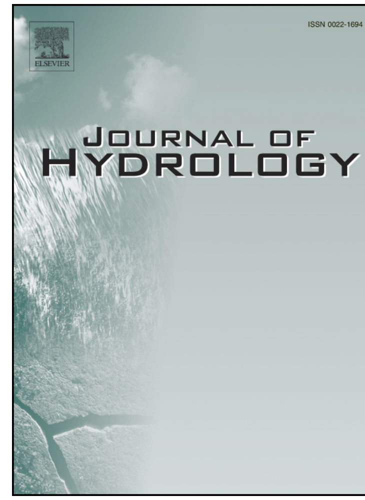

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A comprehensive typology for mainstreaming urban green infrastructure

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Abstract

During a National Science Foundation (US) funded "International Greening of Cities Workshop" in Auckland, New Zealand, participants agreed an effective urban green infrastructure (GI) typology should identify cities' present stage of GI development and map next steps to mainstream GI as a component of urban infrastructure. Our review reveals current GI typologies do not systematically identify such opportunities. We address this knowledge gap by developing a new typology incorporating political, economic, and ecological forces shaping GI implementation. Applying this information allows symmetrical, place-based exploration of the social and ecological elements driving a city's GI systems. We use this information to distinguish current levels of GI development and clarify intervention opportunities to advance GI into the mainstream of

metropolitan infrastructure. We employ three case studies (San Antonio, Texas; Auckland, New Zealand; and New York, New York) to test and refine our typology.

KEYWORDS: green infrastructure, urban planning, typology, stormwater management

1. Introduction and Background

In December 2012, the National Science Foundation (NSF) funded the "Greening of Cities International Workshop on Green Urban Infrastructure" in Auckland, New Zealand. Workshop organizers invited practitioners and researchers from North America, Asia, and Oceania to initiate a discussion around "the potential for incorporating Green Infrastructure [GI] into cities." Participants were charged with identifying research needs and strategies to "provide the knowledge needed to better understand how green infrastructure can benefit… its communities." Specifically, participants were to locate "knowledge gaps" slowing mainstreaming of urban GI (NSF, 2012).

During the meeting, consensus emerged that absence of an effective urban GI development typology was a primary gap. Participants agreed existing typologies were of limited value in two respects. First, they provided little assistance in comparing relative levels of GI development between cities and second, they were inadequate as strategic tools for advancing GI. A more robust typology would enable cities to identify their present stage of GI development and more effectively map out next steps and interventions for mainstreaming GI. In this paper we critically review existing GI typologies and attempt to develop a more robust format addressing participant concerns.

We chose three cities (New York, Auckland, and San Antonio) as case studies to explore both the value of the typology and data compiled in urban GI plans. City selection was not intended to be comprehensive but rather an exploratory sample from different social and ecological settings. New York City and Auckland are both dominant global cities in their respective countries while San Antonio represents a rapidly growing regional metropolitan center. The former cities are situated in deciduous, temperate forest biomes (one in the northern and the other in the southern hemisphere) while the latter is located in a drier, forest/grassland setting. New York and San Antonio have recently been subject to pronounced ecological disturbances while Auckland currently faces more diffuse ecological pressures.

1.1 Defining GI

While the fundamental concept and practice of urban GI dates back to the earliest emergence of cities, it gained particular momentum responding to the Industrial Revolution's social and ecological impacts and subsequent rise in urbanization (Pötz, and Bleuze, 2012; McHarg, 1992; Mumford, 1961; Young, 2007).

As these trends continue, numerous researchers and practitioners have more explicitly refined GI's meaning. Benedict and McMahon's (2002) definition has been widely adopted, identifying GI as "an interconnected network of natural areas and other open spaces that conserves natural ecosystem values and functions, sustains clean air and water, and provides a wide array of benefits to people and wildlife" (Benedict and McMahon, 2002, p. 12).

Other definitions, such as promulgated by the United States Environmental Protection Agency (USEPA), go beyond ecological systems to include human technology, identifying GI as an "adaptable term used to describe an array of products, technologies, and practices that use natural systems - or engineered systems that mimic natural processes - to enhance overall environmental quality and provide utility services" (USEPA, 2011). The NSF Auckland Workshop adopted a similar definition labeling GI: "Natural and engineered ecological systems which integrate with the built environment to provide the widest possible range of ecological, community, and infrastructure services" (NSF, 2012, p. 5).

These latter definitions incorporate "natural" and "human engineered" components (ecological and social elements) as fundamentally defining GI. Another element they share is defining GI as much by its production of ecosystem services as by its existence as physical artifact. Like other structural components supporting metropolitan systems, GI is only *infrastructure* through its ability to deliver goods and services. As a result, our critical exploration includes both ecosystem service and GI typologies. We felt this appropriate to developing a more robust urban GI typology inclusive of both social and ecological elements.

Indeed, as researchers note, merely cataloguing separate social and ecological processes is insufficient. Rather, they argue, to plan and develop them effectively it is vital to understand what Freudenburg et al. (1995) term their "conjoint constitution": the fact that social and ecological spheres not only influence but co-create each other (Dow, 2000; Freudenburg, et al., 1995; Goldman and Schurman, 2000; Pickering, 1995). As Freudenburg et al. note, "What we take to be 'physical facts' are likely to be strongly shaped by social construction processes, and at the same time, what we take to be 'strictly social' will often have been shaped in part by taken-for-granted realities of the physical world" (Freudenburg, et al., 1995, p. 361). Thus ecological and social phenomena, while often studied separately, are in fact two parts of a singular co-creative process or conjoint constitution.

GI, by its very nature, occupies an amplified position at this socio-ecological crossroads: combining ecological and social processes within planning to simultaneously enhance social and ecological health. Successfully uniting these forces requires a similarly unified method. As Redman, et al. note, "[i]t is no longer tenable to study ecological and social systems in isolation from one another" thus invoking an "urgent need to construct new approaches that emphasize an integrative framework equipped with comprehensive models" (Redman et al., 2004, page 161). Constructing a GI planning typology, consistently encompassing social and ecological factors, is fundamental to this framework.

1.2 Typologies

Developing such a framework poses a particular set of challenges. Social and ecological dynamics are immensely complex. This attribute is further amplified by efforts to integrate them (through GI) to transform the functionality of metropolitan landscapes. Challenges of complexity confront many arenas. In response, "typology as a scientific discipline and method of research is used extensively in various fields" (Vujičić, 2011, p.1). Typologies, classifications grouped according to general types, constructively harness this intricacy: "The complexity of…phenomenon…points to the necessity to create a theoretical basis as a starting point from which to direct the process of their transformation. The first step needed to achieve this goal is to systematize the knowledge of this area and subject matter. In that sense, typological classification as a scientific discipline and method represents a solid tool which can enable the systematization of the knowledge that exists, obtain more easily the information and facts which are still unknown, and connect the old with the newly acquired knowledge into a single system" (Vujičić, 2011, p. 1).

Typologies have long provided this function in both the physical and social sciences (Linnaeus, 1735; Park, et al., 1925; Harris et al., 2005). They also offer cross-disciplinary opportunities for more holistic comprehension of particularly intricate issues.

This shared understanding becomes the basis for more accurate planning and policy interventions. For example, in 1998 the United States Department of Agriculture (USDA) established a national farming typology for "statistics portraying the characteristics of the 'average farm' are not representative of most farms" (Hoppe, et al., 2013, p. 1). The typology presented "a more effective policy development tool" for advancing agricultural productivity and resilience (Hoppe, et al, 2000, p.1).

Typologies are widely employed to identify planning and policy opportunities in industry, e-commerce, architecture, agriculture, neighborhood development, river management, forestry, and green infrastructure (Brown, 2000; Hoppe, et al., 2000; Lopez, et al., 2008; Lupton, et al., 2007; Markusen, 1995; Mell, 2009; Turak and Koop, 2008; Zook, 2005).

Their strength derives from the fact that "the development of typologies based on multiple factors takes account of far more complexity in its analysis than simpler categorizations…while producing an end product – the types of areas – which is relatively simple." (Lupton, et al., 2011, p. 8). Researchers note typology used as planning tools "were likely to increase, as departments sought more sophisticated evidence for policy, public funding constraints became tighter, and responsibilities were increasingly devolved to more local levels" (Lupton, et al., 2011, p. 11). Devising a typology encompassing social and ecological factors, while organizing their complexity in a coherent manner, can assist planners and policy makers in shaping more targeted metropolitan GI strategies. Munich offers an example. German researchers, critical of rigid urban planning systems observed that, "in the 1980s, an alternative green space planning typology was developed…that was closer to the themes of green infrastructure…The use of this typology in Munich provided German planners with an alternative view of infrastructure development that allowed greenspace planning to be discussed outside the normal restraints of planning policy." As a result, "by using an alternative process for greenspace planning, Munich was able to highlight the value of its resource base and improve its provision of connective networks of green space" (Pauliet, 2003; Mell, 2010, p. 214).

2. Critique of Existing GI Typologies

Researchers have attempted a number of GI and ecosystem services typologies (Ahern, 1995; Davies et al., 2006; De Groot, et al., 2002; Dunnett et al., 2002; European Environment Agency (EEA), 2011; Millennium Ecosystem Assessment (MEA), 2005; Naumann et al., 2011; Tzoulas, et al., 2007). These attempts derive from stakeholder and academic driven processes and include field research as well as syntheses of existing data. They encompass ecological and social components through a variety of scales and approaches, from global ecosystems to specific ecosystem services and GI mechanisms. Despite differences in scope and approach all eventually aim at enhancing GI outputs through improved social and ecological planning. However, as noted below, existing typologies are weak in several categories critical to GI planning including political, economic, and ecological factors such as ownership and markets (i.e., who benefits from GI mechanisms). As a result, existing typologies function as descriptive tools but provide limited insight into intervention strategies for advancing GI adoption.

Ahern's typology (1995), derived from greenways research in the US and Netherlands is useful, in part, for identifying a GI system's overall elements. Organized around scale, goals, landscape context, and strategy it notes, in general terms, possible political jurisdictions over variously scaled GI. However the typology provides little information regarding where investments in policy and planning could advance community GI to subsequent levels of complexity or service delivery.

De Groot et al.'s typology (2002) proposes to provide "classification, description and valuation of ecosystem functions, goods and services" generated by GI. The authors divide ecosystems according to functions, i.e. regulatory, habitat, production, and information (de Groot et al., 2002, p. 395).

While treating GI outputs more specifically than Ahern, de Groot et al.'s approach remains abstract from specific ecosystem/GI types. Examples of ecosystem process and potential benefits are proposed, however, the authors do not relate them to any particular ecological/GI formations (e.g., grassland, wetlands, green roofs, bioswales). In addition, although de Groot et al. clearly link ecological processes to potential social benefits, they do not include social and ecological drivers influencing these processes and benefits (e.g., political and ecological disturbance regimes, grassroots demands, ecological context).

The typology developed by Dunnett et al. (2002) moves in contradistinction to that of de Groot et al. (2002). Like de Groot, Dunnett divides green space into four main categories: amenity green space, functional green space, semi-natural habitats, and linear green space (subsequently divided into 26 sub-categories), however, they lack the consistency of de Groot et al.'s focus on function.

Instead, Dunnett et al.'s groupings alternate ambiguous concepts of human benefit ("amenity," "functional") with description ("semi-natural") and spatial configuration ("linear"). The typology's sub-categorizations also lack consistency, distributed across a mixture of socially-based meaning (i.e. "recreational green space," "institutional grounds," etc.) and ecosystem descriptors (i.e. "wetland," "woodland," etc.).

The authors' primary focus is to provide "a reporting framework for information about the extent of different types of green space" (Dunnett et al. 2002, p. 9). While this inventory could tally total acres of various, possibly interrelated, categories of green space it leaves potential ecological value, services, or markets unaddressed.

The authors do reference ownership patterns, highlighting issues of access and maintenance, but do not apply them consistently. For instance, the subcategory "private green space" includes only "domestic gardens" while other green space categories remain "value free" in terms of ownership, investment, or appropriated (captured) benefit. In an appendix cataloging a hypothetical community's urban green space, however, the authors apply ownership and access to all green space categories revealing more than half the city's green space under private control and, it can be assumed regimes of private investment and appropriation. While this, ironically, runs independent of their typology, it provides some framework for analyzing potential interventions to advance urban GI.

The United Nations' Millennium Ecosystem Assessment typology (2005) has been widely promulgated. It offers a well-articulated understanding of ecological and social "conjoint constitution" introducing, in a more conceptually comprehensive manner than Dunnett et al., the importance of property relations in determining GI systems.

The MEA's typology identifies four GI ecosystem services categories (*supporting*, e.g., primary production and soil formation; *provisioning*, e.g., food, water, fiber, fuel; *regulating*, e.g., climate and flood regulation; and *cultural*, e.g., spiritual and aesthetic). In addition, it recognizes five social constituents (*security; basic material inputs to a good life*, e.g., shelter and adequate food; *good social relations*, e.g., social cohesion and mutual respect; *health*; and *freedom of choice and action*) affected by GI outputs and driving social and ecological change.

The MEA inventories ecosystem-based GI outputs and supports "response options" to ecosystem degradation. The MEA recognizes their typology's insufficiencies regarding local ecological context, ecosystem health, relationships between GI outputs and human well-being, and social science research, noting "significant advances are needed in models that link ecological and social processes" (MEA, 2005, p. 102). In response, the MEA includes some sub-global assessments.

Davies et al.'s (2006) typology is similar to Dunnett et al. (2002). Stakeholders in Northeast England developed a "Green Infrastructure Planning Guide" "to provide a more informed and systematic way to consider the competing priorities of green infrastructure within the spatial planning process" (Davies, 2006, p.1). This guide generated Davies et al.'s typology.

Like Dunnett et al., the typology's components are defined, in no discernable order, by a variety of means including ecological designation, social function, and status: e.g. "inter-tidal zone," "orchard," and "active and disused mineral workings and quarries" (Davies et al., 2006, p.2). The result is an extensive list (42 categories) lacking clear classifications through which planners could identify strategic GI interventions.

Tzoulas et al. (2007) harnessed GI typology "to formulate a conceptual framework of associations between urban green space and ecosystem and human health" (Tzoulas et al., 2007, p. 2). Their typology's approach is drawn largely from Dunnett et al.'s (2002) report to the UK's Department for Transport "because it includes green spaces of all types of origin, ownership and function" (Tzoulas, et al. 2007, p. 24). However, as noted above, these categories, as presented, are often inconsistent, abstract, and of limited value in determining specific cultural or political strategies for advancing urban GI.

The European Environment Agency's (EEA) report "*Green infrastructure and territorial cohesion*" supports "the European process towards territorial cohesion and green infrastructure development" (EEA 2011, p. 6). Mirroring de Groot et al.'s four principal categories (*regulatory*, *habitat*, *production*, and *information*) with similar designations (regulatory, habitat, provisioning and cultural) and subsequent sub-categories drawn from the MEA, the EEA outlines "benefits of green infrastructure grouped according to main ecosystem service types" (EEA, 2011, p. 10).

While the EEA does not identify the role of specific GI systems producing these benefits, it acknowledges potential opportunities and conflict between EU policies and GI ecosystem service production (for example, directives to increase biofuel production's potential damage to forest cover, ecosystem multifunctionality, and habitat). The report takes closest aim at the policy level, leaving issues of specific strategies, ecological drivers, markets, ownership, and appropriation of GI value beyond the inquiry's scope.

Naumann et al.'s (2011) typology derived from a report to the European Commission, seeks to identify "key parameters…to facilitate an increased understanding of differences in focus, emphasis, and characteristics between initiatives [rather] than to identify distinct types of categories of green infrastructure projects" (Naumann et al., 2011, p. 2).

The "parameters, sub-categories, and definitions" proposed in Naumann's report encompass a robust set of factors. These include *Objectives* (e.g. clean water or biodiversity conservation), *Actions* (e.g. spatial planning or increasing public awareness), *Green infrastructure elements* (e.g. protected areas, reforestation zones or technology implementation), *Ecosystem covered* (e.g. forest, grassland, and rivers), *Sectors affected* (e.g. agriculture, forestry, transport, and urban and regional planning), *Setting* (e.g. rural, urban, or peri-urban), and *Geographic scale* (e.g. local/regional/national or transnational).

Naumann's typology goes a considerable distance in acknowledging and integrating the social and ecological factors constituting GI projects and policies. While the categorization of GI projects currently in Europe is well met, it leaves unexplained the social and ecological forces *driving* different GI efforts into being. Furthermore, it leaves issues of ownership, markets, and appropriation of value generated by GI programs unaddressed. As a result, while offering strong descriptive tools for identifying levels of GI development in communities, the typology provides GI advocates and planners limited insight into intervention strategies for advancing GI adoption.

Dobbs et al. (2011) proposes to refine previous typologies by developing ecosystem output indicators for forest-related urban GI. Like its antecedents, Dobbs et al. highlight connections between ecological functions and social processes. Acknowledging such "conjoint constitution," they argue, could create more useful tools, dependent, however, upon "socio-political as well as biophysical contexts" (Dobbs et al., 2011, p. 197). This context, they observe, is often overlooked. Citing Segnestam (2002), Dobbs et al. note assigning values to GI ecosystem services "does not provide information on the causality behind the value assigned."

While acknowledging this common gap in previous typologies, Dobbs et al. remark a lack of information about social and ecological drivers limits their own framework (Dobbs et al., 2011, p. 197). In addition, similar to typologies discussed above, Dobbs et al. leave specific issues of ownership, markets, and the appropriation of GI benefits largely unaddressed.

In sum, existing typologies function to varying degrees as tools for describing levels of GI development. However, lacking information on social and ecological context, drivers, markets, and value appropriation, current GI typologies provide planners, policy makers, and the general public with limited insight into how to advance GI adoption. Our typology seeks to fill this gap.

3. Planning and Urban GI

Mell (2011) observes "the role green infrastructure holds in urban planning practice" is to placing ecological tools within the planning process (Mell, 2011, p. 29). As a result, "human interactions with this process are central to the success of green infrastructure investments" (Mell, 2011, p. 30). However, divisions between GI policy formulation (occurring largely at national levels) and implementation (occurring largely at regional or city levels) result in "an ongoing debate assessing the value of such policy in translating Green Infrastructure principles into practice" (Mell, 2011, p. 36).

As the MEA notes, a cause of this disconnect is translating general, global, or abstract categories into on-the-ground assessments and intervention strategies. Another cause is under-articulation of critical social factors including political power, markets, property relations, and appropriation of GI-related value. While, as Mell argues, a "green infrastructure approach to planning has provided planners with a far greater scope to review the interactions between people, the landscape and the resource base of a given urban area," not articulating these factors undercuts its planning potential (Mell 2011, p. 36). GI typologies failing to identify these connections cannot bridge the theory/policy gap to support strategic implementation.

4. Toward a New Typology of Urban GI

In response we propose a new typology for urban GI. We do so assuming there is interest in GI systems becoming fundamental to metropolitan infrastructure. We also assume GI capable of producing quantifiably equivalent or superior technical and social outcomes compared to grey infrastructure, thus providing significant components of a city's service-delivery systems (De Sousa, et al., 2012; Dunn, 2010; Wise, 2008). As a result our typology seeks to gather information required to support decision-making and investment necessary to transform GI into a mainstream mechanism of urban infrastructure.

As noted, typologies require "a theoretical basis as a starting point from which to direct the process of…transformation" (Vujičić, 2011, p. 1). To transition to metropolitan-scale GI, the theory must reconceptualize large-scale anthropomorphic systems to encompass a broader ecological basis, identifying a variety of forms, and acknowledging their evolutionary capability (Benedict and McMahon 2002; Costanza et al., 1997; Geddes, 1915).

We draw from Marcel Mazoyer and Laurence Roudart's theory of agrarian systems to inform our approach (Mazoyer and Roudart, 2006). Mazoyer and Roudart characterize agriculture "as a complex ecological and economic object, composed of several categories of production units that exploit different types of terrain and diverse species of cultivated plants and animals" to produce socially useful results (Mazoyer and Roudart, 2006, p. 21). This complexity manifests in "observable forms" which "vary according to place" and as conditions change, evolve over time. Through Mazoyer and Roudart's approach, "the evolution of social structures and technologies is described as a succession of crises and the discoveries to overcome them" providing "a major contribution to the…reflection on the long-term economic, social, and environmental development of society" (Griffon, 2008, pp. 609, 610).

GI can be typified in a similar manner. It is a complex system encompassing social and ecological elements evolving in response to local and general challenges such as flooding, urban heat island effect, climate change, and public health issues. Its drivers and character vary according to region and social priorities. Furthermore, it is capable of transforming anthropomorphic systems to encompass broader ecological dynamics in the production of socially useful outputs. As a result, we view Mazoyer and Roudart's theory as a valuable starting point to critically comprehend and analyze different GI systems.

Our approach recognizes GI systems as ecological and social objects composed of several categories of production units responding to different social and ecological conditions and engaging diverse labor processes, GI strategies, and built forms. We identify specific ecological forces influencing GI formations and include in our investigation social forces incorporating political power and key economic elements such as labor processes, ownership, markets, and appropriation regimes. In this manner we hope to provide the basis for a typology useful in mainstreaming GI systems.

4.1 Trajectory of GI development

It is important to understand a significant part of our typology views GI as dynamic and evolutionary rather than as fixed systems isolated from social and ecological change. Thus the interaction of social and ecological relationships present in a given GI system continually determines its present level of development.

Mirroring Mazoyer and Roudart we suggest four main development categories: *general*, *unequal, contradictory*, and *in-crisis* (Table 1). These categories reflect potential trajectories for GI systems. Their purpose is to provide GI planners, advocates and policy makers the ability to situate the present direction of their overall GI efforts and compare it with other cities' trajectories. Such large-scale categorization is used in many other planning fields. Indicators including GNP, consumer confidence, unemployment rates, or the Dow Jones Industrials provide benchmarks that allow other states, companies, communities, and investors to roughly locate their position in relation to other entities and trajectories of change. While a rising GNP or consumer confidence rating may not reflect similar advancements by individual companies or communities it allows their performance to be situated in relation to overall trends. Strategies altering individual trajectories in relation to larger trends can then be developed.

In our framework, communities can reference more finely detailed information in the typology's examination of social and ecological settings, drivers, production systems, etc. (see below) to determine where investments are necessary to advance their particular program. While finer levels of information will not prescribe whether or where a particular green roof (for example) should be installed, it will help identify broader planning initiatives such as whether to investigate greater incentives for private sector involvement, ramp up efforts to secure more state or federal support, or create more comprehensive regulatory or reporting mechanisms to identify and capture the value generated by GI systems.

(Table 1)

General development reflect GI systems whose social and ecological production units are gaining new ecological and social means of production, growing their operations, and increasing their economic size and income. Acquiring new means of production includes expanding the scale of GI systems (e.g., magnifying GI planning from individual buildings to whole neighborhoods or watersheds) and volume of production (e.g., expanded initiatives in planting street trees, installation of green roofs, rain gardens, urban forests, etc.). This category also includes increasing access to different types of land ownership (e.g., both private and public land).

Operations growth includes expansion and intensification of maintenance and stewardship regimes as well as diversification of GI methods appropriate to a city's biome. It also includes diversification and elevation of the social status of its labor process and institutionalization of effective GI-related governance and decision-making.

Increasing the economic size and income of GI systems includes factors such as expanding the scope and volume of GI benefits. Coupled to this is creating institutionalized market feedback mechanisms to propel further GI development. Markets are not confined to the private sector but can include public and community sector markets as well. Connected to market development is institutionalizing effective means for capturing the ecosystem services value generated by GI. Therefore, increasing income also includes increasing the breadth of the population appropriating value from GI development.

Unequal development describes GI systems where some social and ecological components of the program's production units are developing more quickly than others but are doing so within a general advancement of the system as a whole. *Contradictory development* represents GI systems where some of production units are developing while others regress. Finally, GI systems are deemed *in-crisis* when all of a GI system's social and ecological production units are in regression and tending toward disappearance.

Since dynamic interaction of GI systems' social and ecological factors continually determine development levels, understanding the character and trajectory of settings, drivers, and production systems that provoke and distinguish such systems is vital (See figure two below).

4.2 GI Social System

4.2.1 Setting and drivers

Determining a GI system's social setting and drivers is fundamental to understanding GI context and motivation. Political power is a key force shaping social settings within which GI can advance. Thus our typology includes information on specific governance regimes surrounding GI efforts. Furthermore, determining social components driving particular GI systems both externally and *in situ* strengthen a typology's analytical power. For example, understanding local governance structures enabled Chicago GI advocates to develop more effective coalitions. Bringing together grassroots organizations with the city's "strong mayor" form of government enabled GI planners to rapidly place GI on agendas of city agencies who had no previous commitment to its implementation (Young, 2010). In New York City and Philadelphia leveraging external federal clean water mandates enabled GI advocates to make major innovations in large-scale GI innovation (Madden, 2010; Pires, 2004).

4.2.2 Social production system

Identifying social production systems characterizing GI includes describing specific GI production units at levels of scale and means of production. Determining specific GI systems social configurations including status of GI-related labor, property ownership, and modes of access is also necessary.

For instance, experimenting with diverse sources of community labor enabled Los Angeles and New York City GI planners to accelerate tree-planting operations while building neighborhood-level support for GI. Meanwhile, Denver's inability to induce significant private landholder participation limited the initial reach of the city's GI programs (Young 2011).

Understanding decision-making is also fundamental to grasping the social dynamics of GI production systems. Determining the degree of hierarchical or decentralized decision-making and institutionalized feedback loops for program re-calibration, as reflected in Chicago's experience, is central. Also, identifying specific public, community, and private sectors roles in each is essential to perceiving the trajectory and appropriate intervention points of given GI systems.

Comprehending external social relationships surrounding GI systems is also important. Cataloguing upstream inputs such as funding, policies, and labor can help categorize drivers influencing a program. Identifying downstream outputs are equally important. Components such as local and external consumption of GI ecosystem services, existing markets for those services, and the nature of the appropriation of their value are necessary to locating a program's level of development and influence.

New York City's regional clean water strategy illustrates this point on a grand scale. Understanding the value of ecosystem services generated in the Catskill region and appropriated downstream by the City enabled New York City to promote and secure federal recognition of their regional GI strategy, thus avoiding hundreds of millions of dollars of federally mandated grey infrastructure costs (NYDEC 2013).

4.3 GI Ecological System

4.3.1 Setting and drivers

Identifying GI systems' existing ecological context can provide significant insight about the challenges, possibilities, and purposes of a GI system. This can inform understanding of ecological forces (both *in situ* and external) driving investments in GI. These forces can include recent disturbance events and longer-term ecological transformations.

A case in point is Albuquerque, New Mexico where efforts to advance the city's urban forestry program brought resistance from citizens who doubted that type of GI intervention was appropriate in a high-desert setting. Meanwhile, GI has gained new support in New Orleans and New York where deployment of tidal marshes and riparian and wetland restoration are now seen, in the wake of significant regional ecological disturbance, as important tools in the region's infrastructure development (Young 2011; Gunther 2014).

4.3.2 Ecological production system

Comprehending GI programs' ecological units of production; systems of management, maintenance, and appropriation of ecosystem services; and the relation of cultivated and non-cultivated aspects of GI systems to "external" ecosystems can help identify a community's level of GI development and potential opportunities for intervention. It also illuminates GI systems' external ecological impacts (Table 2).

(Table 2)

While understanding individual social and ecological factors has helped cities move components of their GI programs closer to the mainstream of urban infrastructure, lacking a systematic approach often results in piecemeal implementation. Unifying these factors into a comprehensive typology, however, offers a mechanism for planners, advocates, and decision makers to devise and implement more inclusive GI strategies with greater chances of on-the-ground success.

5.0 Findings: Case studies

We use three case studies (New York City, San Antonio, Texas and Auckland, New Zealand) to test our typology. We chose these cities not as a comprehensive set but as diverse ground to explore the typology's potential value and the sufficiency of data reflected in urban GI plans. New York City and Auckland are principal cities in their respective countries as well as located in deciduous, temperate forest biomes. San Antonio is located in a forest/grassland biome and part of the "Texas Triangle" – the fastest growing conurbation in the United States. While San Antonio and New York experienced significant ecological impacts associated with climate change in 2011 (drought killing over 300 million trees in Texas and Hurricane Sandy in New York), Auckland considers itself facing deteriorating environmental indices and significant population growth, but more diffuse climate change challenges (Anthes, et al, 2006; Peterson et al, 2012; Trenberth, 2012; The Auckland Plan, 2012b; Texas A&M, 2012).

5.1 Case Study-New York City

5.1.1 Social system

Setting and drivers

New York City's municipal government is organized under a City Charter providing a "strong" form of mayor-council governance. As a result, the political setting of the city is more centralized than most other US cities. Public education, public safety, recreational facilities, sanitation and water supply are all among municipal government's portfolio of responsibilities.

New York City's Charter provides local representation through 59 neighborhood Community Boards. The Boards serve an advisory role on issues of service delivery and public development within their neighborhoods. Community Boards must be consulted regarding most land use and development proposals prior to placement of public facilities or zoning changes in their districts. City Council is required to review Community Board recommendations. The city's Charter also enables Boards to initiate their own district growth and quality of life plans.

Social drivers of NYC's GI program include external and internal legislation and planning. External factors include the 1972 Clean Water Act empowering the USEPA to issue regulations to reduce pollution in national waterways. Subsequently, the USEPA's 1994 Combined Sewer Overflow (CSO) Control Policy tightened municipal CSO discharge management, requiring immediate minimum controls and long-term control planning (USEPA, 2013) and was amended by the 106^{th} Congress's Wet Weather Water Quality Act of 2000 (US Congress, 2000).

At the state level, New York State's Department of Environmental Conservation enforcement of the federal Wet Weather Quality Act enables municipalities to deploy GI as an abatement strategy (NYSDEC, 2013).

Internal social drivers include New York City's "plaNYC" comprehensive planning agenda initiated by Mayor Bloomberg. The plan encourages the City to "explore the potential of more natural solutions to cleanse and filter our waterways" (plaNYC, 2007 p. 50). The plan specifies strategies to "expand efforts to harness our environment as a natural water filter" including enhancing NYC's "Bluebelt" system engaging wetlands, stream restoration, outlet stilling basins, and sand filters; planting one million trees; and redesigning streetscapes to slow and filter additional rainfall (plaNYC, 2007 p. 50).

Social production system

NYC's GI programs are currently deployed through neighborhood-scale interventions. There are two major exceptions. First is NYC's program to secure the quality of its regional water supply through conservation easements, land purchases, and nutrient management education in the Catskill and lower Hudson Valley watersheds supplying NYC. The second is NYC's Million Tree planting initiative to plant one million trees citywide over 20 years augmenting canopy cover and increasing water retention and runoff control. A third, minor exception is NYC's distribution of 2,000 rain barrels in four of the City's five boroughs (NYC Green Infrastructure Plan Update 2011).

Beyond regional and citywide programs, NYC is introducing building, block, and neighborhood level GI interventions. Examples include three Neighborhood Demonstration Areas launched "to test the effectiveness of green infrastructure systems on a larger scale" in the Bronx River, Jamaica Bay, and Newtown Creek watersheds (NYC Green Infrastructure Plan Update 2011, p.15). These interventions are mainly deployed on public lands and rights-of-way including streets and public schools and housing.

Means of production

New York City currently deploys and is expanding a full suite of GI means of production including street trees, green roofs, protected wetlands, bioswales, rain gardens, urban farms, and permeable pavement with the objective of managing 10% of NYC's combined sewer tributary areas through GI by 2030. These efforts include planting one million new trees; increasing Greenstreets from 204 to 239 acres; constructing 92 stormwater wetlands to service 13,700 acres; and constructing 5900 new bioswales (plaNYC, 2007).

Social status of labor

Predominately public sector labor constructs and maintains NYC's GI projects. However, the city is creating a community-based "Stewardship Corps" to enable neighborhood-level GI maintenance. The city also issued regulations prompting private developers "to capture more storm water runoff, to provide additional capacity in the combined sewer system, and to reduce street flooding. Enhancing an already existing requirement to manage stormwater, the rule means that developers will employ more green roofs, blue roofs, rain gardens, and detention techniques, and will also minimize impervious areas to the extent possible" (NYC Green Infrastructure Plan Update 2011, p. 9).

Status of property ownership

The majority of NYC GI project installations has taken place and is planned on public lands and rights-of-way. Some new regulations and grant programs require or enable, respectively, private developers and property owners to implement GI methods.

Mode of access to the land

Most NYC GI development consists of public agencies and employees accessing public land to implement and maintain GI projects. Private companies and employees are induced, indirectly through regulation, to include GI systems in "new construction and major building alteration projects" (NYC Green Infrastructure Update 2011, p. 9).

Configuration of decision-making

Traditional top-down public sector planning generates the vast majority of NYC's GI development. Mandates of an agreement between the NYC and New York's Department of Environmental Conservation regarding the City's CSO abatement are the central driver of the City's GI efforts. The Mayor's Office and various city agencies including the Parks, Transit, Public Housing, and Environmental Protection departments have been responsible for selecting, planning, and executing the majority of GI projects related to meeting the mandates.

While planning and decision making resides predominately within NYC's municipal government, the city has established several adjunct bodies to enable input from and communication with citizen, community, and private sector representatives. These include the Green Infrastructure Citizen's group, the Green Infrastructure Steering Committee to "foster stewardship of green infrastructure" (NYCGI Update 2011 p.23).

Inputs

New York City developed a "Green Infrastructure Fund" encumbering $187 million through fiscal year 2015; the City also included $735 million in its 10-year capital budget, "and is prepared to commit $1.5 billion through fiscal year 2030" (New York City Green Infrastructure Plan Update 2011, p. 3).

Outputs

Ecosystem services generated by NYC's GI systems are consumed primarily at the local, neighborhood level. However, as the system grows more robust, municipal agencies responsible for environmental quality will become increasing consumers of ecosystem services predominantly through projected avoided costs.

Municipal government largely appropriates the value (actual and potential) generated by NYC's GI projects as avoided costs through elimination ($1.4 billion) and deferral ($2 billion) of state-mandated grey infrastructure investments. No mechanisms currently exist to capture the value of outputs such as carbon sequestration, pollution or wetland mitigation.

NYC's GI systems' market value is currently captured by centralized public and decentralized community-based appropriation. The centralized public appropriation is manifested in (considerable) avoided costs of meeting state and federally mandated clean water requirements through grey infrastructure. The decentralized, community-based appropriation is manifested in use-value extracted by residents from the greening of their neighborhoods (i.e., reduced flooding incidents, community beautification, etc.).

The GI grant program has recently financed some non-profit and private sector GI investments that may generate increased real estate values privately appropriated by these organizations.

5.1.2 Ecological system

Setting and drivers

New York City is in a coastal, estuary, temperate forest biome standing approximately 33 feet above sea level. The city contains seven watersheds connecting to two major rivers and the Atlantic Ocean. The Hurricane Sandy floods had significant ecological impact, driving the acceptance of GI as part of NYC's infrastructure planning.

Cultivated ecosystem

As noted, NYC's GI program includes adding one million trees to the urban forest, expanding the acreage of meadow-like green roofs and traffic medians, wetlands, rain gardens, and, at an experimental scale, developing a 40,000 square foot rooftop farm.

To manage this urban ecosystem, NYC trained its Parks Department workers to maintain the new GI interventions until 2015. In addition, the city is developing community-based organizations such as the "Stewardship Corps". The few GI systems paid for by NYC Green Infrastructure grants are to be maintained by the grant recipients. Currently, there are no plans to "harvest" materials generated by the GI systems either publicly or privately.

The connection/relation of NYC's GI ecosystems with "external" ecosystems is predominantly focused on water quality. As noted, NYC sits at (and developed because of) the nexus of major river, estuary, and Atlantic Ocean ecosystems. All water-related GI projects are focused on relieving pollution discharges into these bodies.

NYC has also incorporated habitat into its plans. For example, the city recently grant funded a green roof to study connections of bird migration and breeding habitats with GI.

5.1.3 GI development trajectory

New York City's GI program is currently in general development, deploying a wide variety of systems and types of interventions. These systems are socially driven primarily through federal and state regulatory clean water regulations and ecologically by the ramifications of Hurricane Sandy. As a result they are receiving increased funding and resource commitments primarily through the public sector where a majority of GI decision-making power resides.

Despite this growth in public sector engagement, private sector involvement is still embryonic as are market mechanisms for ecosystem services generated by NYC's GI systems. The public sector has appropriated the value of these systems through avoided costs and the public at large through use values while NYC's private sector has yet to significantly drive additional private investments in GI.

5.2 Case Study-San Antonio

5.2.1 Social system

Setting and drivers

Neither San Antonio's Department of Planning and Community Development, its Department of Parks and Recreation, nor its Office of Sustainability yet have a published, integrated GI plan for the city. However, San Antonio has two examples of plans or aggregations of policies with significant GI components. One was the City South Management Authority's (CSMA) annual strategic redevelopment plan (the CSMA was dissolved in January of 2014, henceforth referred to in the past tense in this article); the other is an aggregation of several of the San Antonio Water System (SAWS)'s policies and programs. In addition, the City of San Antonio has a tree planting initiative, housed under its Office of Sustainability and the Department of Parks and Recreation; given the small scale of this program (5,735 trees planted since 2010), this case study will not focus on San Antonio's tree planting initiative as a form of GI.

In 2005, Texas created the CSMA, a governmental entity and state political subdivision, to oversee sustainable redevelopment of a 63 square mile area south of San Antonio (in short, a regional planning process overseen by a state division). After a 2012 assessment ordered by Texas Senate Bill 1493, San Antonio proposed dissolving the CSMA and annexing most of the acreage, returning the rest to county control. The CSMA was subsequently dissolved in January of 2014; 25 square miles of the area is now under limited-purpose annexation and is schedule to be fully annexed by the City of San Antonio in 2017 (City of San Antonio, 2014; Moravec, 2013).

Before dissolution, San Antonio's mayoral leadership and City Council drove GI planning efforts in the CSMA. San Antonio has seen low-density, high infrastructure sprawl development to the north and northwest; the south side has remained more rural and undeveloped. Former San Antonio Mayor Ed Garza developed the idea of CSMA and advocated the planning process in order to promote sustainable economic development. Area residents have been reported as skeptical of these efforts (Place, 2004; Gray, 2013).

A major driver of the early planning process was realization that existing development patterns in the northern part of San Antonio was undesirable for numerous reasons (social, economic, and environmental). In response, there was a desire by the San Antonio government to do things differently in the southern area of the city. The mayor, who holds a degree in land development, was familiar with sustainable development frameworks and GI concepts.

In addition to the curtailed GI implementation in the CSMA, metropolitan San Antonio has a more successful GI example in the San Antonio Water System (SAWS)'s land acquisition and water conservation programs. SAWS is a department of San Antonio's municipal government. Although San Antonio does not have a formal water plan, SAWS is acknowledged throughout the US as a successful and early adapter of municipal-scaled water conservation (BBC Research and Consulting, 2003; SAWS 2014). In addition, SAWS also oversees a watershed land protection program, similar to many other US municipalities.

A key component of their water conservation program includes water-conserving landscaping and xeriscape education materials (such as plant lists, drought-tolerant turf suggestions, watering information) for residents and commercial/residential builders, in addition to water-conserving landscaping rebates for residents. As a result of SAWS education, outreach, and rebate efforts, San Antonio has a lower outdoor water use rate than any other major semi-arid Texas city (67 gallons/per household/per day outdoor water use vs. 125 gallons/household/day in Dallas, 97 gallons/household/day in Fort Worth, and 89 gallons/household/day in Austin) (Hermitte and Mace, 2012).

In addition to being early adopters of water conservation, SAWS also oversees a Sensitive Land Acquisition Program (fee simple and conservation easement) program to protect its drinking water source, similar to many other municipalities. To date, SAWS has protected 9,140 acres of land; this program also fulfills San Antonio's obligation to protect the Edward's Aquifer endangered species (SAWS, 2014).

San Antonio's early adoption of water-conserving landscaping as a tool to bring about water conservation, as well as its watershed land acquisition program, was driven by a federal mandate to comply with the Endangered Species Act. San Antonio is the largest US municipality dependent upon an aquifer for a municipal water source. In the 1990s, the Sierra Club sued San Antonio (in addition to several other municipalities and institutions), arguing that San Antonio's use of groundwater from the Edward's Aquifer resulted in the "taking" of the endangered Texas Blind Salamander, which lives in the aquifer (Abernathy, 2013). In response, the State of Texas formed a political subdivision, the Edwards Aquifer Authority, which works with San Antonio to ensure that SAWS' water withdrawals do not impair endangered species habitat. In sum, water-conserving landscaping GI systems put into place by SAWS, in addition to its watershed land acquisition program, are municipal programs driven by enforcement of a federal law, under oversight by a political subdivision of the State of Texas.

Social Production System

For the CSMA, the 2012-13 Annual Strategic Plan was the primary planning document encompassing GI tools and using the term GI, so while not a specific GI plan, it did encompass some of the planning work needed for regional GI implementation (CSMA, 2012). The plan included goals for low impact development (LID), conservation development to keep large tracts of open space undeveloped, and increasing protected open space through purchase and establishment of parks.

SAWS does not have a published overall plan for GI or for their water system as a whole, but their social production system for water quality and quantity GI includes education and economic incentives focused on water-conserving landscaping at the residential, commercial and institutional scales, as well as the purchase of fee simple lands and conservation easements to protect the aquifer recharge area.

Means of Production

Because of the slow development of the CSMA area, there were few opportunities to build housing developments incorporating LID or conservation lands acquisition. Two privately-owned conservation subdivisions were planned and built, using private-sector wage labor. For these two subdivisions, the conserved land will either be held by the private homeowners association or by private, non-profit land trusts. In addition, until it was dissolved, the CSMA had zoning and bonding authority to regulate private land and purchase public land; however, no public conservation land appears to have been purchased.

In regards to the SAWS programs, citizens and institutions voluntarily participate in the water-conserving landscaping program, which is implemented on both private and public land. Public sector employees manage the land acquisition and water conservation programs. Any land purchased by SAWS for aquifer recharge protection becomes public land; land associated with conservation easements remains privately held. Some fee simple lands are accessible to the public; in general, conservation easements lands are not publically accessible (Lieberknecht, 2009).

Configuration of decision-making

CSMA's decision making was public sector driven. There seemed to be agreement in the private sector that incentives for development were needed, but less agreement that zoning and other regulations were needed.

In the SAWS case the public sector is also driving the decision-making, in response to legal cases brought by the community sector and federal regulations.

Inputs

No external funding was provided for CSMA implementation. The CSMA had authority for bonding, sales tax and special tax districts. Although the CSMA policies, for the most part, were driven by the City of San Antonio, the Urban Institute (UI), a national think tank, was hired in 2005 to do the initial assessment, and development scenarios for the area were derivative of UI's assessment document. The Annual Strategic Plan was written by paid staff and overseen by an appointed board.

In general, SAWS funding is provided by water rates and fees. In addition, a 2000 bond measure increased sales tax by 1/8% to raise funds for the watershed land acquisition program. SAWS has partnered with regional and national land conservation groups in addition to Texas Parks and Wildlife to leverage funds for land and conservation easement acquisition.

Outputs

Conserved land in the form of CSMA conservation subdivisions most directly benefits local residents, but also in a more diffused manner, regional residents (more permeable surfaces, better water quality, etc.). Ecologically both local and external wildlife populations such as migrating birds benefit from these GI efforts.

Aquifer recharge lands acquired through SAWS most directly benefit regional residents who depend on the aquifer for drinking water, in addition to the endangered species and other wildlife that depend on the aquifer. SAWS water conservation programs benefit

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water users (residents but also private sector businesses), regional residents outside of San Antonio who also use the aquifer, and local and regional wildlife populations. Water conservation reduces water bills for residents and businesses in the short term (due to reduction of water use). However, there is some concern that water conservation will result in increased water rates over time, since SAWS (or any other water utility that implements water conservation) will be selling less water. SAWS maintains that overall water bills will decrease over time, even if rates rise, since the need for extra fees to support new water infrastructure and acquire new water sources will decline (BBC Research and Consulting, 2003)

5.2.2 Ecological system

Setting and drivers

The southern part of San Antonio is in the South Texas Plains/South Texas Brush Country Biome (semi-arid forest/grassland). The LID sections of the CSMA plans were driven by cycles of drought in the San Antonio area resulting in attention to water conservation and using stormwater for on-site water needs. The conservation subdivision/open space protection GI components were driven by desires for water quality protection, viewshed protection, and access to recreation lands.

San Antonio's semi-arid climate, and the likelihood that drought events will increase with climate change, also drive the need for water-conserving landscaping programs and the watershed land acquisition program. In addition, land protection also functions to protect groundwater quality, which, given the slow movement of groundwater in some areas, can be extremely sensitive to pollution and difficult to mitigate.

Cultivated Ecosystem

Policy documents do not deal with details of long-term management of LID design, nor long-term stewardship and management needs associated with protected open space either through conservation subdivisions or public acquisition of parkland. Language in the Annual Strategic Plan did indicate awareness of the need to link protected lands in conservation subdivisions and parks with existing open space.

No policy documents available through SAWS' website give an overview of SAWS' approach to long-term management and stewardship of their acquired lands and conservation easements. However, it is likely that given their partnerships with state and national conservation groups and agencies, SAWS is following best practices regarding management and stewardship. Regional groups such as LadyBird Johnson Wildflower Center are developing data about long-term maintenance costs and needs of water-conserving landscaping.

5.2.3 GI development trajectory

San Antonio could currently be considered in a stage of contradictory GI development. While social and ecological factors generated by San Antonio's growth pattern motivated the mayor's office and some citizenry to argue that GI systems are an important infrastructure option, the limited aspect of CSMA's engagement with GI and abandonment of its regional planning component indicate both resistance and regression on the issue. The absence of long-term management plans for deployed GI components and lack of any organized mechanisms or means for public or private markets and appropriation of the ecosystem services values generated by CSMA GI further indicates the low level of program development.

On the other hand, SAWS is considered to be a national leader in regards to water conservation; their water-conserving landscaping education and rebate program comprises part of this success story (Texas Living Waters, 2014). And although SAWS' aquifer recharge protection program is not as extensive as other national examples, outside groups have recognized its success (AWWA, 2004). In particular, the 2000 bond measure for land acquisition, given three other bond measures on the same ballot failed, indicates a strong level of public support.

5.3 Case Study - Auckland

5.3.1 Social system

Setting and drivers

Auckland's semi-hierarchical governance structure is comprised of an elected mayor and councilors ('Auckland Council governing body') and non-elected Auckland Council organization overseeing the city's day-to-day management. In addition, 21 elected Local Boards represent local communities and make decisions with the Auckland Council and a number of council-controlled organizations (CCOs). Despite the CCOs name, the Auckland Council has little direct influence over CCOs beyond negotiating statements of intent guiding each CCO's strategic direction. The mayor of Auckland is responsible for promoting and leading a vision for Auckland.

Auckland's social drivers include population growth, Auckland's contribution to New Zealand's economy, external and newly developed internal legislation, and the regional economic importance of Auckland's natural environment (local recreation and tourism). As New Zealand's largest city, home to around one third of New Zealand's population it is "predicted to take up to 60 per cent of New Zealand's population growth over the next thirty years" potentially adding a further 1 million people to its population of 1.3 million (Auckland Council 2012b; Department of Internal Affairs, 2011). Likewise, Auckland generates over a third of national GDP (Auckland Council 2012b, p19).

Major governmental restructuring in 2010 created opportunities for unified governance across the Auckland region. Entirely new policies covering all aspects of city planning were developed to enable the mayor's vision of "the world's most livable city" projecting 'a green Auckland' as one of several key outcomes. Achievement requires transforming Auckland Council to "strongly commit to environmental action and green growth" (Auckland Council 2012b, p31).

In Auckland's planning documents, interpretation of 'green' and 'green growth' depends on the public sector involved. It may mean physical greening (i.e. the increase of vegetated and natural systems, i.e. GI) but often refers to green technology outcomes e.g. greenhouse gas reductions, renewable energy, reduced water consumption, or expanded public transport.

Newly issued stormwater management requirements provide some statutory support for larger scale GI implementation (Auckland Council 2013b). Additionally, a number of spatial planning and strategy documents explicitly incorporate GI in projects at block or neighborhood scales in the city center (Waterfront Auckland, 2012; Auckland Council, 2012c; Auckland Council 2013a).

The 1991 Resource Management Act (RMA) is the principle statute governing natural resource management in New Zealand influencing planning at local levels. Compliance to the RMA is enforced through the Environment Court. However, New Zealand's government perceives the RMA as restricting economic growth. As a result, urban tree protection has been reduced and reform proposals change relative weightings of environmental and economic considerations (which may erode environmental protection) and require councils to ensure "adequate land supply to provide for at least 10 years of projected growth in demand for residential land in their plans" challenging Auckland's ability to constrain urban sprawl (Gibson, 2013; Environmental Defense Society 2013; Ministry for the Environment 2013; Wright, 2013).

Social Production System

Most water-related GI projects in Auckland are neighborhood or building scale, aimed at solving isolated local flooding or water quality issues. However, a few larger-scale projects have been implemented. For example: Auckland Council-owned Albany Lakes Civic Park incorporates rain gardens, tree pits, and permeable pavement among other technologies to mitigate water quality impacts in "high quality" environments downstream from large commercial development. A wholly-owned subsidiary of Housing New Zealand Corporation (the agency responsible for social housing across New Zealand) has made voluntary commitments to GI across an entire 167 ha, 3000 unit development west of the city. Waterfront Auckland, the CCO directing re-development of Auckland's waterfront on Waitemata Harbour has implemented GI throughout the Wynyard Quarter with plans for further development (Waterfront Auckland, 2012). Likewise GI is planned for major road re-development by the Waitemata Local Board (2013) and re-development of Auckland's central business district is planned to include extensive GI through linear parks linking existing parks in a green network (Auckland Council, 2012c).

Nonetheless, other GI projects are meeting resistance. North of the city, a private 160 ha, 2000 unit development is under construction incorporating GI by Environment Court mandate. In central Auckland, finalized planning documents reduced tree planting by an order of magnitude (Auckland Council, 2011; Auckland Council, 2012c).

Means of Production

Auckland has implemented a full suite of GI: permeable paving, street trees, rain gardens, roadside swales, rainwater harvesting, and green roofs, scattered mostly in isolated projects throughout the city (Auckland Council, 2012 b & c; Waterfront Auckland, 2012). Several sites serve as demonstration projects with Auckland Council investing in research for refining and understanding GI technologies in local contexts, and leading to revision of technical design manuals (Borne et al. in press a, b, & 2013; Fassman &

Blackbourn 2010 & 2011; Fassman and Simcock 2012; Fassman et al. 2013; Fassman-Beck et al. 2013).

Social status of labor

Most of Auckland's GI design, construction, and maintenance projects are contracted to private companies – including Auckland Council's GI projects. However, initiatives involving "tree planting programs may be undertaken in partnership with private landowners, schools, and local community groups" (Auckland Council 2012b, p208).

Status of property ownership

Auckland Council is the main proponent of GI, planning and implementing projects on public land to resolve local water, particularly flooding, issues. Some new zoning and environmental conditions induce private developers and owners to comply with regulations through GI (Auckland Council 2013b).

Mode of access to the land

Most GI projects in Auckland are on public land; however, the Auckland Council reserves the right to monitor GI on private land.

Configuration of decision-making

Auckland's GI is largely driven by public sector decision-making. However public sector departments involved in public access-ways, economic and urban development, and tourism typically do not regard 'a green Auckland' as a primary to their activities (Auckland Council 2012a, vol. 2). The CCOs "operate at arm's length to the council" under governance of their boards of directors or trustees and as business concerns (Auckland Council 2012a, vol. 5). CCOs responsible for water, wastewater services, and transportation do not prioritize GI (Watercare Services Ltd. 2012; Auckland Council 2012a vol. 2, p97). Only one of 21 local boards explicitly advocates water-related GI initiatives, while two other local boards refer to creating greenways (Auckland Council 2012a, vol. 4).

Inputs

No external funding has been provided for GI implementation in Auckland. Public sector GI is funded through rates (local taxes) and financial contributions required by legislation. Where GI is implemented in private developments, the cost appears to be bundled with property prices and passed on directly to buyers.

Outputs

GI benefits Auckland's 'green' image by producing (unquantified) benefits for Auckland's tourism industry. No clear financial benefits to Auckland Council or Auckland's residents have been publicized.

5.3.2 Ecological system

Setting and drivers

Auckland is situated within 2400 km of marine coastline on an isthmus between Manukau and Waitemata Harbors, extending along the Hauraki Gulf. It has a subtropical climate, averaging 137 "wet" days (precipitation of at least 1 mm) delivering 1240 mm of precipitation relatively evenly over the year (NIWA Science 2007). Public beaches line the city's coastline, with swimming and fishing popular activities even in the central city.

External ecosystem impact is a key driver for urban GI. For example: Waterfront Auckland strives to "[m]aintain and improve water quality of the Waitemata Harbour through ongoing investment in stormwater initiatives, low-impact and water-sensitive design approaches and aquatic habitat restoration where applicable" (Waterfront Auckland 2012, p112). State-of-Environment 2013 "Report Cards" for Auckland's marine environments show poorest water and sediment quality in generally the regionally most densely populated and oldest neighborhoods (Auckland Council 2013c). The isthmus, which includes the central city, is noted as one of the poorest terrestrial environments with almost 90% urban landcover and only 3% native forest/scrub landcover (Auckland Council 2013a). Researchers have identified heavy metals and nitrogen as pollutants in stormwater runoff, contributing to adverse effects on the region's social, cultural, and economic value (Auckland Regional Council 2003; Boston Consulting Group 2004; Hauraki Gulf Forum 2011). CSOs cause public health concerns in isolated catchments, however alleviating overflow using only grey infrastructure is projected to cost NZ$800 million in a single area of the city (Watercare Services 2012).

Cultivated Ecosystem

A cohesive plan for Auckland-wide GI does not exist. The cultivated ecosystem will evolve as new areas are developed or redeveloped. Retrofits focus on neighborhood-scale or block-scale issues, rather than watershed management. Despite the recognized opportunities, policy documents do not deal with long-term GI management details.

5.3.3 GI development trajectory

Despite ecological indications of need for intervention, Auckland fits best within the contradictory stage of GI development. Evaluation of the social system suggests the mayor's vision and high-level plans for the city appears to strongly support GI. However, while some public agencies actively engage GI as forward-thinking best practice, other agencies appear unaware of GI's potential and associated benefits, or simply do not regard 'a green Auckland' as their mandate. The absence of financial or investment information in planning documents suggests tenuous commitment to GI since most are likely to be local, small-scale projects. Information on community involvement is also limited, as is private sector GI implementation. This information's fragmented nature indicates the piece-meal, experimental approach to GI currently characterizing Auckland.

6.0 Discussion

Typologies discussed in Section 2 approach GI from a variety of perspectives encompassing health, economic analysis, reporting and stock-taking, policy initiatives, and specific GI methodologies such as urban greenways and forests. Despite this diversity, each recognizes GI at the nexus of social and ecological forces. Additionally, each typology's motivation resides in believing such tools can support broader GI implementation. Despite this consensus, they insufficiently address fundamental patterns and processes underpinning GI formation and implementation.

While the authors identify the importance of social factors in creating the need and opportunity for GI, they frequently overlook or leave underdeveloped the most influential social forces determining GI (or any other) initiatives. Political power is undeniably central to any social process. Ahern (1995), the MEA (2005) and the EEA (2011) provide partial recognition of this fact, either incompletely or at a level of abstraction (i.e. global, continental) well above the needs of metropolitan decision makers. This is especially acute given a majority of GI efforts focused at the city and regional level.

The second social component severely underrepresented in existing typologies is economic factors including markets, land ownership, labor, and appropriation (value capture) regimes. Economic influences should be fundamental to any GI typology. While De Groot et al. (2002) acknowledges the importance of GI's economic dimension and Dunnett et al. (2002) the relevance of property ownership affecting GI, they discuss these factors in general terms without reference to specific market or appropriation regimes. GI benefits are frequently referred to in this manner, reflecting the supposition that infrastructure benefiting the general good should and will therefore be implemented. This rather naïve analysis ignores that existing metropolitan infrastructure serves specific constituencies and interests connected to specific property and appropriation regimes. To leave issues of political power and economic influence unspecified eliminates the possibility of an analysis that might develop a sophisticated strategy for mainstreaming urban GI.

The influence of ecological forces is also largely overlooked. Although some authors reference GI's ecological benefits, they rarely seek out the ecological setting and drivers of particular metropolitan GI systems. Typologies lacking specific, place-based understanding of these elements are of limited value for GI advocates seeking to understand and leverage vulnerabilities and opportunities of their metropolitan areas. Scale also contributes in this regard. As most GI implementation happens at the metropolitan or sub-metropolitan level, abstract global or continental typologies are difficult to translate into metropolitan *real-politik*. Including political and economic factors into GI typologies brings vulnerabilities and leverage points into clearer focus. The social and ecological drivers of federal and state water quality regulation and Hurricane Sandy are fundamental to understanding the rapid implementation trajectory of New York City's recent GI efforts. Equally important is the strong-mayor orientation of the city's governance regime that made GI an accepted component of New York's infrastructure options. Less developed ecological drivers and social governance structures helps identify the intermittent and contradictory nature of GI implementation in Auckland and San Antonio.

The combination of strong environmental regulation and mayoral leadership has also created public markets for widespread GI implementation in New York. The financial realities resulting from state interventions and mayoral vision have provided clear opportunities for reaping large-scale grey infrastructure avoidance costs that in turn contribute to extensive GI planning commitments in New York while those in Auckland and San Antonio lag behind. New York's regulatory and market opportunities generated clearly defined, measurable objectives and timelines in GI implementation while other cities' remain amorphous. By the same token, emergence of strong public sector markets for GI in New York outlines the embryonic level of private GI markets, offering GI advocates a target for expansion.

This type of analysis also highlights opportunities to shift Auckland's trajectory. Planning documents need a clear definition of "green Auckland" solidifying GI's place in Auckland's infrastructure planning. The city's institutional structure needs to identify specific responsibility for GI implementation and maintenance as Auckland's current governance fragmentation (namely through CCOs) precludes unified citywide planning.

External influences to Auckland's GI systems are more challenging to address. For example, the federal government's potential to seek increased density through allocating future housing areas and its proposed reforms to the RMA could, if not appropriately designed, undermine large-scale GI in Auckland. For Auckland to advance from a contradictory to general trajectory, the Auckland Council must contest constrains imposed by the central government's RMA reform proposals which fundamentally challenge achieving "a green city."

Similarly, San Antonio's private sector development model remains uncommitted to GI. In the CSMA case, this ambivalence has resulted in some retrenchment regarding GI. This is especially poignant in the wake of the recent drought that destroyed over 5 million urban trees in Texas. On the other hand, the public sector (SAWS) has shown moderate success in promoting and implementing some GI technologies for water quality and quantity protection. Advocates need to work on illustrating and institutionalizing specific and potential economic values generated by GI, connecting them to the city's future resiliency in the face of further ecological drivers such as drought cycles and climate change.

These are a few examples of strategic and tactical information that can be drawn from the typology we present in this paper. Hopefully its use lies in assisting communities to define and advance GI systems within the specific context of their communities. We offer it as a starting point toward developing the tools necessary to bring GI into the mainstream of metropolitan infrastructure. In doing so we hope to contribute toward establishing the living city as the centerpiece of modern urbanization.

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Development stage	Production unit dynamics
General development	Social and ecological production units making progress, by: ○ acquiring new means of production, ○ developing their operations, and ○ increasing their economic size and income
Unequal	Some units making progress more quickly than others
Contradictory	Some units progressing while others are regressing
In-crisis	Every type of production unit is in regression and tending toward disappearance

Table 1. Green infrastructure system development trajectory.

Table 2

Social system	**Ecological system**
Setting: Type of existing social system (e.g., regional government, municipal government, mayor/city manager, strong executive/weak executive, strong/weak neighborhood councils)	*Setting:* Type of existing ecological system: (e.g., desert biome, forest biome, etc.)
Drivers: Social components driving the GI system (*in situ* and external) (e.g., recent elections, social unrest, new state/federal regulations, fed/state/local policies, funding, community needs)	*Drivers:* Ecological components driving the GI system (*in situ* and external) (e.g., recent disturbance event [flood, drought, pest, fire, etc.], longer-tem ecological change [e.g. climate change], etc.)
Social production system: GI production units • Scale (building, block, neighborhood, city-wide, metropolitan region) • Means of production (e.g., street trees, green roofs, wetlands, swales, rain gardens, open grassland, permeable pavement, etc.) GI social configuration of labor • Social status of its labor (e.g., familial, wage, cooperative, volunteer, coerced [i.e. inmates]) • Status of property ownership (e.g., public, private, non-profit/community lands) • Mode of access to the land (owner occupied, permitted access to public lands, permitted access to private lands, illegal access to public or private lands) GI social configuration of decision-making • Hierarchical/decentralized • Community, private sector, and public sector roles • Institutionalized feedback loops for program recalibration	*Cultivated ecosystem:* • GI subparts (e.g., forests, meadows, gardens, etc.) • System (schedule and level of technology) of management, maintenance, and "harvesting" (capturing ecosystem services, e.g., potable water) • Connection/relation of cultivated ecosystem to "external" ecosystems (e. g., connects to greenbelt, natural riparian ways)
External relationships: Upstream (input) relationship analysis: • Funding • Policy • Labor (e.g., outside contract labor/consulting) Downstream relationship (output) analysis: • Consumption of ecosystem services (local/external) • Markets of ecosystem services (local/external/in-kind/none) • Appropriation of value from ecosystem services (centralized/decentralized, public/private, reinvested/expropriated)	*External relationships:* • Impact of ecosystem services on other green infrastructure/ecological systems

Table 2. Green infrastructure system typology.

Highlights

We derive an urban green infrastructure typology from a nexus of social and ecological forces.

Place-based ecology, political power and economic elements underpin planning to mainstream GI.

A city's GI development trajectory is described as *general, unequal, contradictory,* or *in-crisis*.

Applying the typology to NYC, San Antonio, and Auckland reveals city-scale planning opportunities.

The typology can be used to leverage vulnerabilities and opportunities within individual cities.