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Review Article

A 'green' chameleon: Exploring the many disciplinary definitions, goals, and forms of "green infrastructure"

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HIGHLIGHTS

- We find geographic and disciplinary variation in conceptualizations of GI.
- GI is used as a greenspace planning, urban ecology, & stormwater management concept.
- Disciplinary GI literatures represent distinct scholarly communities.
- Not all GI is created equal and must not be assumed to provide all benefits.
- It is critical to clearly define GI, but studies often fail to do this.

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ABSTRACT

While the concept of green infrastructure (GI) is increasingly popular, definitions, terminology, and goals differ based on geographic and disciplinary context. This paper examines these differences through a three-part systematic review: 1) content analysis of academic GI review publications, 2) bibliometric review of academic publications focusing on GI and GI-associated terms, and 3) an online search for grey GI literature. Parsing out conceptualizations of GI, and the agendas they support, helps us better understand its probable outcomes in different contexts. We find that urban planning, urban forestry, ecology, engineering, landscape architecture, and law have epistemic claims to GI, and use divergent conceptualizations to implement the concept. Moreover, there are a number of related concepts, each of which is associated with a distinct scholarly community. These different conceptualizations and terms can be grouped into three primary categories: GI as 1) a greenspace planning concept, 2) an urban ecology concept, and 3) a water/stormwater management concept. Cutting across these categories we find the ecosystem services concept, a focus on specific engineered facility types, and a gradient of implicit GI definitions. A surprising number of publications (41% of those reviewed here) do not define GI, which can cause confusion or lead to implementation of GI projects that fail to meet expectations. We therefore argue that scholars and practitioners need to be explicit and specific about how they are defining GI and its purpose to avoid the siloing of research and practice and to take advantage of opportunities to address multiple agendas simultaneously.

1. Introduction

Green infrastructure (GI), while widely cited in both research and practice as a strategy for addressing environmental, socio-cultural, and economic challenges, remains a contested concept. Differing definitions and metrics across contexts can change the implementation and outcomes of GI (Meerow, 2020), and as with all environmental planning, dominant political discourse shapes the use of GI (Hansen et al., 2019). Variation in concepts and geography makes it difficult for GI practice to achieve consensus globally (Mell & Clement, 2019; Wright, 2011). The

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resulting ambiguity is a double-edged sword: it allows GI to adapt in response to localized needs because it is not grounded in a 'fixed ideal,' but it also can lead to confusion, unintended consequences, or unmet promises for GI installations. Because of varied meanings and applications, GI has been called a "boundary object" (Garmendia et al., 2016): a concept that is both flexible and robust, facilitating intersections across disciplinary divides (Star & Griesemer, 1989). However, emerging 'proto-boundary objects' can lack the coherence to function effectively across disciplines, often causing more confusion than clarity (Huck & Monstadt, 2019). It is unclear whether this is the case for GI.

What is clear is that GI has many manifestations. This chameleon quality jeopardizes the ability of GI advocates to deliver on promises of multi-benefit provision. GI today is promoted for its ability to provide and meet a vast array of services and goals: specific GI facilities can offer stormwater control as part of water management plans (Rouse & Bunster-Ossa, 2013); urban tree canopy can be counted as part of a GI network, bolstering street tree planting efforts (Norton et al., 2015); GI can be an urban renewal tool used to address issues of vacant land (Schilling & Logan, 2008); and GI facilities have been shown to provide mental health benefits (Jorgensen & Keenan, 2011), which can mitigate growing social unrest and anxiety in urban areas (South et al., 2018; Barton & Rogerson, 2017). Although GI may be promoted as a treatment for many ills, the services provided will vary by GI application type (e.g. green roof, bioswale, large forested park). In other words, the variation in how planners, arborists, ecologists, engineers, and landscape architects apply GI means that any given application *may not provide all desired services*.

Moreover, GI approaches differ significantly within and between geographical regions (Mell & Clement, 2019), highlighting the influence of policy drivers on the differentiation of multiple GI approaches and terms. In particular, a focus on decentralized stormwater management is prominent in GI planning in the United States (US) to meet the obligations of federal-level water management regulations (Grabowski et al., in press), while in Europe, GI planning is predominantly conceptualized around socio-economic functions of greenspace (Mell, 2016). Chinese GI planning, meanwhile, is focused on aesthetic improvement, real estate value, and the promotion of "sponge cities" to deliver the government's urban sustainability agenda (Li et al., 2017). According to Lindley et al. (2018), GI research in Africa uses many different frameworks. One study of GI in South Africa (Schäffler & Swilling, 2013) and a broader review across Sub-Saharan African nations (du Toit et al., 2018) both emphasize multiple ecosystem services and disservices.

Such variation in understanding of what GI *is* and *how* it should be planned is a prominent issue. This is especially pertinent as conflicting conceptualizations are used implicitly in distinct standardization efforts around the world; for example, the discussions by the UK government around creating a national GI standard conceptualizes GI as a broad network of greenspace (Jerome et al., 2019), while the development of the National Green Infrastructure Certification Program in the US to certify professional green infrastructure maintainers (NGICP, 2018) is focused on the conceptualization of GI as engineered stormwater control measures. These widely variable GI types make it challenging for scientists to assess GI performance as a whole (Venkataramanan et al., 2019; Meerow, Natarajan, & Krantz, 2021), complicating the creation of local and international standards.

Recent studies recognize the conceptual fuzziness of the term "green infrastructure". Efforts to more precisely define and categorize GI were explored by Koc et al. (2017) who address the geographical variation in GI definitions, implementation, and use of distinct disciplinary typologies. Wang and Banzhaf (2018: 760) highlight the "definitional creep" associated with GI, identifying the most prominent conceptual and practice-based elements of GI to frame the direction of the field going forward. Their research suggests that GI is not consistent between locations and researchers, and that the use and context of GI should be explored with a broad global review.

Depending on how GI is defined, it is often associated with other concepts, adding to the confusion. Escobedo et al. (2018) explore the intersection of GI and 'ecosystem services' (ES), 'nature-based solutions' (NBS), and 'urban forestry' in landscape planning disciplines. Their analysis illustrates the variability of geographical applications of GI terminology, i.e., the growing focus on NBS in Europe, but not in the US. When different terms are used for the same concept, it can lead to scholars acting like "ships in the night", exchanging knowledge in a limited and often contradictory fashion (Vogt, 2018:199).

In this paper, we seek to systematically examine both challenges: the multiple meanings of GI and the multiple terms that are related to these different GI conceptualizations. Our research objectives are to 1) examine how disciplinary and contextual influences shape the concept of GI, 2) examine how these influences and the conceptualizations of GI evolve over time, and 3) explore a possible consensus between conceptualization and practice of GI implementation.

Our overarching goal is to test our own stories and experienced trajectories of GI and better understand conceptual differences that may limit knowledge sharing or lead to persistent implementation roadblocks and unintended consequences. This is motivated by an observation by Mell (2016) and the authors of this paper: namely an initial grounding of GI in landscape planning principles of connectivity and delivery of multi-functionality, its subsequent ballooning into other disciplines and scales, and a current fragmenting into discrete articulations. For example, in the US, GI began as a broad planning concept from environmental conservation initiatives (Benedict & McMahon, 2002) but is now most commonly used to describe engineered stormwater management facilities (that may or may not be connected to GI's initial landscape planning principles) (Allen, 2012; Fletcher et al., 2015). Our analysis seeks to characterize the complexity and fragmentation of conceptualizations of GI today.

Our systematic, multi-method approach is distinct from previous reviews of GI and related concepts (Escobedo et al., 2018; Koc et al., 2017; Wang & Banzhaf, 2018). First, we begin with a review of other review papers as a way to encompass insights from as many studies as possible in our analysis and explore the ways authors across disciplines frame the concept of GI. In contrast to Koc et al. (2017), we include any review that that uses the term "green infrastructure" in the title, abstract, or keywords, even if it is not focused on conceptualization.

Second, we build on reviews like Escobedo et al. (2018) that examine the overlap of GI with alternative terms, but we identify terms used within our initial set of review papers, rather than choosing alternative terms *a priori*. We focus on a systematic methodology, rather than using our own expert knowledge to determine what 'counts' as GI-related research. Examining the academic scholarship on these alternative terms using bibliometric analyses allows us to document temporal and spatial patterns in GI research. We do this to challenge our own understanding of GI's development and evolution, and to locate potential alternatives to dominant narratives about what GI is and does.

Third, we compare how GI is understood in theory and practice by comparing academic conceptualizations of GI (from the review of reviews and bibliometric analyses) with those in the grey literature, identified through a series of geospatially specific Google searches.

We find significant variation in how GI is understood, with three distinct conceptualizations that focus on GI as 1) a greenspace planning concept, 2) an urban ecology concept, and 3) a water/stormwater management concept. Use of different terminology within and across these three categories in various disciplinary, geographic, and sociocultural contexts may lead to confusion and impede the sharing of GI knowledge. The varied specificity of type and purpose of GI in these disciplinary categories can dramatically influence its physical manifestation; therefore, for productive flexibility to remain, we argue that specificity must be communicated clearly and openly in research and implementation efforts.

2. Methods

We examine both academic and practitioner applications of GI (Fig. 1).

2.1. Review of reviews

To begin exploring the uses of the GI concept globally, we undertook a review of reviews accessing all 125 GI review papers published in the academic citation database Scopus through June 2018. Scopus, Web of Science, and Google Scholar are the three primary academic citation databases, but each have their strengths and weaknesses (Harzing & Alakangas, 2016). We used Scopus, rather than Web of Science because it yielded more results, which prior research (Harzing & Alakangas, 2016) suggests is a larger trend. We did not use Google Scholar because it does not have the same transparent quality filter as Web of Science and Scopus, nor does Google Scholar have the same features for filtering (e.g. to only include review papers) or bibliometric analysis (e.g. data downloading) that we needed for this study (Halevi et al., 2017). We nevertheless acknowledge that relevant papers may be missing from these databases, which systematically exclude books, non-peer reviewed literature, and underrepresent social science, arts, design, and humanities scholarship (Archambault & Lariviere, 2010). Despite Scopus filtering, after examining the abstracts, a number of papers were determined to be case studies rather than review papers and excluded. 75 papers (Appendix A) were subsequently categorized by discipline and GI definition.

We conducted a content analysis of each of these papers (Appendix A) following Friese's (2014) Computer Aided Qualitative Data AnalysiS (CAQDAS) techniques using ATLAS.ti software. Our codebook included extracting each paper's general definition of GI, the facility types (e.g. bioswale, parkland, etc.) discussed, and lists of co-benefits/goals of GI promoted by each paper. Additionally, this review identified alternative terms for GI or closely related concepts. A total of 13 alternative terms were identified that appeared in 5 or more of the review papers. These were then used to perform a bibliometric analysis of the wider GI literature (see Section 2.2).

2.2. Bibliometric review of the academic literature

Bibliometrics, or quantitative analyses of a body of literature, provide valuable insights into the structure and characteristics of a field (Ellegaard & Wallin, 2015). We conducted literature searches for GI and each of the 13 alternative terms identified by the review papers in the Web of Science citation database (see Table 1 and Appendix B for specific search terms). We focused here on Web of Science, rather than Scopus, for two reasons. First, Web of Science's historical coverage (pre-1996) has been shown to be better than Scopus (Harzing & Alakangas, 2016) and we were interested in evolution of the terms over time. Second, it is the preferred source for use with the Bibliometrix package in R (Aria & Cuccurullo, 2017). All Web of Science results for each term were analyzed using Bibliometrix to determine 1) the number of articles published each year between 1900 and 2018, 2) the top countries where first authors of publications are based, 3) the most published authors, 4) top keywords, 5) top journals, and 6) most cited papers.

2.3. Exploratory grey literature review

To review the grey literature as it relates to GI practice – something often excluded from other review papers – we conducted geospatially-specific Google searches. While a formal review of the grey literature is beyond the scope of our analysis, we are interested in characterizing how GI is understood in both theory and practice. Our goal in conducting an exploratory grey literature review was to learn what information about GI is available to practitioners in different locations (rather than conducting a synthesis of all the grey literature). We assume

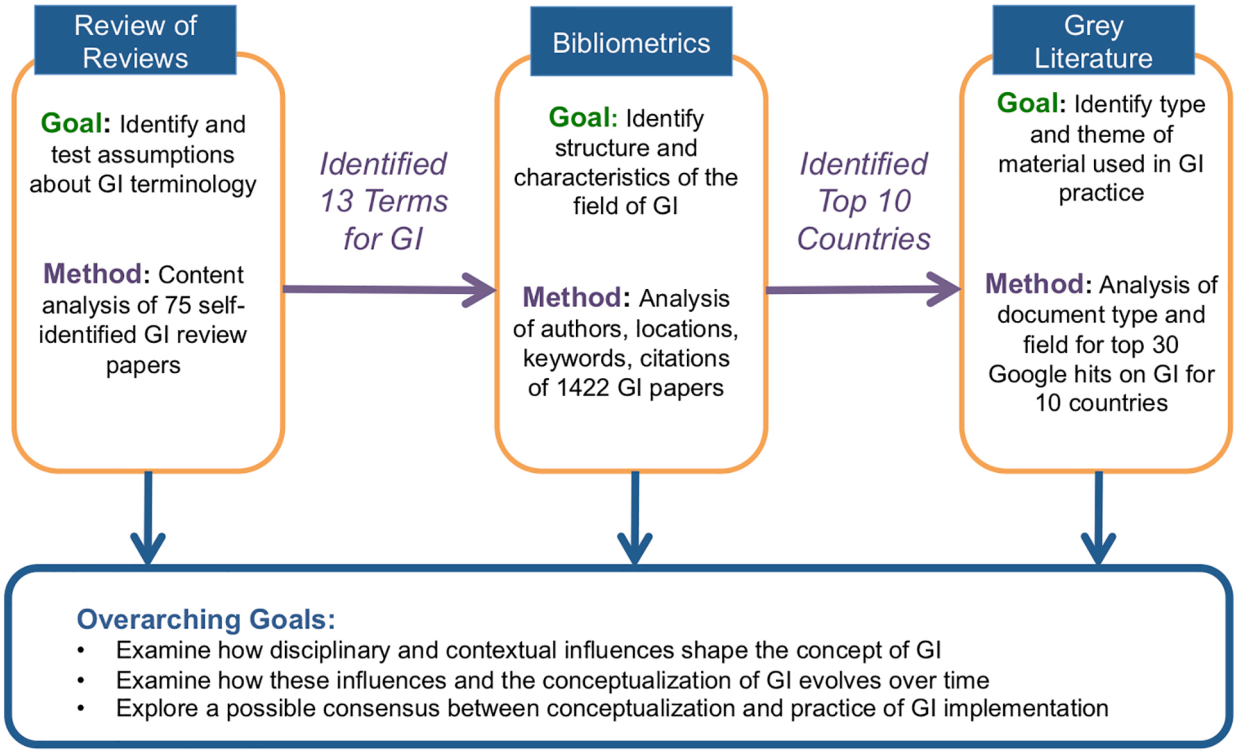

Fig. 1. Overview of methodological approach and goals of the literature analyses. Multiple sources of evidence were sequentially used to illustrate the evolution of the concept of GI in research and practice. Purple horizontal arrows indicate information from one phase of analysis informing the next phase of analysis. Information from each phase of analysis also contributed directly to the overarching goals of the study (blue vertical arrows). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Alternative GI terms from review of reviews.

Terms	# of review papers term was found in	# of citations in Web of Science database
Ecosystem services	57	26,127
Low impact development	19	665
Best management practice	13	3603
Blue-green infrastructure	11	50
Sponge city	10	103
Garden city	9	481
Greenway	9	368
Water sensitive urban design	9	161
Greenbelt	8	581
Sustainable urban drainage system	8	145
Nature-based solution	7	170
Urban forestry	7	535
Ecological infrastructure	5	100

that practitioners seeking information about GI will begin with internet searches, rather than searching the academic literature. Thus, the Google search analysis is expected to reflect the conceptualization of GI that practitioners draw from the grey literature. The top ten countries for lead authors of the GI academic literature identified in our bibliometric analysis (USA, Spain, The Netherlands, Canada, Germany, Sweden, China, Italy, Australia, and the UK) were used to populate ten different searches. For each, a 'local' Google search for "green infrastructure" was conducted by changing the location of the search in settings. The first twenty Google hits from each country were tabulated and reviewed to highlight the type of material being presented and how GI was conceptualized. Again, our approach tries to mimic how people use Google to find information and focuses on the top 20 hits, rather than a more exhaustive analysis. We recognize that Google search algorithms are not transparent and results change over time, but argue that a brief snapshot is informative. Websites were categorized as *policy, practice, academic, government,* or *commercial* to illustrate the variability of sectors engaged in the GI discourse.

3. Results

Combining quantitative bibliometric analysis of the academic literature on GI with a qualitative in-depth content analysis of review articles and online searches provides valuable insights regarding conceptualizations of GI as a practice, and its temporal and spatial evolution. Most notably, we identify three primary starting points for current GI work, each of which provides different, and somewhat contradictory, perspectives on GI implementation around the world.

3.1. Review of green infrastructure review papers

From 75 review papers (Appendix A) we identified common themes related to: 1) explicit and implicit GI definitions, 2) the frequency of use of the term, and 3) the GI facility types and/or services described. Specifically, we find overlapping perspectives of GI that reflect the different scales, functions, and designs of GI research. Three dominant categories of GI conceptualizations emerge from this review: GI as 1) a greenspace planning concept, 2) an urban ecology concept, and 3) a water management (primarily referring to stormwater management) concept, along with a fourth smaller category of GI as an engineering component of the built environment. Multiple definitions of GI are used within and across review papers in each of these categories (Fig. 2), including GI as a 'network of greenspaces' (often citing germinal work of Benedict and McMahon (2002)), GI as a synonym of Low Impact Development (LID) and other development terms, or GI implicitly as whatever facility the paper reviews (e.g. no definition is offered but the term 'GI' is used as a keyword in a paper discussing green roofs). This final grouping of papers essentially offers no definition of GI, suggesting that authors assume GI is a well-known and well-defined term.

Most papers did not review the concept of GI itself, but instead focused on a specific type or benefit of GI. For example, a sub-set of papers focused on parameters of a single facility type (e.g. green roofs, bioretention cells, or constructed wetlands; N = 17) or a single ecosystem service (e.g. biodiversity, mitigating urban heat island effect, or recreation; N = 21). Additionally, most papers did not offer explicit definitions of GI. For example, Hunter et al. (2014) and Medl et al. (2017) both examine green walls/green facades and only use GI as a synonym for their focal facility type. Others implicitly assume GI to be "greenspace" and do not speak to the connection between their focal facility type and this assumption. For example, Lorbek & Martinsen (2015) do not explicitly define GI, but use GI as a synonym of "vegetation." Some papers only list GI as a keyword, but do not employ it in the text. For example, Lopez-Ponnada et al. (2017) and Smith (2009) both provide extensive technical reviews of specific engineered GI, but only list the term GI in the keywords. The papers in this 'no definition/implicit definition of GI' category (N = 31) appear to assume the audience shares their definition.

Through the review of reviews we also identified 13 alternative terms for GI (Table 1). Ecosystem services (ES) is one of these, but it is unique in that it is not used as a synonym of GI in reviews that employ it (N = 24). Instead, ES is a common tool used to measure the performance

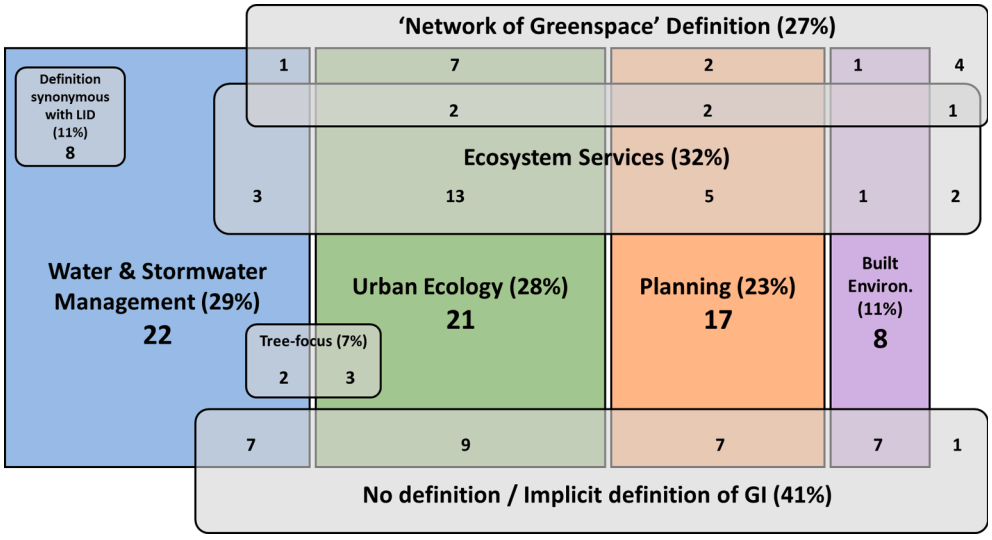

Fig. 2. Review of Reviews: count of GI review papers found across primary conceptualizations of GI and related concepts (7 of the 75 total review papers did not fit into these primary categories (colored boxes), but they are included in the subcategory counts (grey boxes)). Percentages refer to the number of papers in a category or subcategory (sum of an entire box) out of the 75 total papers reviewed. For example, 17 of the 75 review papers used GI as a Greenspace Planning concept (23%), and 2 of those papers also used the concept of Ecosystem Services and a 'Network' Definition of GI.

of GI and a majority of reviews employing ES use it this way, reviewing a single ES provided by GI in depth. For example, Schwarz et al. (2017) focuses on biodiversity; Hegetschweiler et al. (2017) focuses on cultural ES; and Russo et al. (2017) focuses on food production. A subset of these papers use ES in their definition of GI. For example, Lennon and Scott (2014) define GI as a way of "operationalising" ES, Duvall et al. (2018) as a way to "apply" ES to planning, and Shuster and Garmestani (2015) as a way to "enable" ES. This shows the importance of the concept of ES to GI generally; the two concepts are intertwined in the disciplines of ecology and urban planning (62% and 29% of review papers in each category using ES respectively). However, fewer stormwater management or built environment papers employed the ES concept (14% and 12% respectively).

Eight of the ES-focused review papers do not offer a definition of GI. For example, Derkzen et al (2015) only use the term "green infrastructure" as a keyword and once in passing. Instead, they use the term "urban green space" throughout the paper, implying that they view GI as all greenspace in a city. This paper uses a robust review to create useful metrics for specific bundles of ES from specific types of urban greenspace, a tool which could be quite useful for GI planning efforts. However, the types of urban greenspace analyzed are difficult to map onto common GI facility types used in practice in city planning and engineering, i.e. green roofs; this conceptual mismatch means their findings are less useful to the city planning efforts they wish to inform.

Few reviews address the history of the GI concept. The earliest references point to a local planning effort in 1994 (Basiago, 1996), Little's (1990) book, *Greenways for America* (Adegun, 2017), and "authors interested in landscape architecture" publishing in the 1980s (Basnou, 2015: 2). However, the source materials cited remain brief references to GI, lacking in definition and relying on other terms. Eight reviews cite Benedict and McMahon's (2002) definition as their own working definition and those that provide a history of GI see this as the beginning of the concept's coherence as a distinct entity in planning (for example, Allen (2012)).

The engineering and law reviews reviewed here rarely reflect these earlier origins of the GI concept, instead focusing more frequently on the US Environmental Protection Agency's (US EPA) stormwater-focused definition (officially endorsed by the agency in 2007). Indeed, nearly a third of all the papers reviewed explicitly or implicitly defined GI as synonymous with LID or other stormwater best management practices (BMPs). Most commonly, these papers paired GI with stormwater-focused terms. For example, Zhang and Chui (2018) use the compound term "LID-BMP-GI" throughout their paper. Many papers in this 'stormwater management' category did not go beyond an implicit understanding that GI was for stormwater management: Muerdter et al. (2018) refer to "stormwater management green infrastructure" without definition, and Tao et al. (2014) mention the US EPA's encouragement of GI to mitigate combined sewer overflows (CSOs). The importance of CSO regulation as a driver of GI development in the US is highlighted in law reviews by Holloway et al. (2014) and Subramanian (2016). A small proportion of papers recognize the geographical distinctions within stormwater interpretations of GI. For example, Shafique and Kim (2018) point out techniques similar to LID employed in Australia, UK, and China, although using alternative terms (i.e. WSUDS, SUDS, or Sponge Cities). Vogel et al. (2015) offer a unique perspective in this category by explicitly asserting the interdependence of the concept of GI with LID; they consider GI to have a broader, networked greenspace definition and conceptualize LID as one way to implement GI. Overall, the strong linkage between GI and stormwater management in recent review papers provides support to the history proposed by Mell (2016) and observed by the authors of this paper: that GI begins as a broad planning concept but has currently been narrowed (primarily in the US) to mean only engineered stormwater management (see Berland et al. (2017) and Allen (2012)). We examine these relationships further in section 4.

3.2. Bibliometric analysis of green infrastructure and alternative terms

Our Web of Science search for 'green infrastructure' literature identified 1,422 articles. Scholarly use of the term GI is relatively new, with over 50% of all studies published in 2017 and 2018 alone, and over 98% within the last ten years (Fig. 3). American researchers appear most prolific, with 446 of the studies led by a US-based researcher. The term is also widely used among researchers in the UK, whose researchers accounted for 125 of the studies. This may be partially explained by our focus on English-language publications. However, Chinese researchers led 96 articles, and Australian and Italian scholars both led 77 articles. GI research is clearly multidisciplinary: the most prolific individual authors include Per Angelstam and Marine Elbakidze, both Swedish experts in forest management, Stephan Pauleit, a German planning scholar, and William Shuster, a hydrologist formerly with the US EPA. The journals that contain the largest number of GI studies in the database are also multidisciplinary. The most common keywords associated with GI also point to the multiple functions and disciplinary perspectives on the topic. The two most highly cited studies both review the health benefits of GI, which they broadly define as natural or green spaces (Hartig et al., 2014; Tzoulas et al., 2007) (see Fig. 4).

Our review of reviews uncovered 13 concepts that are commonly associated with, or used interchangeably with GI (Table 1), and we examine the literature on each of these. Appendix C in the supplementary material shows the top 10 results for the countries where corresponding authors are based, the most prolific authors, top keywords, journals, and most cited papers for each of these alternative GI terms. The fact that we see limited overlap between terms suggests that these literatures are distinct, and these terms are associated with different scholarly communities. For example, 78 out of 103 (76.7%) articles on sponge cities are from China and 3 (2.9%) from the US, whereas 442 out of 1422 (31%) publications on GI are from the US and just 96 (6.8%) are from China. Additionally, we can see that the relative frequency with which these terms are used in the literature changes over time (Fig. 5). For example, use of the term greenways has fluctuated over the past 50 years in academic scholarship, whereas research on ES has rapidly increased in the last decade.

3.3. Green infrastructure in the online grey literature

Similar to the academic literature, the grey literature on GI (as identified here through Google searches) is diverse and refers to different definitions, functions, and facility types. These include stormwater management, urban ecology, and greenspace planning conceptualizations, suggesting that the variation we found in research extends into practice.

A number of common organizations appear in internet searches for "green infrastructure" from multiple countries. For example, European Commission (EC) and European Environment Agency (EEA) definitions and GI program pages were found in all countries searched except Canada, and the US EPA's "What is Green Infrastructure?" webpage appeared in all countries' top hits except for Sweden, China, and the UK. Likewise, American Rivers, an environmental non-profit in the US, was found on all the top-20 lists except for Spain, China, and Italy.

The European Union (EU), a supranational governmental organization comprising 27 member states that sets legislation at a pan-regional level, references a combined greenspace planning and urban ecology definition of GI as "a strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services…" (EEA, 2017), whereas the US EPA, an executive agency of the US federal government, defines GI explicitly as a stormwater management technique: "a cost-effective, resilient approach to managing wet weather impacts that provides many community benefits…" (EPA, 2015). American Rivers, an environmental non-profit organization, presents a definition that is narrowly-focused on water management like the EPA, but offers a much

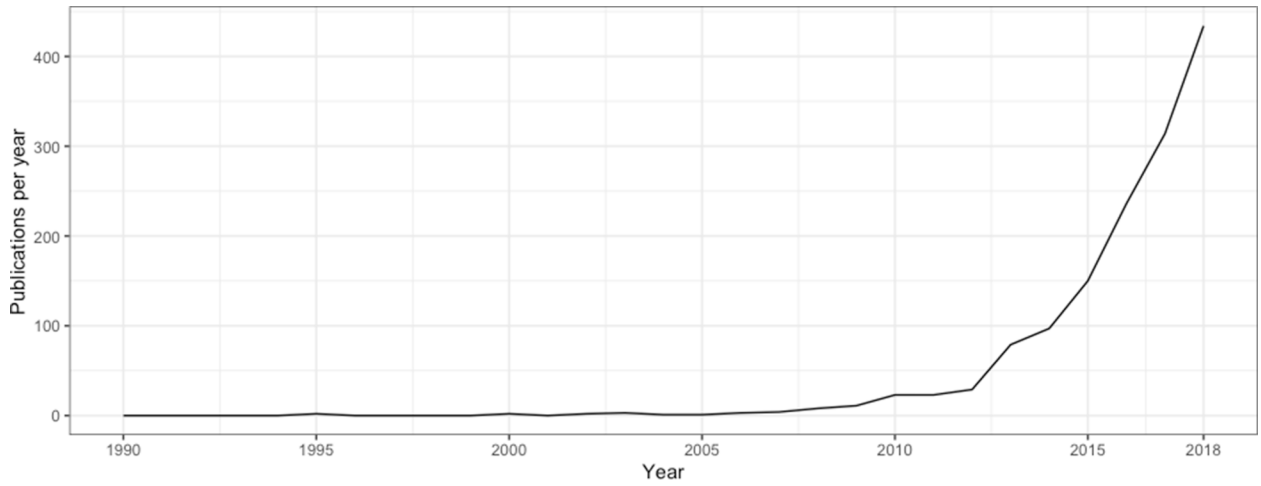

Fig. 3. Green infrastructure publications in Web of Science 1990–2018, by year of publication. There were no publications prior to 1990.

Green Infrastructure

Top Countries	Most Prolific Authors	Top Keywords
1. United States	1. Angelstam, P	1. Green Infrastructure
2. United Kingdom	2. Elbakidze, M	2. Ecosystem Services
3. China	3. Pauleit, S	3. Urban Planning
4. Australia	4. Shuster, WD	4. Climate Change
5. Italy	5. Montalto, F	5. Sustainability
6. Sweden	6. Jim, CY	6. Stormwater Management
7. Germany	7. Haase, D	7. Stormwater
8. Canada	8. Kowarik, I	8. Urbanization
9. Spain	9. Manton, M	9. Biodiversity
10.Netherlands	10.Andersson, E	10.Low Impact Development

Top Journals	Most Highly Cited Papers
1. Urban Forestry & Urban Greening	1. Tzoulas K, 2007, Landscape Urban Plan
2. Landscape And Urban Planning	2. Hartig T, 2014, Annu Rev Publ Health
3. Sustainability	3. Gomez-Baggethun E, 2013, Ecol Econ
4. Science Of The Total Environment	4. Pataki DE, 2011, Front Ecol Environ
5. Water	5. Fletcher TD, 2015, Urban Water J
6. Land Use Policy	6. Schilling J, 2008, J Am Plann Assoc
7. Ecological Engineering	7. Norton BA, 2015, Landscape Urban Plan
8. Ecosystem Services	8. Cameron RWF, 2012, Urban For Urban Gree
9. Urban Ecosystems	9. Pugh Tam, 2012, Environ Sci Technol
10.Ecological Indicators	10.Lovell ST, 2013, Landscape Ecol

Fig. 4. Summary of the green infrastructure academic literature in Web of Science: Clockwise from upper left the boxes show the top ten: 1) most frequent countries where corresponding authors of GI studies are based, 2) authors with the most GI studies, 3) most frequently used keywords for GI studies, 4) most frequent journals where GI research is published, and 5) most highly cited publications on GI in the Web of Science database.

wider definition of facilities that includes restoration and conservation techniques more reminiscent of the European definition:

"Green infrastructure … means planting trees and restoring wetlands, rather than building a costly new water treatment plant. It means choosing water efficiency instead of building a new water supply dam…" (American Rivers, 2017)

Some organizations acknowledge the confusion in definitions of GI. For example, the EU's Interreg group's GI website lists no less than 8 different definitions, noting: "Because of its multifunctional character, Green Infrastructure (GI) has been defined in numerous ways…" (Interreg, 2013, a strategic investment fund supported by the European Commission's Regional Development Fund).

In terms of geographical differences, the US was unique in returning several sewer utilities' websites, which supports the existence of strong links between GI, the Clean Water Act (1972), and federal funding in the US; this is a process not visible in other nations where utilities companies do not readily contribute to GI investment. This reinforces the finding from the review papers that stormwater management conceptualizations are particularly influential in US GI work. Sweden was unique in that its first page of hits contained all Swedish organizations, rather than American Rivers, EU, and US EPA websites, potentially indicating a distinct national vision of GI. The least overlap of websites with other countries was found in China; many of the webpages were academic papers by Chinese authors that tended to adopt a broader greenspace planning conceptualization of GI. However, we recognize that Google is restricted in China and therefore the search we conducted is likely not representative of how the concept of GI is displayed online within the country.

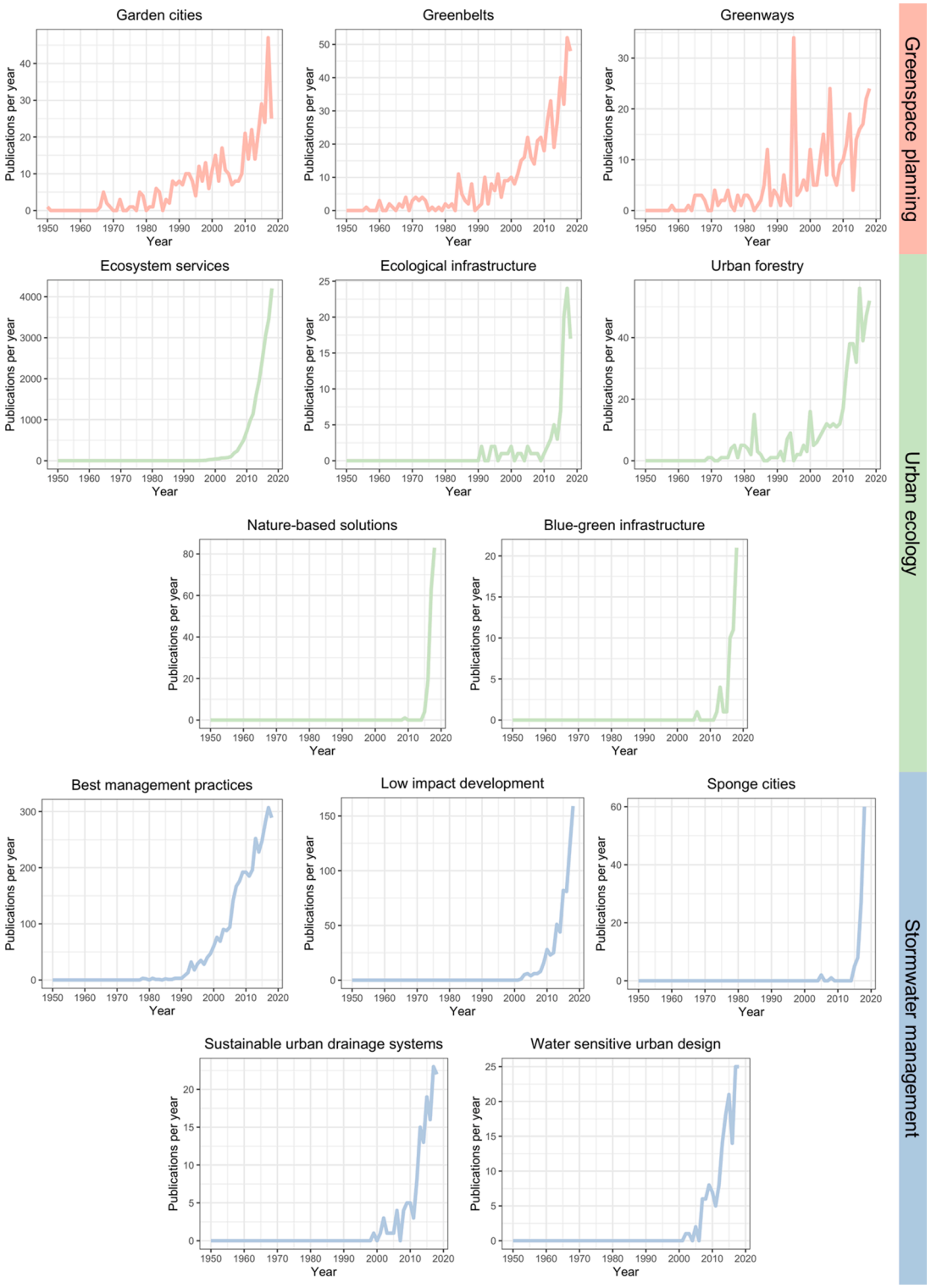

Fig. 5. Number of publications in Web of Science for 13 alternative GI terms, by year of publication. Note: Vertical scales differ by term to highlight variation over time for each term.

4. Historical and contemporary influences on GI

Drawing on bibliometric analyses, we explore the academic literatures for the 13 alternative GI terms (Table 1) to better understand the influences on the concept of GI across time and space (Figs. 5, 6, and Appendix C in the supplementary material). When examining these literatures, we identify that they fit into the same three overarching categories as the reviews: greenspace planning, *sensu lato*; urban ecology concepts that bring a nature-based perspective to GI; and practical/policy-led stormwater management concepts. The built environment (a fourth category that was less predominant in the review of review articles) did not emerge as a significant category for the alternative GI terms, reflecting the relative dominance of water-related conceptions of GI across the engineering literature found in this study.

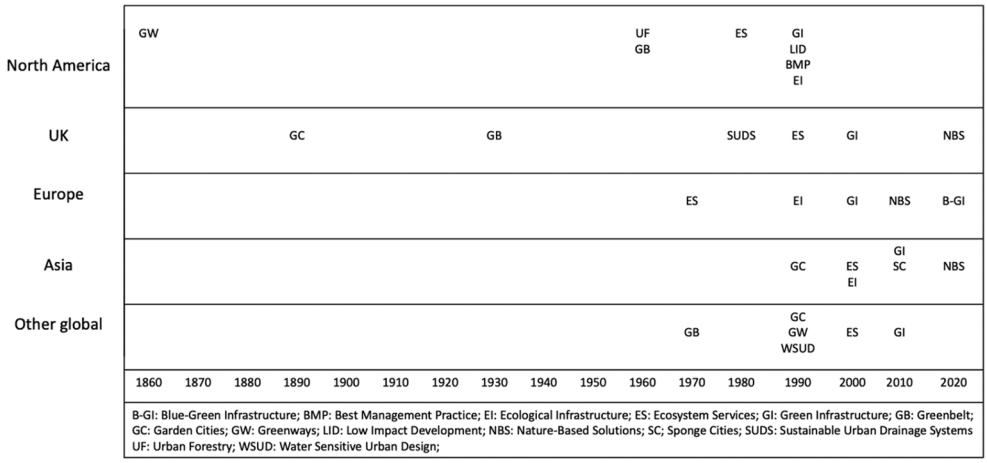

Fig. 6. The spatial and temporal evolution of alternative GI terms.

Fig. 6 lists the geographic and temporal evolution of the alternative terms found in review papers. In combination with the results of the bibliometric analysis, Fig. 6 highlights the fact that discussions of GI and related concepts in the academic literature have expanded in the late twentieth and early twenty-first century. As Mell (2016) notes, this reflects an increasing robustness of the evidence base supporting GI discussions and growing prominence within policy/practice worldwide. In addition, there is a growing set of localized terminology being used in some regions of the world, i.e. Forest Cities in China, which are adapting GI to local context using new terminology.

In the following paragraphs we explain how the 13 alternative GI terms fit into the three main conceptual categories first identified in the review of reviews, drawing on our bibliographic analysis (Figs. 5, 6, and Appendix C). We also show how research on conceptually similar terms can have very distinct geographies, with implications for the sharing of GI knowledge.

4.1. Greenspace planning concepts

Garden cities, greenbelts, and greenways are all primarily planning or city design approaches for integrating nature into the city. They are often analyzed at large scales (e.g. city-wide), rather than being site-specific, and tend to represent an understanding of how natural areas fit into the overall spatial pattern of the landscape. These concepts represent early efforts to employ nature to improve the quality of cities, and modern GI and related concepts build off these ideas.

Garden cities appear to be the oldest of the alternative GI terms. The first publication in the Web of Science database is from 1906 (Fig. 5), although the concept is usually traced back to Ebenezer Howard's *Tomorrow: A peaceful path to real reform* (Howard, 1898), which proposed a new form of city design in response to public health and poverty concerns in the UK. The fact that garden cities is related to urban planning is clearly evidenced by associated keywords, which include "urban planning", "regional planning", and "town planning" as well as journals including *Planning Perspectives* and *Architectural Review*. Greenbelts are another established planning concept, whose use in academic literature has ebbed and flowed over the last century (Fig. 5). Rings of open space were commonly built around European cities prior to the 19th century (Kühn, 2003), and more recently greenbelts have been seen as a way to control urban growth through the provision of protective boundaries composed of open space, agricultural land, and water (Sturzaker & Mell, 2017). The concept appears most commonly used by US researchers, followed by those based in China, India, Canada, and the UK. Greenways, which typically refer to linear corridors of undeveloped land within urban areas, emerged in the US and were famously promoted by Frederick Law Olmsted as a way to make nature accessible to urban populations (Fábos, 2004). A classic exemplar of a greenway in the US is the Olmsted-designed 'Emerald Necklace' in Boston, but there are now many international examples (Fábos & Ryan, 2004), from Italy (Scudo, 2006) to China (Lui et al., 2019).

4.2. Urban ecology concepts

ES, ecological infrastructure, urban forestry, and NBS are categorized here as concepts that focus on ecological benefits and systems. This group of terms shows how conceptualizations of GI as a multifunctional network of vegetation in the city are still common and support the use of "nature" as an important tool in the management of urban areas.

Of all the alternative GI terms, ES had the largest number of publications, over 21,000, with the most prolific countries being the US, UK, and China. This is unsurprising as the concept is broader in scope than other alternative GI terms, referring to a wide range of benefits humans receive from ecosystems. This is evidenced by the fact that ES is a common keyword for many of the alternative GI terms, but the top keywords for ES are broader concepts like biodiversity, conservation, and sustainability. The term rose to prominence in the mid-2000s following the publication of the Millennium Ecosystem Assessment, which introduced an influential framework for understanding the relationship between humans and ecosystems, categorizing benefits into provisioning, supporting, regulating, and cultural services (Carpenter et al., 2009). Recent scholarship also identifies ecosystem *disservices*, or ecological outcomes viewed as dangerous or undesirable (Lyytimäki et al., 2008).

The second term, 'NBS,' has only really emerged in the last decade (85% of all NBS studies published since 2016) and is most commonly used in Europe, with authors being most commonly from Italy, the UK, and Sweden. NBS are explicitly focused on the provision of 'nature' or ecological resources within urban areas, and NBS research is being heavily invested in as part of the European Union's Horizon 2020 initiative (European Commission, 2015; Raymond et al., 2017).

Ecological infrastructure is another inclusive term that according to the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2019) includes "the natural or semi-natural structural elements of ecosystems and landscapes that are important in delivering ecosystem services." IPBES even notes in their definition that it is "similar to green infrastructure"; the latter being more urban. Like many terms, the number of publications using ecological infrastructure have been increasing in recent years, with over 60% of all publications being released between 2016 and 2018, especially in China, South Africa, and the US. The top keywords (e.g. "ecosystem services", "natural capital", and "biodiversity") confirm that ecological infrastructure is associated with multiple environmental benefits.

Blue-Green Infrastructure is a newer variant of the GI concept specifically focusing on water features – and in the case of the most highly-cited study in this dataset – agricultural production (Barthel & Isendahl, 2013). This still relatively small literature (N = 50) is also dominated by European scholars, with the top countries of leading authors being the UK, Italy, and Sweden.

Unlike the other terms in this category, urban forestry is not a new concept, and indeed the bibliometric analysis reveals publications from the 1960s onwards. Its use in the academic literature fluctuates over time, with less of an exponential increase in recent years than other alternative terms. Research on urban forestry appears to be led by North American scholars, with US and Canadian researchers accounting for over 40% of the total. Konijnendijk et al. (2006:93) define urban forestry as "the art, science and technology of managing trees and forest resources in and around urban community ecosystems for the physiological, sociological, economic, and aesthetic benefits trees provide society." The literature suggests that urban forestry is closely related to GI, which is one of the top keywords in the dataset, but the focus is not necessarily on stormwater. As a consequence, urban forestry is instead connected to keywords such as "carbon sequestration" and "climate change", or broader concepts such as "urban ecology", and "sustainability".

4.3. Water and stormwater management concepts

BMPs, LID, sponge cities, sustainable urban drainage systems (SUDS), and water sensitive urban design (WSUD) are all closely associated with GI, but specifically refer to GI as an alternative approach to stormwater management that engineers systems to mimic natural processes. As evidence of this focus, the top journal for all five terms has the word "water" in the title. This category shows that scholarly communities have emerged in different countries (e.g. US, UK, Australia, China) around a narrower conceptualization of GI.

BMPs broadly refer to techniques that reduce water pollution, which is evidenced by top keywords including "water quality," "nonpoint source pollution," and "phosphorus." Much of the research focuses on techniques for agricultural management (e.g. Prokopy et al., 2008), but a subset of the BMP literature specifically focuses on managing stormwater, or stormwater BMPs, and in these cases the term may be used interchangeably with GI or LID. BMPs, which include both structural (e.g. physical construction, plantings) and nonstructural practices (e.g. policy development, cultural changes), seem to be a largely North American concept. US researchers dominate, representing nearly 60% of all studies, with Canadian studies coming in second at 7%. Compared to GI, the number of publications on BMPs increased in the early 2000 s and remained relatively steady over the last ten years.

LID was first developed in Maryland (USA) to manage excess stormwater runoff from expanding impervious surfaces associated with urban growth (Tzoulas et al., 2007), and its use has increased over the last ten years. LID designs focus on maintaining pre-development hydrology, for example by clustering development and adding bioretention gardens (Dietz, 2007). This stormwater focus is apparent in the keywords most frequently used in LID research, such as "stormwater management", "bioretention", "infiltration", and "SWMM", the latter being the US EPA's Stormwater Management Model. LID remains most widely used among US researchers, with 45% of all studies in the dataset led by US-based scholars. China accounts for a further 20%; European researchers seem to engage less frequently with the concept.

SUDS appears to be primarily the UK's, and to a lesser extent other European countries', answer to LID. UK researchers led more than a third of all SUDS publications in the dataset. Like LID in the US, the SUDS concept was developed to address stormwater management problems resulting largely from urban runoff, and it is now mandated by law in much of the UK (Fletcher et al., 2015). The goal is to mimic natural drainage systems, with the assumption that this will be more sustainable (Davies et al., 2006). Like LID, the keywords for SUDS (e.g. "urban drainage", "clogging", and "stormwater management") demonstrate that it is more narrowly defined as a water management approach. Both terms are also commonly associated with GI since it is one of the most common keywords in the SUDS literature.

Water sensitive urban design (WSUD) is similar to SUDS and LID, but dominated by Australian researchers. More than 60% of all publications in this dataset are Australian. According to Fletcher et al. (2015) the concept was first developed in Australia in the 1990s, although the first publication in our dataset is from 2002, with most being published in the last decade. Whereas SUDS' focus is on urban drainage and stormwater management, WSUD can include water conservation and harvesting (Wong & Brown, 2009). This may explain why "integrated urban water management" is a keyword, although in practice it is often stormwater focused (Fletcher et al., 2015). For example, "stormwater" and "stormwater management" are two of the most common keywords in the dataset. Like SUDS, "green infrastructure" is a commonly associated keywords, as is "low impact development".

While most of the examined concepts developed primarily within Europe or North America and have been subsequently applied in other parts of the world, sponge cities seems have originated in Asia. This is clearly evidenced by the fact that 78 (75%) of all the sponge city publications are authored by Chinese researchers, with the next country being the Netherlands with just 4 studies. Sponge cities are debated in China as a mechanism to address urban flooding, air pollution, and climate change (Li et al., 2017). The concept is evolving as developers, designers, and planners attempt to integrate GI or LID (both top keywords in the dataset) approaches to stormwater management into developments (Jia et al., 2017).

5. Discussion

5.1. Green infrastructure: One concept, multiple meanings

Our review of the academic and grey literature confirms that GI conceptualizations remain inconsistent across disciplines and continue to evolve. We find that current understandings of GI, as well as alternative terms, can be grouped into three primary categories, which we describe as *greenspace planning*, *urban ecology*, and *water/stormwater management* conceptualizations. It is important to parse out these conceptual differences because each can lead to dramatically different implementation and benefit provision; this occurs because each of these conceptualizations focuses on a different scale, emphasizes different functions, privileges certain disciplines or research methodologies, includes and excludes different types of installations, and ultimately leads to different success metrics for implementation.

We find those that frame GI as a *greenspace planning* concept broadly discuss the overall spatial patterns in which greenspaces are woven into urban areas – e.g. through ribbons of greenways or encircled by a greenbelt – to provide various social and environmental benefits. An *urban ecology* conceptualization of GI focuses on the science of ecology, or description and analysis of ecological functions and the ES provided by different types of natural systems in urban contexts. Within greenspace planning and urban ecology conceptualizations, GI is often defined broadly as a network of vegetated land or open space. Those that ascribe to the *water/stormwater management* concept tend to define it more narrowly, often focusing on site-level designs that improve hydrological functions, some of which might not even include vegetation (e.g. permeable pavement). Each of these is a distinct vision of GI, which is not necessarily encompassing of the other two.

The breadth of conceptualizations for GI is not a problem in and of itself, but it does have important implications for GI implementation. On the one hand, it can work as a bridging concept to promote greater interdisciplinary collaboration, for example between hydrologists, engineers, ecologists, decision-makers, and planners regarding stormwater management (Mell & Clement, 2019). Such variation may enable GI to be considered in greater depth by researchers who have not traditionally

engaged in greenspace discourses. Unfortunately, a lack of consensus reinforces disciplinary divides and creates blind spots in implementation efforts; fragmented definitions of GI limit its use and integration into wider service delivery efforts (Matsler et al., 2021).

Given the implications of how GI is conceptualized, we argue that scholars and practitioners need to be cognizant of the perspective they are using, clearly specifying the type and purpose of the GI they are employing in their communications. Yet our review of reviews shows that all too often studies fail to do this. 41% of review papers examined here did not offer a working definition of GI. As da Silva and Wheeler (2017: 32) assert, this can "lead to misunderstandings and the fragmentation of the issue" which works against development of a robust policy agenda, can mislead communities, and end up with unmet promises of service delivery (Finewood et al, 2019; Heckert & Rosan, 2016).

5.2. Multiple terms, similar meanings

Perhaps because GI is an open-ended term, it is associated with many other concepts. When we apply bibliometric techniques to examine the academic literature on alternative terms, we find that they can also be categorized under the greenspace planning, urban ecology, or water/stormwater management conceptualizations found in the review of review articles. For example, ecological conceptualizations of GI are related to ES and NBS. Stormwater management-focused GI is very similar to LID, WSUD, and SUDS. Further emphasizing the fragmenting of the GI concept into discreet articulations, we find that the literature on these different GI-related concepts remains siloed with limited geographic and scholarly overlap, i.e. limited overlap in most published authors, highly cited papers, or keywords. For example, the notion of sponge cities seems to be primarily discussed by Chinese researchers, WSUD by Australian researchers, and SUDS by British researchers. These concepts are similar, yet researchers in each of these communities may miss important scientific developments and innovations in implementation made elsewhere if they are not using the same terminology. Additionally, these stormwater management concepts are for the most part implemented without integration in the wider landscape planning conceptualization of GI, highlighting an ongoing tension in the field (Grabowski et al., in press). Thus, we would argue that it is at least important for scholars and practitioners to know that these different terms and conceptualizations exist.

5.3. Limitations and avenues for future research

While we believe that delineating these distinct conceptualizations of GI is an important step for both research and practice, this review has obvious limitations and highlights a number of future avenues for research. First, given the broad scope of the review, our results are limited in their depth. This review primarily focused on content analysis for specific information, including definitions, services/benefits, and frequency of mentions of GI and other alternative terms in both review papers and Google searches. We acknowledge that citation databases have limitations and a Google search may not accurately capture the state of GI practice in different countries. Our use of Google search analysis was expected to illustrate the conceptualizations of GI that would be available to practitioners when seeking information on the internet. Future studies should explore the three categories we identified in more detail through case studies and directed surveys, as well as a more formal review of the breadth of GI grey literature (including, planning and policy documents, design and maintenance guidance and specifications, and training manuals). Second, our results are limited in generalizability in that they begin with a seed of 75 review papers drawn from the Scopus academic citation database. As noted in the methodology, this database has limitations, and some relevant work (e.g. design literature) may therefore be missing. Future studies could compare our findings with results from other databases and nonacademic sources. To mitigate this relatively small sample we 1) focused on review papers with the assumption that they encapsulate a larger body of research and thus would capture as broad an understanding of GI as possible, 2) used only self-identified GI review papers, and 3) included bibliometric analysis of alternative GI terms identified through the review of reviews and geographically-specific Google searches. Our results usefully contribute to the growing body of GI literature by outlining three primary categories of GI conceptualizations for future work to examine and for future scholars and practitioners to situate themselves within.

6. Conclusion

This study was motivated by our professional observations of inconsistent conceptualizations of GI among different practitioners and academics, conflicting expectations for GI, and a lack of awareness about how the concept was used in other disciplines or geographies. Through the development of the arguments made in this paper, we gained a greater appreciation of the boundaries limiting interactions between disciplines, policy, and practice around GI, and the need to connect different terminology and literatures to facilitate greater exchange of knowledge across space and time. The duality of GI definitions – both as a broad planning/ecological network approach and as a narrow engineering technique – is critical to understanding how GI is framed and used in different locations and at different points in time, as practitioners are required to work within a specific policy/funding framework, which will shape their use and presentation of GI (Meerow, 2020; Matsler et al., 2021). We ask for GI advocates to look beyond disciplinary silos to engage and collaborate with alternative perspectives to ease this tension.

We ultimately argue that ambiguity in GI terminology remains both an advantage and a challenge. On the one hand, the term's flexibility has enabled it to be utilized as a boundary object between alternative academic and practitioner interpretations of its meaning, thereby supporting its growing appeal and facilitating multi-partner and cross-disciplinary efforts to meet significant urban challenges. Moreover, the growing visibility of GI research, in its various forms and alternative vocabularies, allows academics and practitioners to capitalize on its broad conceptual base to deliver more GI. But flexibility cannot be assumed to be a positive attribute in all contexts and we must remain cautious as a community of interest; ambiguity can lead to frustration and greenwashing, where broken promises of multi-functionality sour public opinion and leave cities vulnerable to the threats GI was supposed to address (Finewood et al., 2019).

We do not advocate for any one of the identified conceptualizations of GI we found, nor support the use of one alternative term over another, but rather urge those working on GI to be clear how they are conceptualizing this emerging urban resilience technique, i.e. by specifically referring to "green stormwater infrastructure" if working on stormwater management, and acknowledging alternative terms in their frameworks to maximize knowledge exchange. As a community of interest, we must also acknowledge the tension between broad planning conceptions of GI and narrow engineering technologies. It is important to communicate to other researchers, practitioners, and communities that not all GI is created equal – everything called GI today does not provide the full suite of benefits that are ascribed to specific sub-sets – and to clearly specify the type and purpose of the GI being employed.

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Appendices. Supplementary data

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