

What is green infrastructure? A study of definitions in US city planning

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In response to interdependent challenges, city planners are increasingly adopting “green infrastructure” (GI). Reviewing 122 plans from 20 US cities, we identify what types of city plans address and define GI, including the concepts associated with GI, as well as the types, functions, and benefits of GI. The most common plans that feature GI, some of which focus exclusively on GI, comply with US Clean Water Act regulations for stormwater and sewer systems. Municipalities also address GI through diverse planning processes, including the creation of comprehensive citywide plans. Many of these plans (~40%) do not explicitly define GI. When they do, stormwater concepts predominate, followed by landscape concepts, along with an emergent emphasis on integrating GI with other built infrastructure systems. Large differences in GI types, functions, and benefits across concepts, plan types, and cities indicate a need for synthesis of GI definitions. To facilitate this synthesis, we provide a database of GI definitions from plans used in our analysis. We conclude with a broad synthetic definition of GI to provide clarity and stimulate discussion in rapidly evolving planning, policy, and research arenas.

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In cities, a diverse array of urban challenges stem from the relationships between social forces, the built environment, and ecosystems (Pickett *et al.* 2001; McPhearson *et al.* 2016). Anthropogenic climate change (Steffen *et al.* 2018), rapid sea-level rise (Hinkel *et al.* 2018), and global toxification (Landrigan *et al.* 2018) all highlight the need to beneficially integrate social,

technological, and ecological systems for improved urban sustainability and resilience (Andersson *et al.* 2019). Green infrastructure (GI) has emerged as a primary tool to do so.

■ Defining GI in US city planning

For many ecologists, GI evokes a multi-scalar network of ecological elements providing multiple functions and benefits (Benedict and McMahon 2001). This landscape concept has roots in 19th-century landscape design and planning in the US, such as Frederick Olmsted park systems (Eisenman 2013; Rouse and Bunster-Ossa 2013), and other traditions of spatial planning in the UK and Europe (Grădinaru and Hersperger 2019). A landscape concept of GI continues to guide planning efforts to equitably provide high-quality green spaces (CNU 2000), manage environmental risks (Hodson and Marvin 2009), and improve urban public health (Tzoulas *et al.* 2007). In 2007, the US Environmental Protection Agency (EPA) formally defined GI as a set of stormwater control practices used to comply with Clean Water Act (CWA) regulations (EPA 2019). However, since the EPA has no formal regulatory authority over land use/land cover, CWA application of the GI concept is limited to specific control technologies, often referred to as “best management practices”. These hybrid stormwater control measures are engineered facilities operating across a “gray-green continuum” (Bell *et al.* 2018), and have widespread application within the US (McPhillips and Matsler 2018) and around the world (Mell and Clement 2019).

GI in the US and elsewhere embodies a paradox. On the one hand, GI’s roots embed a landscape-oriented concept in research and planning; on the other hand, GI is often focused only on stormwater management. Although the landscape

In a nutshell:

- City planning often fails to explicitly define “green infrastructure” (GI), but when it does, stormwater concepts of GI are much more prevalent than landscape or integrative concepts
- Types of GI vary widely and significantly, and often exclude parks and larger urban green spaces in favor of smaller engineered facilities
- Functions of GI are primarily hydrological, although more functional diversity is provided by landscape and integrative definitions of GI
- Stormwater concepts of GI appear to engage in green-washing by purportedly offering the greatest number of benefits despite circumscribing types and functions of GI
- Future research and planning should be informed by a new broad definition of GI, one that focuses on the relations between ecological and built infrastructure systems to facilitate the production of social benefits

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concept is *inclusive* of stormwater management, bounding GI as a stormwater management technology can *exclude* consideration of landscape ecosystem structure and function. In response, an integrated concept of GI is emerging, one that considers engineered infrastructures in the context of ecological networks (Szulczewska *et al.* 2017; Childers *et al.* 2019).

However, confusion persists regarding what GI is, exactly. Many analyses utilize implicit conceptualizations to examine how a collection of elements considered GI function within plans, without examining how the term itself is defined (eg Hansen *et al.* 2015; Mascarenhas *et al.* 2015; Cortinovis and Geneletti 2018). Others specify the term within specific plan types, such as “sustainability plans”, providing important but only partial insights (eg Benton-Short *et al.* 2019). Comprehensive analyses, such as Pauleit *et al.*'s (2019) synthesis of European urban GI practices, can improve the conceptual foundations of planning and research. Planning research on GI using implicit definitions or focusing on subsets of plans mirrors a larger fragmentation in academic research. A singular, standard, global definition of GI does not appear in the GI literature, with many authors using amorphous rather than explicit articulations. This lends GI a chameleon-like quality (Matsler *et al.* 2021), making its operationalization more a matter of social power than conceptual coherency, limiting the engagement between research and practice required to successfully implement a transformational planning concept (Wright 2011; Mell 2013; Meerow 2020).

Here, we provide (to the best of our knowledge) the first systematic review of what types of city plans in the US utilize and define the GI concept, and how they do so. Our primary objective was to examine the conceptual foundations of GI in US urban planning. In contrast to the qualities of systems (such as sustainability or resilience), defining GI as a system and examining its properties enables consideration of its boundaries and relationships to other systems (de Weck *et al.* 2011). Reviewing city plans allows exploration of how municipalities use GI to construct desirable futures, communicate political visions, comply with regulations, and coordinate public and private actors (Stemler 2001; Lyles and Stevens 2014). We analyze the types of plans that use the term “green infrastructure”, examine their definitions of GI, and present results of the diversity of types, functions, and benefits of GI across cities, plan types, and conceptual orientations. Finally, drawing upon these results, we offer a synthetic definition of GI to serve as a boundary concept (Star 2010), guiding a research and practice agenda to link the often-fragmented efforts of public, private, and community actors engaged in infrastructural work and urban greening.

■ Data and methods

City and plan selection

We selected 20 medium and large US cities broadly representative of US biomes, including recognized “leader cities”

in GI, such as Milwaukee, Philadelphia, Portland, and Seattle (Figure 1; WebTable 1; Hopkins *et al.* 2018). To identify plans addressing GI in each city, we first obtained current sustainability, climate, or comprehensive plans. Using keyword searches for the term “green infrastructure”, we identified plan sections containing the term and references to other city plans. Plans were screened to examine whether they were current plans authored or endorsed by city agencies. Our plan analysis excludes regional and metropolitan planning efforts, along with plans created without support from city governments.

Content and statistical analysis

Using the software package ATLAS.ti (v8.4.2) we abductively coded (Freise 2019) plans according to type; their definitions of GI; and the types, functions, and benefits of GI they describe. Plan types refer to the scope of the planning domain (Lyles and Stevens 2014). Definitions refer to strong declarative statements about GI, and were coded according to their conceptualization (following Szulczewska *et al.* 2017). GI types consist of nouns considered part of GI (Hansen *et al.* 2015; Bartesaghi-Koc *et al.* 2017). Functions refer to what GI does, often in order to provide benefits, which were defined as the larger impacts of GI as an infrastructure system (Conrad and Seitz 1994; Jones *et al.* 2016). Using these initial codes, we coded definitions as sentences, paragraphs, and in a few cases as plan subsections, and classified them with a single concept. Within definitions we identified types, functions, and benefits as individual text strings and coded them as classes, categories, and subcategories in a consensus-based process (WebTable 3; Friese 2019). Initial and final distributions of coded entities were visualized in R (package *ggplot2*; Wickham 2016).

Using Fisher's exact tests of independence for count data (R package *stats*; R Core Team 2018) and Goodman–Kruskal tau two-way categorical correlation tests (R package *GoodmanKruskal*; Pearson 2016), we also examined statistical independence and correlations between cities; plan types; and the concepts, types, functions, and benefits of GI. Correlation tests were also used to test for significance of relationships between select city characteristics, the number of plans examined, the proportion referring to GI, and the number of plans referring to GI (data are presented in WebTable 1).

■ Results

Plans referring to GI

Of the 303 documents screened, 122 met our inclusion criteria (WebFigure 1; WebTable 2). Plans containing the term GI were more recently published than those not containing the term (mean of ~2014 versus ~2012, Student's *t* test, $P < 0.001$). Plan types varied significantly in their likelihood of including the term “green infrastructure”. GI plans ($n = 9$) all contained the term, as did almost all combined sewer

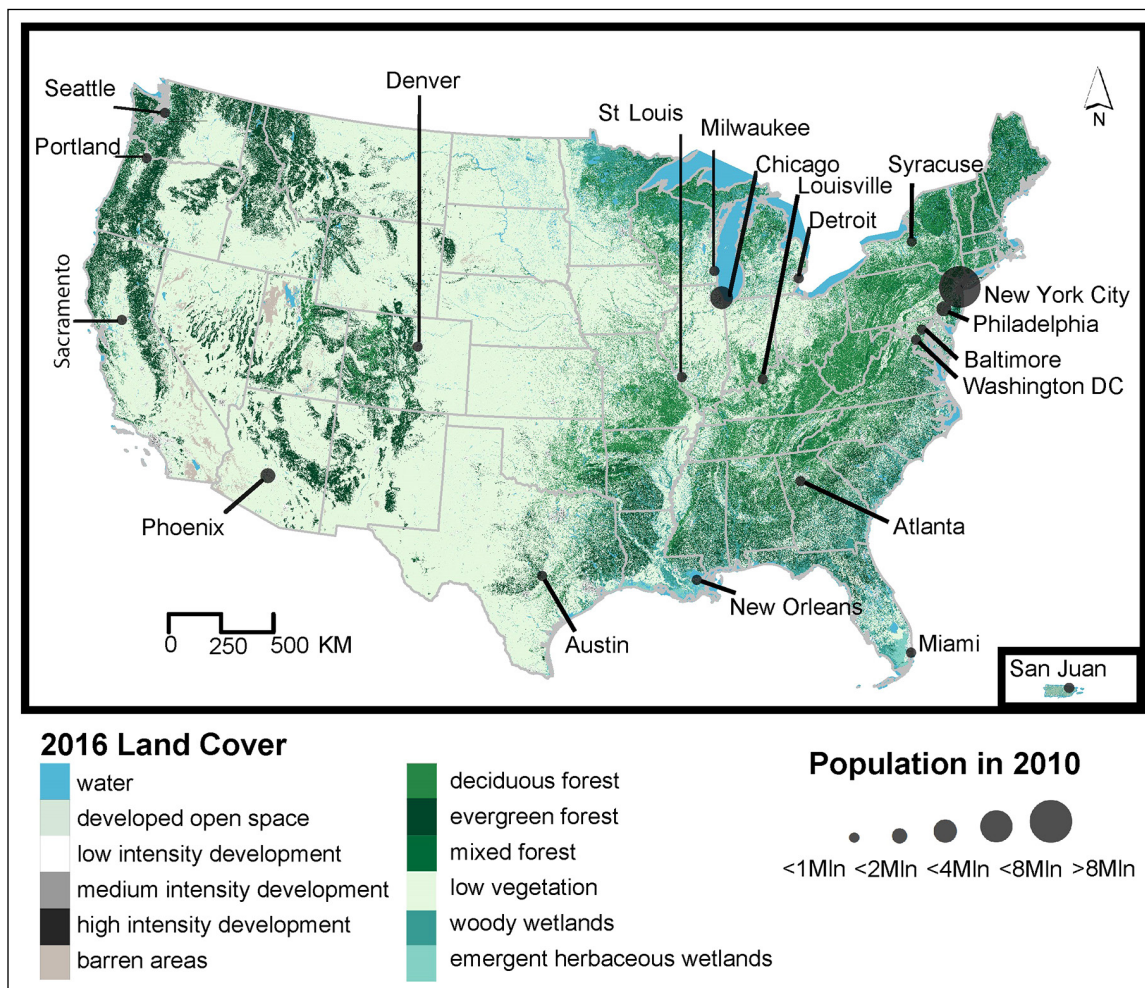


Figure 1. Study cities. Circles denote population size according to the 2010 US Census. Colors indicate land cover reclassified from the 2016 Multi-Resolution Land Characteristics National Land Cover dataset.

overflow (CSO) control plans (examined $n = 18$; 94%), followed by sustainability plans ($n = 11$; 82%) and comprehensive plans ($n = 24$; 75%). Despite finding a large number of references to neighborhood and area plans, only a small proportion of them used the specific term ($n = 54$; 31%).

Cities varied significantly in the percentage of plans referring to GI. In most cities, over 50% of screened plans referred to GI, with some, like Syracuse and Milwaukee, at 100%. The number of plans examined per city varied significantly (mean = 10.5, median = 7.5, standard deviation [SD] = 7.5), were non-normally distributed (Shapiro–Wilk test, $P > 0.1$), and were not significantly correlated with the percentage of plans referring to GI (Spearman's correlation, $P > 0.1$). We did not detect any significant correlations between the percentage of plans referring to GI and a wide range of ancillary city data such as land cover, population density, land area, and the number of plans referring to GI (WebTables 1 and 5). The overall number of plans screened in a city was significantly and positively correlated with total estimated population (as of 2018) (Spearman's $\rho = 0.58$, $P < 0.01$). Larger cities therefore appear to have more plans but do not utilize the GI concept more frequently within them.

Conceptualization of GI

GI remains poorly conceptualized in city planning, although diverse explicit definitions were found across plans (WebFigure 2 and WebTable 4). Over one-third of the examined plans failed to provide an explicit definition of GI ($n = 48$ of 122; 39%), and all cities had at least one plan that did not include a definition of GI. Plans defining GI contained 153 total unique GI definitions, with stormwater concepts most prevalent ($n = 90$; 59%), followed by landscape ($n = 26$; 17%), integrative ($n = 23$; 15%), and other ($n = 14$; 9%) concepts (Figure 2). Across all 74 plans containing definitions, 32 (43%) contained one definition and 42 (57%) contained multiple definitions. Plans with one definition were dominated by stormwater concepts ($n = 18$), with the remainder evenly split between landscape, other, and integrative concepts ($n = 5$, 5, and 4 respectively). Cities displayed varying levels of coherency in their conceptualization of GI. Although integrative concepts were most frequent in the 11 cities with multiple conceptualizations of GI in their plans ($n = 9$; 82%), the 9 cities with a single concept of GI across their plans predominantly

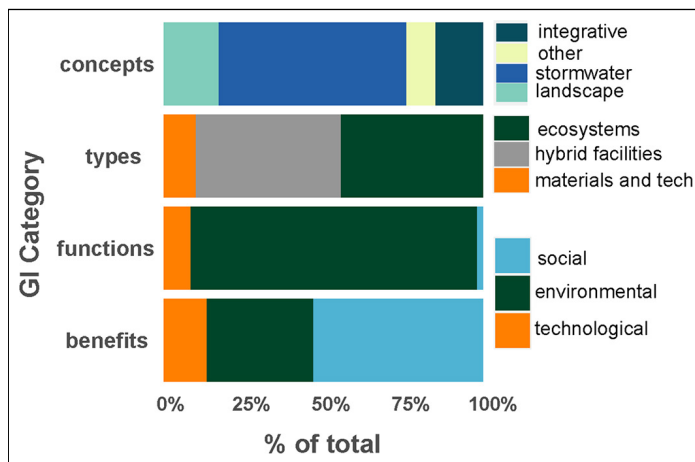


Figure 2. Summary of green infrastructure (GI) concepts, types, functions, and benefits. “Concepts” bar represents percentage of definitions utilizing each concept. “Types” bar displays percentage of all types categorized as ecosystems, hybrid facilities, and materials and tech. “Functions” bar displays percentage of all functions categorized as social, environmental, or technological. “Benefits” bar displays percentage of all benefits categorized as social, environmental, or technological.

focused on stormwater, followed by landscape and other concepts ($n = 5$, 2 , and 2 , respectively). Of the 42 plans containing multiple definitions, most utilized the same concept across definitions ($n = 25$; 60%), which were again dominated by stormwater concepts, followed by landscape, integrative, and other concepts ($n = 20$, 3 , 1 , and 1 , respectively). Of the 17 plans containing multiple conceptually different definitions of GI, most included an integrative concept ($n = 13$; 76%), with the remaining combining landscape, stormwater, and other concepts. With regard to plan types, comprehensive plans and watershed improvement plans had the most overall definitions, with the former favoring landscape concepts amidst an even distribution of integrative, stormwater, and other concepts, and the latter emphasizing stormwater concepts with some use of integrative and landscape concepts. Stormwater concepts were prevalent in CSO, green infrastructure, watershed restoration, sustainability, and water system plans, as well as area and neighborhood plans; landscape planning concepts were prevalent within open space and climate plans; and transportation plans had the most proportionally frequent use of integrative concepts, alongside stormwater and other concepts. Capital improvement plans did not define GI at all and were therefore excluded from further analysis (WebFigure 2).

Types of GI

Cities, plan types, and concepts varied widely and significantly in considering what counts as GI (Fisher’s exact test, $P < 0.05$; WebFigures 3 and 4). Across the 153 definitions, we coded 693 GI types comprising 286 unique text strings, reclassified to 26 categories fitting within three classes of ecosystem elements, hybrid facilities, and green

materials and technologies (Figures 2 and 3). The most commonly considered types of GI included trees (90% of cities), bioretention (75% of cities), “other stormwater facilities” (55%), blue–green corridors (60%), and green roofs (65%). Some cities had a very restricted set of types (such as San Juan, Louisville, and Detroit; $n = 2$, 2 , and 1 , respectively), whereas others described numerous elements (including Milwaukee, Austin, and Atlanta, which defined 20, 17, and 16 types of GI, respectively) (WebFigure 3). In general, cities with fewer definitions had fewer recognized types of GI, although Baltimore and Portland had an average number of types despite multiple definitions using different concepts. We also found wide variation in cities utilizing only a stormwater concept, such as New York having 16 distinct types of GI, in contrast to Syracuse, Philadelphia, and Detroit having five, four, and three, respectively.

Across plan types, comprehensive plans had the largest number of types ($n = 24$), followed by open space plans ($n = 20$). GI plans, watershed improvement plans, and sustainability plans were tied ($n = 18$ for each), closely followed by CSO plans ($n = 17$). Watershed restoration plans and water system plans had only four and one identified types of GI, respectively. Across concepts, integrative concepts contained almost the full range of types (omitting only parkways). Stormwater concepts completely omitted trails, farms, gardens, waterfronts, and parkways, and largely omitted parks. Landscape concepts omitted stormwater facilities, rain gardens, cisterns, soil, and rain barrels (WebFigure 4).

Functions of GI

GI functions largely pertain to GI’s role in the environment, dominated by hydrology; otherwise, functions varied significantly between plan types, cities, and concepts (Fisher’s exact test, $P < 0.05$). Our initial search for functions within GI definitions yielded 283 total and 225 unique text strings, which we recoded into three classes of social, environmental, and technological functions and into eight categories: hydrological, ecological, transportation, built environment performance, cultural, thermal regulation, air quality, and other. Given an overwhelming emphasis on hydrological functions (85% of cities), we also created subcategories pertaining to 12 different hydrological functions. Most cities included in the analysis specified three or more functions of GI, with 20% of cities including five or more functions in their definitions. Half of the examined cities focused on two or fewer functions within two or fewer concepts of GI, and one city (Detroit) had no functions described at all. No city addressed all nine major functional categories (WebFigure 5).

Plan types likewise varied significantly in the functions ascribed to GI (Figure 4). Hydrological functions were addressed across all plan types, with built environment performance, ecological functions, and air quality being present in the majority

of plans. Overall, comprehensive plans addressed the most functions ($n = 7$), followed by sustainability, neighborhood, watershed restoration, and climate plans ($n = 5$ for each). Across GI plans, four functions were addressed, namely hydrological, built environment performance, ecological, and thermal regulation. CSO, resilience, water system, and watershed improvement plans were the most limited in the functions described (WebFigure 6). Stormwater concept definitions were dominated by environmental (and largely hydrological) functions, while landscape and other definitions were more balanced between social, environmental, and technological functions. Integrative definitions of GI did not guarantee a multifunctional focus, as highlighted by Baltimore and Chicago, and in general more closely matched the functions described by stormwater rather than landscape concept definitions (Figures 2 and 3).

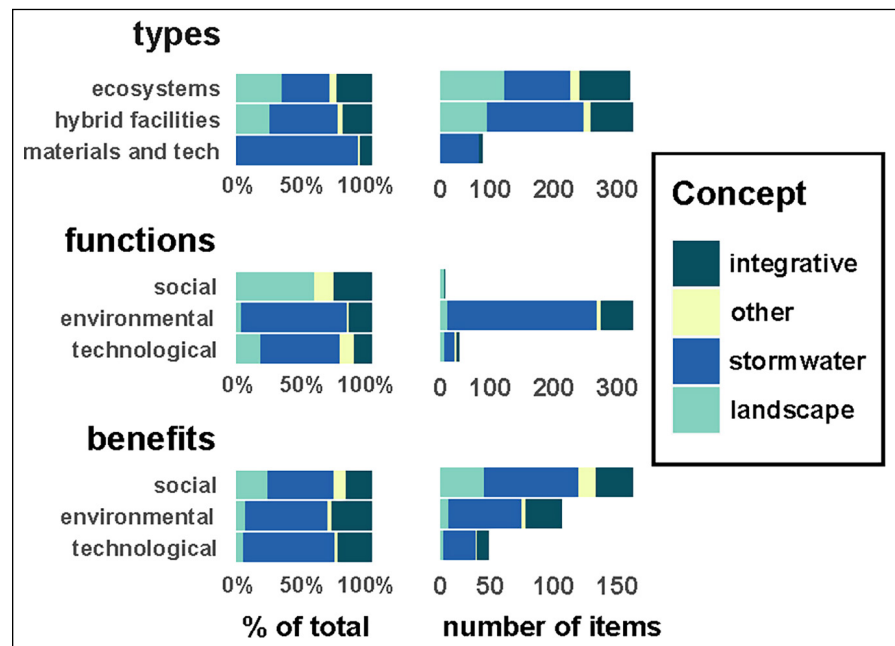


Figure 3. Proportional and absolute numbers of coded types, functions, and benefits, color-coded by GI concept. Left column represents percentages of each major class; right column presents absolute numbers within each major class.

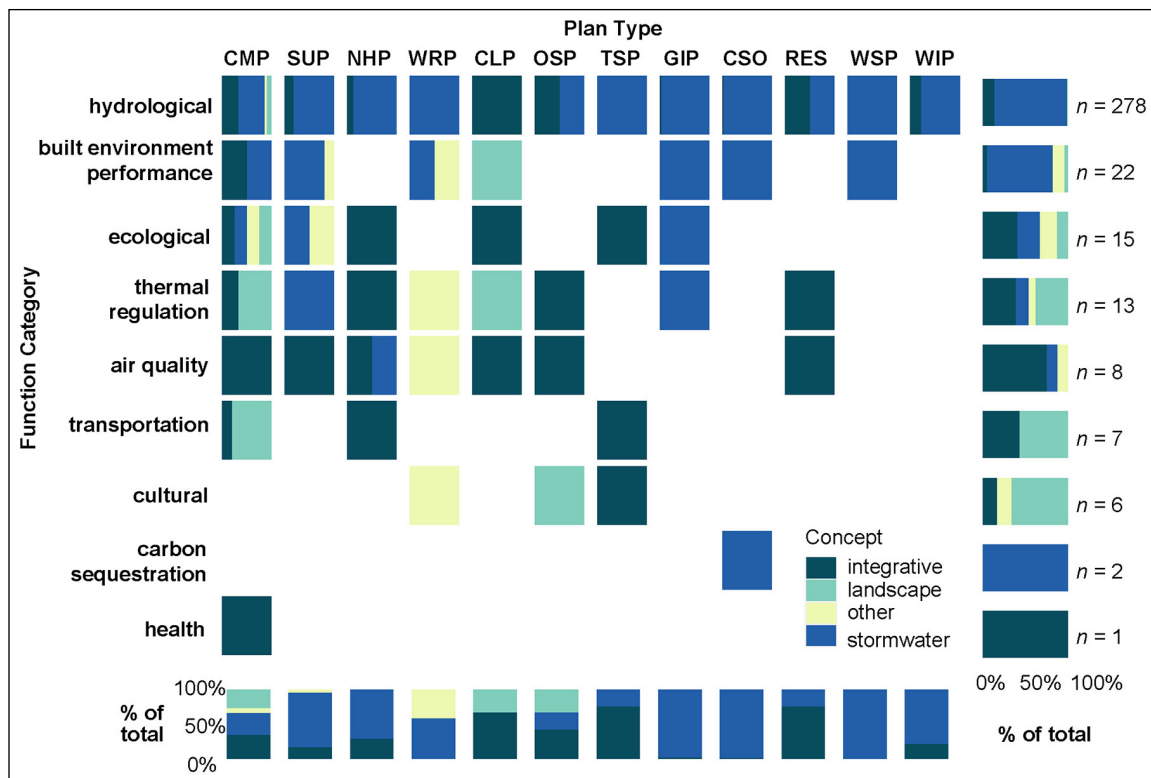


Figure 4. Function categories within GI definitions across plan types. Central grid displays proportion of each function category (rows) from definitions from each plan type (column) color-coded by concept of definitions containing the function. Right-side bar chart summarizes function classes by concept. Bottom bar chart summarizes functions from different concepts per plan type. Plan types ordered left to right by total number of unique function classes, functions ordered top to bottom based on absolute prevalence. Plan types: CMP = comprehensive/strategic plan, SUP = sustainability plan, NHP = area/neighborhood/master plan, WRP = watershed restoration plan, CLP = climate plan, OSP = open space/parks/tree plan, TSP = transportation plan, GIP = GI-specific plan, CSO = combined sewer overflow long-term control plan, RES = resilience and/or hazard mitigation plan, WSP = water system plan, WIP = municipal separated storm sewer (MS4) and total maximum daily load plans. Note: CIP (capital improvement plans) did not contain any GI functions and are not listed in this figure.

Benefits of GI

The benefits attributed to GI are predominantly social, although definitions focus on the environment more than built infrastructure (Figures 2 and 5). Benefits varied significantly across concepts, cities, and plan types (Fisher's exact test, $P < 0.05$; WebFigures 7 and 8). Initial coding yielded 259 unique strings of text coded into three classes, eight categories, and 49 subcategories of benefits. Across cities social benefits were the most common category, followed by environmental, economic, built environment, and ecological benefits. Atlanta covered all nine classes of GI benefits identified, followed closely by Milwaukee and New York. Benefits did not appear to be limited by concepts used by cities, although many cities had non-overlapping benefits from definitions with different concepts. Benefits were more evenly distributed between social, environmental, and technological classes in integrative and stormwater definitions, and more focused on social benefits in landscape and other definitions (Figure 3).

Examining benefits by subcategories, we found that water quality, recreation, health, livability, and property value were the most consistently defined, and were addressed by the majority of cities. Plan types were also characterized by significant variation in benefits. GI plans collectively had the most benefits attributed to GI, followed by comprehensive, CSO, and open space plans. Both water quality and property value are emphasized by stormwater concepts, as compared to recreation, health, and livability in landscape and integrative definitions. Some rare benefits highlight the specificity of definitions of GI, such as an emphasis on the cost of recovery from extreme events (Washington, DC), the creation of new

business opportunities (Miami), and broader goals of social revitalization (Atlanta). Many definitions of GI also have unspecified broad social, environmental, and economic benefits.

Statistical analysis of coded content

Correlation tests of coded content indicate that cities primarily drive what types of plans address GI and what concepts are utilized. Plan types also significantly correlate with conceptual orientations. While concepts do not drive what types of things are considered to constitute GI, specific types of GI are strongly related to concepts, indicating that rare types are associated with specific concepts. Variation between cities drives the variation in defined functions of GI, although plan types and concepts also appear to be significant. Benefits are much more dispersed, although subcategories of benefits are associated with specific cities, plan types, and concepts. These results indicate that city-level differences are the most powerful drivers of how GI is defined (WebTable 5). Statistical analysis supports our descriptive results, in that while there is a large degree of overlap between GI types, functions, and benefits among cities, plan types, and concepts, the content of GI definitions varies significantly across those categories of analysis.

Discussion

Toward a synthetic definition of GI

Plans broadly seek to integrate ecological and built infrastructures using diverse GI concepts. However, the divergence between stormwater and landscape concepts in US city planning exceeds the conceptual differences noted by Wright (2011), and suggests a much greater focus on the use of GI to satisfy stormwater regulations in the US than in the EU (Szulczewska *et al.* 2017). Conceptual differences carry over into differences between types, functions, and benefits, as defined by different plan types and cities. Plans with integrative GI concepts provide the most comprehensive coverage of different types of GI, as well as greater balance in functions and benefits than stormwater or landscape concepts alone. In particular, the prevalence of integrative concepts in comprehensive plans, in cities that have diverse conceptualizations across their plans, indicates that higher level planning can integrate diverse planning efforts within the city. The diversity of definitions present within plans suggests that GI as an applied planning concept has emerged as a boundary object integrating diverse conceptualizations and planning practices, and can be defined as follows:

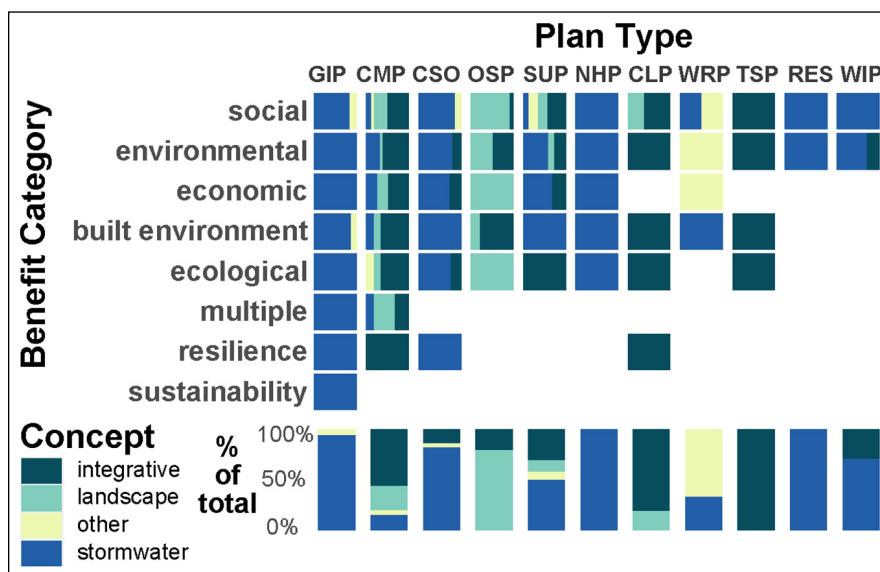


Figure 5. Benefit categories across plan types. Grid displays proportion of each benefit category present with definitions from each plan type. Plan types ordered left to right based on number of unique benefit categories; benefit categories ordered top to bottom based on overall prevalence across plans. Bottom bar chart summarizes conceptual orientation of definitions containing benefits for each plan type. Plan-type abbreviations are the same as those described in the Figure 4 caption, aside from the omission of Water System Plans (WSP), which did not specify any GI benefits.

Green infrastructure (GI) refers to a system of interconnected ecosystems, ecological–technological hybrids, and built infrastructures providing contextual social, environmental, and technological functions and benefits. As a planning concept, GI brings attention to how diverse types of urban ecosystems and built infrastructures function in relation to one another to meet socially negotiated goals.

Although broad, this synthetic definition offers a framework for consistently conceptualizing what GI is (eg GI types), what GI does (functions), and why we care (benefits), and as a boundary concept should facilitate rather than foreclose a more expansive discussion (Opdam *et al.* 2015). Applying this framework has the potential to transform the way that urban infrastructure systems are planned, designed, and implemented. These specific subsystems of GI can and should take many forms, such as including “green stormwater infrastructure”, “green transportation infrastructure”, and a general “greening of the built environment”. While we focus on institutional efforts (plans) here, in practice GI also includes a diverse array of citizen-led ecological and infrastructural interventions (Manuel-Navarrete *et al.* 2019).

Implications for planning and research

Numerous questions remain as to how GI will evolve in practice. Given the diversity of concepts in plans, what is the influence of different conceptual orientations on the implementation and outcomes of GI programs and policies? Given the diverse ecological, hybrid, and technological types identified here, how do they provide functions and benefits at different spatial and temporal scales? What trade-offs are persistent and how can they be addressed in system-level planning? What are the administrative hurdles and power dynamics at play in this type of integration? (Finewood *et al.* 2019). Given that these living and hybrid elements are affected by gray infrastructure systems and associated urban pollutants, more research is needed on the interactions between ecological and built infrastructures within urban systems (McPhearson *et al.* 2016). Given current dominance of hydrological concepts, GI planning and research may require an intervention from ecologists and landscape planners. While certainly supporting a wide variety of ecosystem processes and human activities (Boltz *et al.* 2019), hydrology is highly interdependent with other ecological processes such as soil building, nutrient cycling, and ecosystem engineering (Jones *et al.* 1994). Furthermore, GI does not operate only biophysically. By occupying space and changing the character of places, GI enables certain social interactions and prevents others. Diverse urban residents and non-humans will therefore differentially experience benefits of GI. Who or what entity sets the goals and priorities for a diverse array of GI programs

(Finewood *et al.* 2019)? How does GI play a role in reinforcing or addressing inequalities in amenities and hazards while addressing housing displacement (Gould and Lewis 2017)? What legacies of planning, governance, and development must be overcome for GI systems to evolve (Grabowski *et al.* 2017)?

Conclusion

Our analysis presents the most comprehensive examination of GI in US urban planning to date. Results indicate that many plans do not explicitly define GI, and when they do, they vary considerably, with some cities coordinating diverse plan types using integrative concepts. However, stormwater management dominates GI planning, causing confusion around the meaning of the term through the creation of the GI paradox. In response, and drawing upon emergent integrative concepts, a synthetic definition of GI is suggested to guide future research and planning. Future work should focus on the relationships between ecosystems, technological infrastructures, and society. Overall, we hope to stimulate a more inclusive and robust discussion and implementation of GI planning, policy, and practices, facilitating its use as a boundary concept for equitable urban greening.

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