country. The more boxes checked in a city reflect greater understanding of widespread green infrastructure as part of a sociotechnical system. The table was constructed based on the evaluation of each of the 27 cities' green infrastructure plans [35,101–159]. CSO: combined sewer overflow; EPA: US Environmental Protection Agency.

Cities	Green Infrastructure Motivations															
	Water Quality				Economic					Environmental				Social		
	EPA Consent Decree	Reduce CSOs No Consent Decree	Clean up Local Waterways	Improve Drinking Water Quality	Increase Property Values	Promote Green Jobs	Decrease Floods and Basement Backups	Reduced Wastewater Treatment Costs	Conserve Energy	Mitigate Urban Heat Island Effect	Improve Ambient Air Quality	Adapt to Climate Change	Provide Habitat for Local Wildlife	Reduce Violent Crime	Improve Public Mental and Physical Health and Safety	Create Aesthetically Pleasing Green Spaces
Atlanta, GA				✓	✓								✓		✓	✓
Austin, TX			✓				✓									✓
Baltimore, MD			✓				✓			✓	✓		✓			✓
Boston, MA							✓			✓		✓			✓	✓
Charlotte, NC			✓		✓								✓		✓	
Chicago, IL	✓		✓				✓					✓				
Cleveland, OH	✓		✓										✓			
Dallas, TX			✓													
Denver, CO			✓				✓		✓	✓	✓	✓				✓
Detroit, MI	✓		✓		✓			✓						✓	✓	✓
Honolulu, HI								✓	✓							
Indianapolis, IN	✓		✓													
Kansas City, MO	✓		✓	✓			✓								✓	
Los Angeles, CA			✓	✓												
Milwaukee, WI		✓	✓				✓									
Minneapolis, MN		✓	✓				✓									
New Orleans, LA	✓									✓						
New York, NY	✓		✓								✓					✓
Philadelphia, PA	✓		✓													✓
Portland, OR		✓	✓		✓		✓	✓	✓	✓	✓	✓	✓		✓	✓
Providence, RI				✓			✓									
San Antonio, TX			✓					✓								
San Francisco, CA					✓			✓	✓	✓	✓		✓		✓	✓
Seattle, WA		✓	✓		✓							✓				
St. Louis, MO		✓	✓		✓											
Tampa, FL			✓													
Washington, DC	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓					✓

Cleaning local waterways, consent decrees, decreasing flooding, and creating aesthetically pleasing green spaces are the most-cited drivers for green infrastructure adoption across the 27-city study (Table 1). Nine cities are motivated through consent decrees (legal mandates stating that the city is lawfully bound to decrease CSO volumes) and, consequently, incorporate green infrastructure as a part of their solution. All nine cities cited at least one additional motivation, thus showing recognition of green infrastructure benefits beyond the obligation of the decrees. Additionally, it is interesting to note that many cities cited cleaning local waterways as a motivation for green infrastructure; however, only a small subset of these cities cited improving drinking water quality as a motivation

(Table 1). Many of these cities are upstream on rivers, and their local waterways affect other cities' drinking water quality, including many smaller municipalities on the same waterways that are not included in this study. The observation that many cities strive to clean up local waterways but not necessarily improve drinking water quality suggests an isolationist approach to water management and a limited—from a motivation perspective—understanding of the water cycle. Overall, such a variety of motivations shows diverse interpretation of the green infrastructure definition and its many benefits. Theoretically, all cities should recognize that most—if not all—of these motivations viably support green infrastructure implementation and ought to consequently craft initiatives that allow green infrastructure to reach its fullest potential across economic, environmental, and social lines.

Cities that have a green infrastructure plan usually incorporate both public and private measures to achieve their implementation goals. Five cities focus almost exclusively on public measures, while 16 of the cities utilize both private and public means to implement green infrastructure. Cities such as Seattle, WA, Austin, TX, Charlotte, NC, Chicago, IL, New Orleans, LA, Washington, DC, and Philadelphia, PA strongly encourage the installation of green infrastructure in new developments through legislation and post-construction runoff controls. For instance, Seattle, WA has requirements for on-site stormwater management, flow control, and treatment, and urges developers to utilize green infrastructure as a tool to fulfill all three requirements [157]. Additionally, local building codes such as those in New Orleans, LA needed updating to permit green roofs, rain gardens, and pervious pavement [158]. Several cities led the way in retrofitting existing public buildings with green infrastructure; Chicago, IL and Minneapolis, MN built green roofs on numerous municipal buildings [133,142]. Based on our study, cities with a public green infrastructure plan tend to have more ubiquitous implementation than plans with a private owner focus. Cities can utilize public spaces like parks, rights-of-way, streets, and alleyways. However, there is room for collaboration with homeowners and business owners who have space for green infrastructure elements.

There are multiple stakeholders in green infrastructure plans within the municipality itself. Municipal water authorities or water utilities lead green infrastructure projects in 17 of the evaluated cities. Of these cities, water authorities in five cities also work in collaboration with public works/transportation departments. Six cities feature an exclusive department or task force dedicated to green infrastructure proliferation. We assert that such collaboration between city departments and water utilities is vital for the implementation of green infrastructure because green infrastructure affects a variety of entities. For instance, increasing tree canopy along a right-of-way also affects automobile drivers' line-of-sight, and incorporating a rain garden near an airfield might bring unwanted birds into the area. Engineers, landscape designers, environmental scientists, social scientists, and policymakers all offer unique expertise and perspective. Through collaboration, each can add value to green infrastructure projects to increase the effectiveness of green infrastructure.

Our study of green infrastructure plans yielded a large number of best management practices that cities label as green infrastructure. We present these different types of green infrastructure in categories pertaining to some of the motivations associated with green infrastructure plans; see Table 2. A majority of these measures targeted stormwater management through infiltration (e.g., permeable pavements, planter boxes) and plant uptake of water (rain gardens, increased tree canopy). One of the most popular measures was permeable pavement; 22 cities use permeable pavement as part of their green infrastructure implementation plan. Structural green infrastructure components included green roofs, cisterns (large scale rainwater harvesting), and blue roofs (non-vegetated source controls that detain and gradually release stormwater [118]). Furthermore, razing abandoned buildings and replacing the site with turf is a large part of St. Louis, MO's green infrastructure plan [154,159]. Additionally, Honolulu, HI named solar panels as green infrastructure measures [114], indicating the ambiguity of the phrase "green infrastructure" and that it does not just reflect stormwater management. Green infrastructure types are not exclusively tied to the goals listed, and feature secondary benefits; for example, increased tree canopy—besides providing water benefits in the form of stormwater uptake—also provides shade, reduces heat island effect, and creates habitat for wildlife. The variety

in this list illustrates how cities use numerous means to define green infrastructure, emphasizing the need for flexible, iterative, location-specific decision-making. From a policy standpoint, this variation complicates defining green infrastructure universally. We therefore recommend that the definition of green infrastructure remain flexible and adaptable, allowing interpretation by cities based on local needs.

Table 2. Green infrastructure types vary widely based on system goals and motivation.

Green Infrastructure Types and Goals					
Infiltration	**Transportation**	**Natural Systems**	**Stormwater Reuse**	**Buildings**	**Other**
• Permeable pavements • Infiltration planters/ Planter boxes • Bioretention areas • Bioswales/ Biostrips • Vegetated detention strips	• Street bumpouts • Permeable pavements • Traffic calming bioretention	• Increased tree canopy • Constructed wetlands • Restoration of wetlands • Creek daylighting • Abandoned lot greening	• Cisterns • Rainwater harvesting	• Green roofs • Blue roofs • Cisterns	• Non-structural measures (policy) • Solar panels

A majority of the cities recognize that operations and maintenance are important steps in accomplishing their green infrastructure goals. Of the 24 cities that have a structured green infrastructure plan, 19 include specific measures for maintenance. These measures include: providing resources for private landowners to maintain their green infrastructure, creating maintenance teams, and forging agreements with local businesses and homeowners to maintain green infrastructure. Additionally, several cities require municipal agencies to inspect these green infrastructure projects on private land. For instance, the Metropolitan St. Louis Sewer District requires that green infrastructure on private property be maintained by the owner and inspected by the agency [95]. Five of the twenty-four cities with green infrastructure plans do not include maintenance measures in their plans, which might prove troublesome in the long-term sustainability of the implemented green infrastructure measures. Maintenance is a critical process for the long-term success of green infrastructure experimentation and the learning process associated with it [56]. To implement a successful green infrastructure experiment, it is essential to include details on maintenance and operation.

It is important for cities to evaluate initial projects and to determine how to improve moving forward. Since green infrastructure plans are relatively new (i.e., within the last ten years) initiatives in many of the study cities, reiterating plans within the context of an urban experiment encourages learning and improved implementation of the green infrastructure system. Of the 24 cities with a green infrastructure plan, 15 outline how they will monitor existing or initial projects and craft adjusted policies or performance criteria to complete the PFC. Performance criteria are utilized in cities such as Atlanta, GA, where new and redeveloped sites must capture and treat the first 2.5 cm (1 inch) of rainfall on-site [104]. Furthermore, Baltimore, MD is striving to reach 40 percent tree canopy by 2037, and Honolulu, HI has programs in place that aim to install over 44 megawatts of power capacity through photovoltaic solar panels [108,114]. Five cities plan to monitor projects, but do not necessarily have a method to reiterate, and three cities do not have evaluation plans. Four cities (Chicago, IL, Boston, MA, Philadelphia, PA, and St. Louis, MO) have intentionally already used or plan to use the evaluation of green infrastructure to create new plans. Many cities cite water quality as a motivation for monitoring and evaluating the effectiveness of green infrastructure. While many of the studied cities take initiative to provide monitoring and evaluation frameworks, these documents are not always

up to date, leaving the status of their green infrastructure plans in question. For example, the last Minneapolis Local Surface Water Management Plan update was in 2006 [143]. Policies can help ensure that the urban experiments are completing the proposed PFC to better address the effectiveness of green infrastructure.

It is common for green infrastructure to be a collaborative effort between municipal entities, water utilities, environmental groups, and local research universities and organizations. Municipal departments and regional water utilities often play lead roles. Other departments and environmental groups engage the lead players to ensure that green infrastructure is a readily-accepted solution for community involvement, speaking to their potential as knowledge brokers within the urban experimental framework. With a broad definition of green infrastructure, urban sustainability requires city leaders to collaborate with stakeholders equally as diverse as the green infrastructure techniques they implement.

6. Discussion

The process of developing the new green infrastructure technology within the urban environment requires an experimental and iterative mindset from policy. This experimental framework relies upon an iterative policy feedback cycle to implement green infrastructure in cities. We propose this framework not as a guide to specific green infrastructure, but as a means of developing the policy of green infrastructure across all cities. Revisiting the six requirements stated in the development of the experimental framework yields three interesting observations. (i) Defining system boundaries informs motivation and data collection; (ii) Capturing the interest of non-scientists and stakeholder involvement is paramount in the experimentation of green infrastructure; (iii) The recursiveness of the green infrastructure experiment is not fully visible in the current regime of stormwater management.

Green infrastructure is a sociotechnical system within the urban environment, requiring the integration of technical, engineering, policy, and social factors to develop and maintain a sustainable system. The variety of green infrastructure found during our study ranged from permeable pavements to wetland rehabilitation to photovoltaic solar panels; see Table 2. This wide range of best management practices requires a flexible and fluid definition of green infrastructure from a policy perspective across cities. This definition reflects the defined system boundaries of an urban laboratory and is an important first step for cities [81]. Green infrastructure incentives at the national or state level would need to account for the fluid interpretation of these measures. Additionally, system boundaries are evident in the motivations of green infrastructure and vary between cities (Table 1). These motivations must inform the data collection process within the urban experiment system boundaries.

The first requirement of the societal laboratory identified by Latour [90] is that it must capture the interests of non-scientists—namely, the community. Green infrastructure as a sociotechnical system is predicated upon such community feedback and participation. One means of promoting feedback in the experimental framework is to provide important information to the public via municipality websites. This information could help to promote an understanding of the motivation for green infrastructure and create a more invested community in the plan. For example, Philadelphia publishes an interactive map with detailed information concerning green infrastructure throughout the city [160]. Philadelphia also features several nonprofits and other organizations that aspire to spread green infrastructure throughout that city, such as PlanPhilly, the Pennsylvania Horticulture Society, and PennEnvironment. Multiple cities in our study had web pages that had not been recently updated, with minimal readily accessible information. Governing policies date back a decade in some cities. A continuous social learning effort might help to promote the widespread implementation of effective green infrastructure. We highlight efficient communication as an important and vital tool for the implementation of green infrastructure as an urban experiment.

Finally, we propose the implementation of a recursive experimental framework to coincide with a policy feedback cycle that links knowledge production through a knowledge broker. Only 15 of the 24 cities with green infrastructure plans had plans to create an iterative process. This gap

leaves opportunities for policies to focus on an urban experimentation framework for sustainable transitions in stormwater. There are opportunities for non-governmental organizations or research organizations to become knowledge brokers within the urban experimental framework. Utilizing an iterative experimental process for green stormwater infrastructure helps to further cities toward water resiliency. Our results indicate that cities recognize the need to progress into a twenty-first century stormwater management regime, and cite numerous motivations for the path forward. Simply implementing green infrastructure without monitoring or evaluation efforts does not aid in the transition towards sustainable stormwater infrastructure. Implementation of an iterative and circular process for experimentation is a priority for the propagation of sustainable design and sociotechnical transitions.

7. Conclusions

In this study, we synthesize urban experimentation and sociotechnical transition literature and apply it to green infrastructure. We present six requirements of an urban experimental framework and discuss them in relation to green infrastructure plans proposed by cities. We argue that a sociotechnical regime change is necessary in stormwater management, and an iterative experimental approach is required for this urban stormwater regime change. Our study provides an engineering perspective on the green infrastructure plans of 27 cities across the United States and the applicability of an urban experimental framework for the advancement of urban stormwater sustainability.

The required regime shift in urban stormwater can be facilitated through an experimental process. Successful experimentation is imperative in transforming the existing regime structure towards sustainability [17]. However, in describing the experimental framework, it is important to propound the metric of success [22]. Success metrics for green infrastructure experiments must be rooted in the motivation for the project. The experimental motivations inform the evaluation and operation stage and determine best management practices within the PFC. Sustainability by itself is not a valid motivation for urban experimentation; sustainability is so commonly utilized that it is no longer an authentic character [96]. Therefore, our results suggest future green infrastructure experiments embed themselves within the sociotechnical system and define their stakeholders and motivations to develop a manageable transition framework for urban stormwater sustainability.

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Abbreviations

The following abbreviations are used in this manuscript:

CSO	Combined Sewer Overflow
CSS	Combined Sewer Systems
CWA	Clean Water Act
EPA	United States Environmental Protection Agency
GI	Green Infrastructure
MS4	Municipal Separate Sewer Storm System
PFC	Policy Feedback Cycle

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