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Towards the intentional multifunctionality of urban green infrastructure: a paradox of choice?

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Decades of research on multifunctional Green Infrastructure (GI) has yet to translate into holistic implementation in the built environment. This oversight stems from assumptions that many ecosystem services occur passively and thus potential synergies are overlooked during planning and design. This study offers specific guidance for coordinating GI planning, design, and construction by examining the current state of academic literature on these aspects. It identifies 15 GI elements (e.g., green roofs) and 15 objectives (e.g., biodiversity) to collectively consider before implementation. The literature tends to isolate discussions of "engineered" GI elements with water-related objectives, while more "natural" GI are linked to biodiversity and human well-being. Coordinating across GI objectives and elements remains imperative, but evaluating too many options risks a paradox of choice. This study recommends short-term adherence to principles of adaptive design and, in the long-term, reemphasizes multifunctionality assessments, inter and transdisciplinary collaboration, and political will.

Nature-based Solutions (NbS) are mitigation measures seeking to protect, manage, and restore ecosystems to address environmental challenges, support human well-being, and benefit biodiversity[1–3]. This broad definition, stemming from landscape ecology and social–ecological systems literature[1], encompasses structural (e.g., physical infrastructure) and non-structural (e.g., policy and planning) actions[2–4], such as the construction of green infrastructure[5], the sustainable management of existing ecosystems, and community-driven protection of natural landscapes[1]. This NbS umbrella term[6] has the potential to bring disciplines together since academics[7,8], practitioners[9,10], governments[11–14], and NGOs acknowledge that NbS can holistically address numerous urbanization and climate challenges, especially in cities[15,16]. Here we will refer to structural NbS in the urban landscape by a common term, "green infrastructure" (GI). Although the definition of GI varies[5], it typically refers to a network of (semi) natural elements, such as trees, green roofs, bioretention basins, or constructed wetlands, that are intentionally placed to provide ecosystem services, such as stormwater attenuation[17], climate regulation[18,19], or habitat conservation[5,20–23]. One particularly compelling aspect of GI is its potential multifunctionality, or potential to simultaneously perform multiple ecosystem functions[24,25] or services[26–28] in a way that intentionally promotes synergies and reduces trade-offs[5,25,29–31].

Based on principles of physics and ecology, it can be inferred that these systems, which use natural processes, would convey several benefits or ecosystem services, such as heat mitigation (due to evaporative cooling and shading)[18,19], biodiversity protection (by reducing environmental filters and providing habitats)[22,23], stormwater management (by attenuating polluted stormwater runoff before it reaches the sewer or receiving water)[5,32], or human health protection (by diminishing water pollution and providing restorative areas for mental health)[33]. At the landscape level, this seems to be true. For example, GI implemented to attenuate stormwater have been shown to improve the water quality of the receiving waters[34] and thus indirectly contribute to the health of humans and aquatic ecosystems. Studies have also shown that neighborhoods with increased green space are cooler[18,19] and have happier residents[35]. In fact, numerous studies show that different GI elements (an individual unit at the site-scale) contribute many services to people, or "co-benefits," including CO_2 mitigation[36,37], biodiversity conservation[22,23], and improvement of human health[33] and well-being[38]. There are now bodies of literature, in particular in the fields of

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landscape ecology and social-ecological systems, dedicated to valuing the ecosystem services and assessing the multifunctionality of GI that are already installed[31,39–41].

Due in large part to these proven ecosystem services, distributed GI systems are increasingly incorporated into the strategic plans of many cities worldwide[29]. However, after two decades of discussion, the potential of GI to address multiple ecological, social, and economic factors[29,31] is too often considered *after* GI elements are installed and thus are not well accounted for in engineering design and construction at the municipal level[29]. For instance, properties of vegetation in a rain garden that may improve evaporative cooling[42], carbon sequestration[37], or biodiversity are generally not considered. Street trees, on the other hand, installed for shading and esthetic purposes[43] or biodiversity conservation[44,45] may fail to consider stormwater connections (e.g., from curb cutouts) to ensure trees have sufficient water (which is particularly detrimental in the face of climate change). Permanent water access is not prioritized, despite the potential to provide species habitat[46], water treatment[47], and cooling[48]. In addition, low-income neighborhoods continue to experience an inequitable distribution of GI[49]. This lack of systems thinking in the design of individual GI elements could not only lead to missed synergies between water, heat, ecology, and social systems[50], but also to disservices, i.e., negative or unintended consequences[41], such as mosquitos or inaccessibility of GI to humans or animals.

The current disconnected approach is a result of both variation in terminology[5] and the separate approach of siloed agencies and regulations that govern different ecosystem services associated with GI planning, design and implemenation[29]. These public and private entities (e.g., city parks, water and wastewater departments, architecture firms) made up of actors such as planners, arborists, ecologists, engineers, and landscape architects are often driven by regulations or initiatives that target a single issue, such as water quality (e.g., the Clean Water Act in the USA), water scarcity (in Melbourne/Berlin[51]) or habitat loss (e.g., the Federal Act on the Protection of Waters in Switzerland[52]). Each entity has its own conceptualization of ecosystem services, multifunctionality, and GI planning and design goals. From the perspective of landscape architecture and urban planning, GI plans have the potential for a broad range of environmental and social functions, including recreation, health, and livability[32]. From an engineering perspective, GI is designed for a specific purpose (e.g., stormwater management) with a measurable performance outcome typically incentivized by a regulatory requirement. Although these are just two examples of the stakeholders and perspectives involved in urban space decision-making, these differing perspectives within the entities in charge of funding, installation, and management often result in GI elements scattered across a city, with no strategic connection to each other. Thus the lessons learned, management, and best practices of GI systems remain siloed among local stakeholders.

Multifunctionality is not yet an intentional consideration throughout the planning, design, and construction phases of GI[53], resulting in continued procrastination on pressing issues[54], such as climate change[55], urban biodiversity[56], and social justice[57]. Luckily, an increasing number of studies offer solutions, including stronger coordination between entities in charge of GI planning, design, and construction[40] through a proactive, systems approach to GI[50,58]. Urban planning methods and engineering practices will need to inform each other to ensure GI systems support multifunctionality before implementation[29,31,39]. Network-level planning must start to consider different aspects at the site-scale (e.g., vegetation and substrate selection, inclusion of water pools, pipe connections), while localized engineering decisions at the element level must also acknowledge system-scale relationships (e.g., placement within an ecological network, groundwater, urban canyon geometry). These things will need to be considered across a range of GI installations and types (e.g., green roofs, wetlands, street trees) and their managing entities.

While it is clear that coordination is needed, given the extent of literature on GI systems and multifunctionality, it may be unclear how to actually do so. The goal of this study is to provide specific guidance on the aspects that could be jointly considered between GI planning, design, and construction entities, where the academic literature stands on these aspects, and what remains to be addressed. Through a comprehensive literature review, we first establish definitions and vocabulary for a common set of "GI Elements" and "Objectives" that should be actively considered throughout GI planning, design, and implementation. We then highlight gaps in the literature across this GI Element/Objective (E/O) matrix where discussion of multifunctionality is lacking and coordination is particularly needed. This manuscript concludes with the challenges and opportunities presented by multifunctional GI planning and design and a path forward to address them.

Results

Defining green infrastructure elements and systems

The definition of GI varies by region or sector[5]. In the US, for instance, GI, often referred to as "green stormwater infrastructure" (GSI) or "Best Management Practices" (BMPs), is a means to manage stormwater. This focused viewpoint originated in the early 2000s after the U.S. Environmental Protection Agency (EPA) defined GI as a "range of measures that use plant, soil, [or permeable] systems to store, infiltrate, or evapotranspire stormwater"[59]. This definition encompasses the concept of a sponge city[60] (a term coined in China), which refers to the ability of GI to absorb and release water like a sponge in order to restore a more natural water balance. Although the urban water management community generally agrees on this definition, terminology differs. For instance, in the UK, GI are referred to as "Sustainable Drainage Systems" (SuDS), and in Australia, "Water Sensitive Urban Design" is the common term[5,61,62].

However, when discussed through the lens of urban ecology or urban greenspace planning, GI are not only seen as "infrastructure," but also "green spaces"[56,63–65] or "service providing units" (SPU)[66], that restore and enhance biodiverse habitats and connectivity, which in turn, provide ecosystem services or "nature's contributions to people," including water management[67]. "Blue-green infrastructure" (BGI) is a newer term, popular in Europe, that tries to encompass both perspectives. BGI is used to emphasize the "blue" in green infrastructure, as this is often lost to non-native English speakers, who think GI must mean only green vegetation. Stovin and Ashley highlight that BGI could be used across stakeholders and languages, to encompass a broader perspective that is needed to take on the simultaneous and interconnected challenges related to GI[68]. Along these lines, Childers et al. also suggest the term "urban ecological infrastructure," similarly acknowledging the fact that not all "green infrastructure" are green, particularly in deserts where these features may be brown or unvegetated[58]. While the authors agree with these visions, we use GI in this manuscript to encompass all of these definitions to allow for comparison with other research focused on this topic.

We henceforth classify GI according to the system level (landscape scale) and the element level (site scale)[69]. Shown in Fig. 1, this GI system consists of green, blue, or gray elements that leverage natural processes. These elements span across the built environment at the landscape, city, or neighborhood scale. High-level concepts, such as the urban fabric or blue-green corridors, are considered part of the larger GI system, but are too broad to be considered individual elements.

In an urban context, we limit the definition of a GI element to a natural or semi-natural component that can be conceived, engineered, or implemented by humans, within reasonable means. The definition of a GI *element* thus excludes preexisting, natural systems that cities have surrounded, such as old-growth forests, rivers, and lakes that are too old or too large to be constructed today. Natural systems do, nevertheless, provide high-value ecosystem services and are still regarded as part of the larger GI *system* (and a Nature-based Solution[70]) that should be accounted for when planning, designing, and implementing a GI *element*. The coastlines or buffers surrounding these natural features can, however, be engineered, e.g., through river restoration, urban stream daylighting (where previously culverted streams are brought to the surface), or planting forest buffers, and are thus included as types of GI elements.

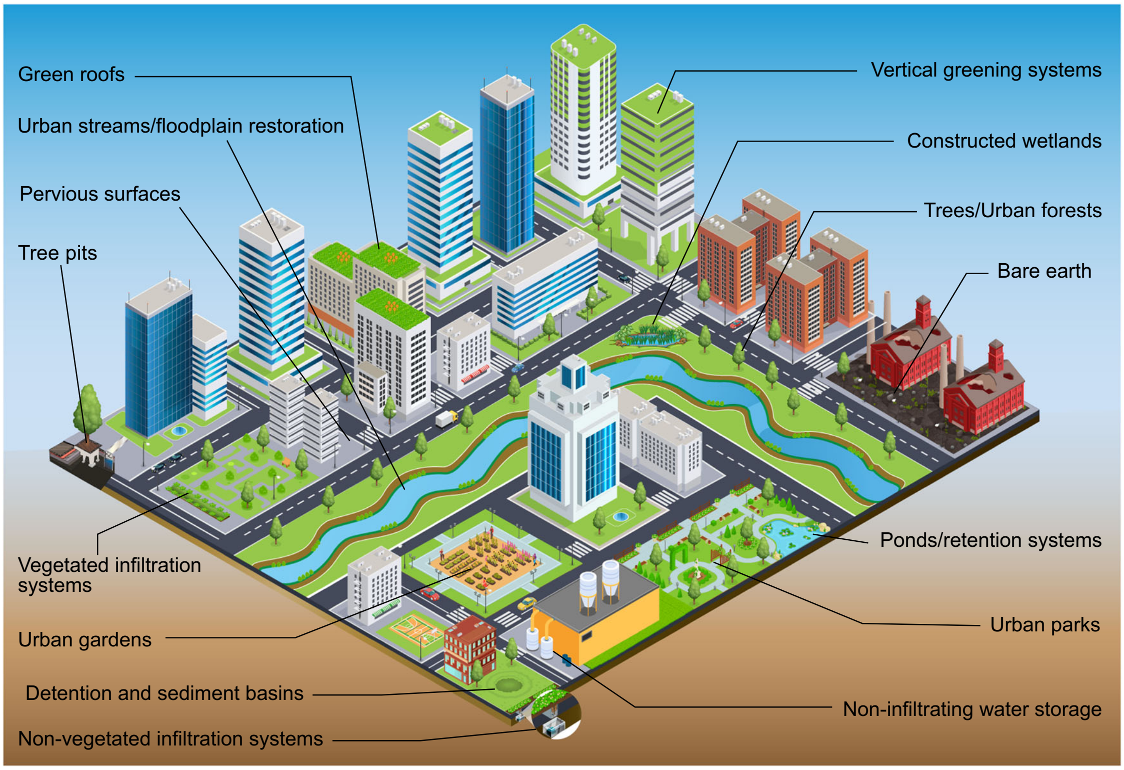

Fig. 1 | GI system and its elements. GI system consists of green, blue, or gray elements that leverage natural processes at the site level, connected across the landscape. The rendering provides an example of 15 types of GI elements at the site scale that make up a GI system at the landscape scale.

In the literature, GI elements vary widely in function, size, and terminology, often depending on the discipline describing the element. Typical examples referenced by numerous disciplines include trees, green roofs, and parks[32,58,71], while other types are often discipline-specific. Engineering disciplines often refer to permeable pavements, bioretention basins, and wet ponds, which are included in a catalog of more than 20 different types of BMPs presented by Liu et al.[72], as well as, in a list of 13 components of blue-green systems compiled by Probst et al.[48]. The latter authors do not include rainwater harvesting (e.g., rain barrels or cisterns) explicitly as a blue-green system, referencing it only as a water source. However, many other sources, such as the U.S. EPA[59] and Petsinaris et al.[73], who review 37 different types of NbS and gray solutions, do include rainwater harvesting explicitly as a type of GI or NbS. From an ecological rather than engineering perspective, Pauleit et al.[74], who also compiled a list of 44 urban GI types, also include areas that are abandoned or left alone, such as vacant lots or rocks[74], that among many benefits, add a diversity of habitats for species and slow water flows.

Guided by this previous literature and our own expert opinion, we gathered more than 40 terms that categorize the different types of GI and distilled this list into 15 distinct categories of elements, shown in Fig. 2 and defined in Supplementary Table 1 in the Supplementary Information. These categories amass terms that refer to similar aspects of GI, such as: vegetated basins designed to infiltrate stormwater (e.g., rain gardens, bioswales); basins designed to trap sediments (e.g., sediment basins); areas that permanently hold water with no infiltration (e.g., urban pond); storage tanks meant to collect water above the surface (e.g., cisterns) or below it (e.g., soakaways, infiltration trenches); areas used for food production (e.g., urban gardens, orchards); or land that remains undeveloped or unvegetated (e.g., bare earth, railyards, ruderal areas). Grass, shrubs, and other types of vegetation can be associated with a range of GI elements, thus are not attributed to a particular category.

Identifying multifunctional planning and design considerations

The elements described in Figs. 1 and 2 can provide various ecosystem functions, services, disservices, and benefits (or value). Elegantly defined within the Ecosystem Services Cascade Model[75], functions are specific natural processes related to water, energy, and nutrient cycling[27], such as infiltration, storage, filtration, or carbon sequestration[31,76]. Ecosystem services are positive contributions of these functions to humans in the broad areas of hydrology, energy, climate, environment, ecology, and the humanities that may be direct or indirect[76]. Disservices are, on the other hand, negative consequences of these functions, such as pests, litter, diseases, and allergens[77].

Shown in Fig. 3 in the first column, the literature provides a range of perspectives and examples of the functions, services, disservices, or benefits of GI[6,21,32,51,58,66,69,71,73,76,78–91]. Prudencio and Null compiled ten types of ecosystem services of GI, including material production for food and energy, water supply and storage, water purification, climate regulation, flood control, carbon sequestration, economic/cultural/social values, recreation, education, and biodiversity and habitat[90]. Veerkamp et al.[78] also include waste treatment, which was also deemed relevant by Haase et al.[66] and Schwarz et al.[79]. Haase et al. and Schwarz et al. also emphasized services related to food production and natural resources, which were also highlighted by Anderson et al.[80].

Often missing from these lists, however, are services related to water quality and soil remediation, which are often lumped together with hydrological functions, as is the case in Grabowski et al.[32] However, similar to Lovell and Taylor[71] and Wang et al.[76], we argue that these aspects are independent from stormwater management. Some aspects such as social justice and noise mitigation are often intertwined with another broader concept: human health and well-being. However, both social justice and noise warrant explicit attention due to their specific needs that are often overlooked by typical human health considerations (e.g., physical and emotional well-being).

Regardless of terminology and partitioning, GI elements interact with each other across the system through these ecosystem functions, services, disservices, and benefits, henceforth referred to as "objectives." For instance, a GI element that attenuates stormwater or provides habitat will influence other GI elements across the landscape by absorbing and releasing water

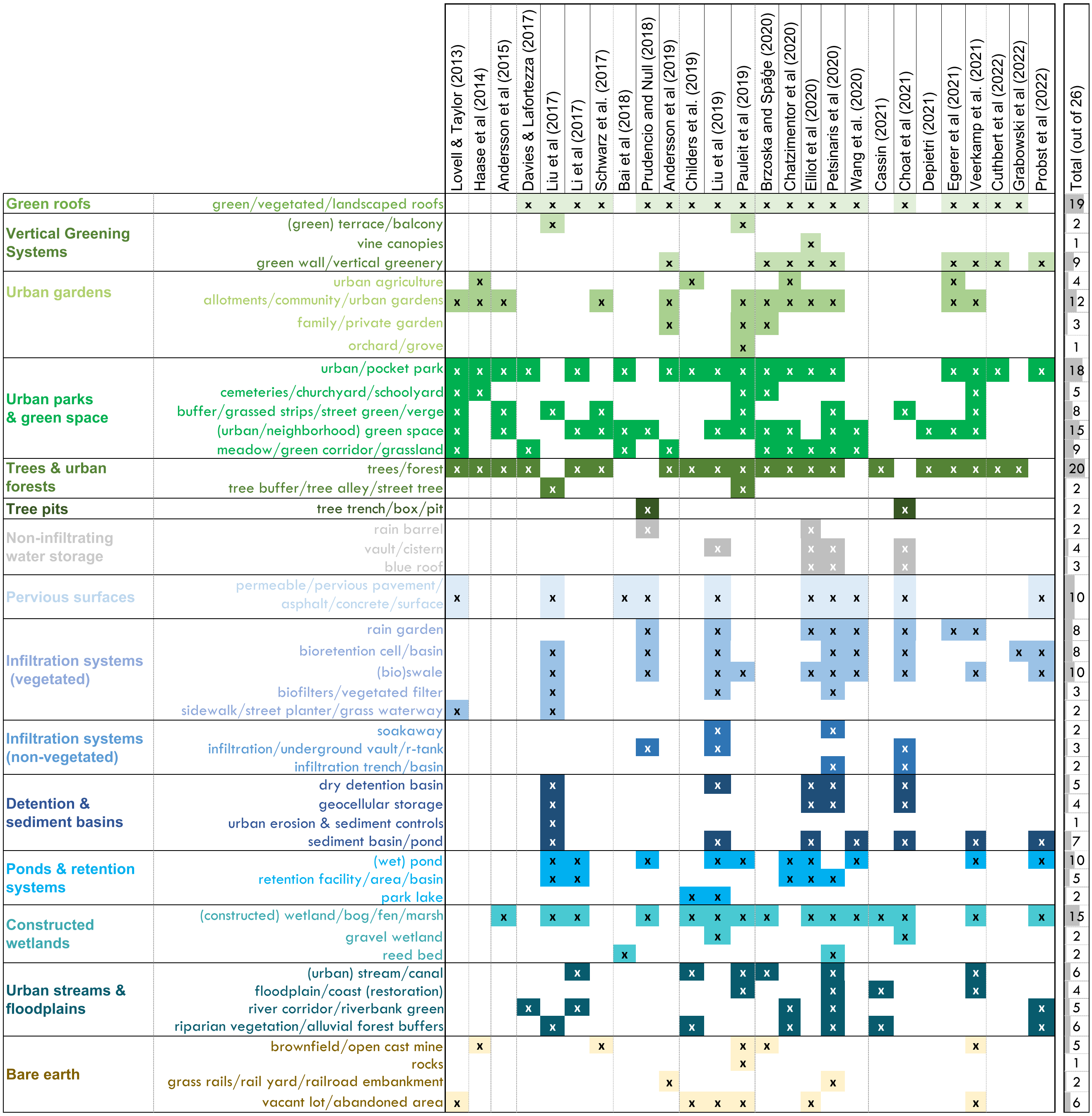

Fig. 2 | A summary of more than 40 terms referred to as GI in the literature (second column), compiled into 15 distinct categories of GI elements (first column) used in this study. The total (last column) represents the number of the 26 listed studies that mention the term. Vertical dashed lines divide the years of study.

throughout the catchment and by providing a pathway to other GI elements across the city.

Intentional and holistic planning and design of GI must encompass this spectrum of interacting objectives by taking a systems approach. Yet, given the range of terminology and definitions, it can be difficult to discern the categories of objectives for GI that encompass an array of multi-functional aspects[76] and are specific enough to be implementable and assessable. Shown in the last column of Fig. 3 (and defined in Supplementary Table 2 in the Supplementary Information), we offer a list of 15 broad and distinguishable objectives that can support a coordinated, multifunctional system of GI. Excluded from this list are aspects related to coastal restoration, as we limit the scope to the built environment. Also excluded are transportation and energy systems, which are considered to be infrastructure systems rather than GI functions or services. As shown in the first column of Fig. 3, these broad objectives can be represented by a plethora of terms in the literature (more than 73 examples are summarized from 24 studies, yet there are likely more). It will not be possible to consider all of these individual factors for each GI installation; however, awareness of the breadth of vocabulary related to these objectives is a step towards coordination across the GI system.

The matrix of green infrastructure elements and objectives

To aid in achieving this multifunctional system, we have incorporated the 15 different GI elements (aggregated based on Fig. 2, Supplementary Table 1) with the 15 objectives (compiled based on Fig. 3, Supplementary Table 2) previously identified *from peer-reviewed literature* into a multi-dimensional matrix that can be intentionally considered during planning and design. This matrix (Fig. 4), hereby named the E/O matrix, shows the results of a

Fig. 3 | Summary of 15 broad, distinguishable objectives grouped together from examples of these terms found in 24 studies that describe the functions, benefits or services provided by GI. The total column represents the number of the listed studies that mention the term.

example of terminology for ecosystem functions, services, disserivces, and benefits	Total (out of 24)	Lovell & Taylor (2013)	Haase et al. (2014)	Andersson et al (2015)	Davies & Lafortezza (2017)	Li et al. (2017)	Liu et al. (2017)	Raymond et al (2017)	Schwarz et al. (2017)	Prudencio and Null (2018)	Bai et al (2018)	Andersson et al (2019)	Childers et al. (2019)	Brzoska and Spãge (2020)	Elliot et al (2020)	Cassin (2021)	Chatzimentor et al (2020)	Petsinaris et al (2020)	Wang et al. (2020)	Choat et al (2021)	Depietri (2021)	Egerer et al (2021)	Veerkamp et al. (2021)	Cuthbert et al (2022)	Grabowski et al. (2022)	broad objective
flood risk mitigation/ flood control	8			x						x	x					x		x	x			x		x		stormwater mgmt & flood control
(storm) water mngmt/ regulation	8					x		x					x		x		x	x				x	x			
water flow/ erosion control	6			x		x				x				x	x	x										
runoff/ flood peak reduction	5			x		x	x	x											x							
water infiltration	4	x												x				x			x					
hydrological benefit	1																								x	
disaster risk reduction/ coastal resilience	5					x		x							x	x	x									disaster mitigatn
moderate extreme events	2		x						x																	
reduce vulnerability to natural hazards	1																				x					
improve water quality	6			x			x						x		x	x		x								stormwater quality
water treatment	3	x											x		x											
water filtration/purification	3					x				x						x										
pollution removal	2						x					x														
reduce combined sewer overflows	2																		x	x						
mitigate runoff pollution	1																		x							
wastewater treatment	2		x						x																	waste mngmt
waste treatment / litter or trash capture	2					x																	x			
water supply/provision/storage	7					x				x			x	x	x	x					x					water provisn
groundwater recharge/storage	5				x	x				x			x					x								
surface water resource	2				x									x												
lower ambient/mean temperature	8			x		x		x					x						x	x	x			x		heat mitigation
climate/temperature/humidity regulation	8		x						x	x		x		x	x		x						x			
reduce urban heat (island effect)	6					x						x							x		x	x		x		
microclimate control	5	x				x							x	x			x									
thermal regulation	5			x										x			x	x							x	
heat risk mitigation	3										x					x								x		
evaporation	2												x											x		
shade	2												x									x				
soil conservation & soil building/formation	7	x				x				x			x	x	x			x								soil remediation
nutrient sequestration	3					x							x							x						
decomp. and fixing processes	3					x								x						x						
nutrient cycling	2					x									x											
(improving) air quality	10			x		x		x							x	x	x	x	x		x				x	air quality
air quality regulation	5		x	x					x					x									x			
carbon sequestration & storage	13	x	x	x					x	x	x		x	x				x	x	x		x			x	carbon stor & GHG reduc
energy efficiency	5			x													x	x	x		x					
CO_2 emission reduction/climate mitigation	5					x		x								x	x		x							
energy resource management	1													x												
(improving) biodiversity	10		x		x	x			x	x	x					x			x		x	x				biodiversity
pollination	9		x	x					x				x	x	x			x				x	x			
(wildlife) habitat (for species)	8	x	x			x			x	x			x		x							x				
(ecological) conservation	7				x		x						x			x	x				x				x	
biological (pest) control	6		x	x					x				x	x	x											
plant biodiversity/metabolism	4	x															x	x		x						
genetic diversity	3		x						x					x												
(ecological) connectivity	2							x									x									
species richness	1							x																		
green space mngmt	1							x																		
recreation/entertainment/physical activity	14	x	x	x	x	x			x	x		x	x	x	x		x	x			x					human health & well-being
education/research	11	x		x		x				x			x	x	x		x	x	x			x				
cultural resource/historical preservation	10	x		x		x				x				x	x	x	x				x				x	
aesthetic value/visual quality/art	8	x		x		x							x	x	x				x		x					
social capital/benefits	8		x			x			x			x	x		x			x			x					
residents' well-being	8			x				x				x		x		x	x		x		x					
health	7				x	x								x		x	x	x							x	
quality of life/livability	6			x	x									x			x	x							x	
cognitive development/stress relief/spiritual	4			x											x		x	x								
social inclusion/justice/cohension	4				x			x									x				x					social justice
address societal challenges	2															x					x					
green space accesibility/reduce inequalities	2							x													x					
address environmental justice	1																x									
participatory planning and governance	1							x																		
food/ biotic material production	12		x	x					x	x		x		x	x	x	x	x			x	x				managemnt of raw materials
(plant) production	4	x		x										x								x				
raw material mngmt	3		x						x						x											
medicinal resource mngmt	3		x						x						x											
territorial cohesion	1																x									
increased provisioning	1																				x					
noise mitigation	5			x								x		x	x			x								noise
economic development/growth/oppotrunities	6							x		x			x		x		x	x								economic developmt
land/property value increase	3												x				x	x								
income generation	2															x		x								
green jobs / job growth	1							x																		
Total (out of 73)		12	15	22	8	25	4	15	15	15	4	8	22	25	24	17	24	23	14	6	19	11	5	5	8	

Web of Science query of *peer-reviewed* articles that list both the GI element term and objective (search terms for each are shown in Supplementary Tables 1 and 2) in the title or keywords (see Methods). It should be noted that since these queries are based on academic literature (hence research funding) they may not reflect municipal action and understanding (although some do[47]); the highlighted gaps are likely an artifact of the respective research funding awarded to each area and not intentionally excluded from studies. This is an important caveat that should be addressed in future analyses because it is often infeasible to align the recent academic findings with the requirements imposed on implementers due to funding and timeline constraints.

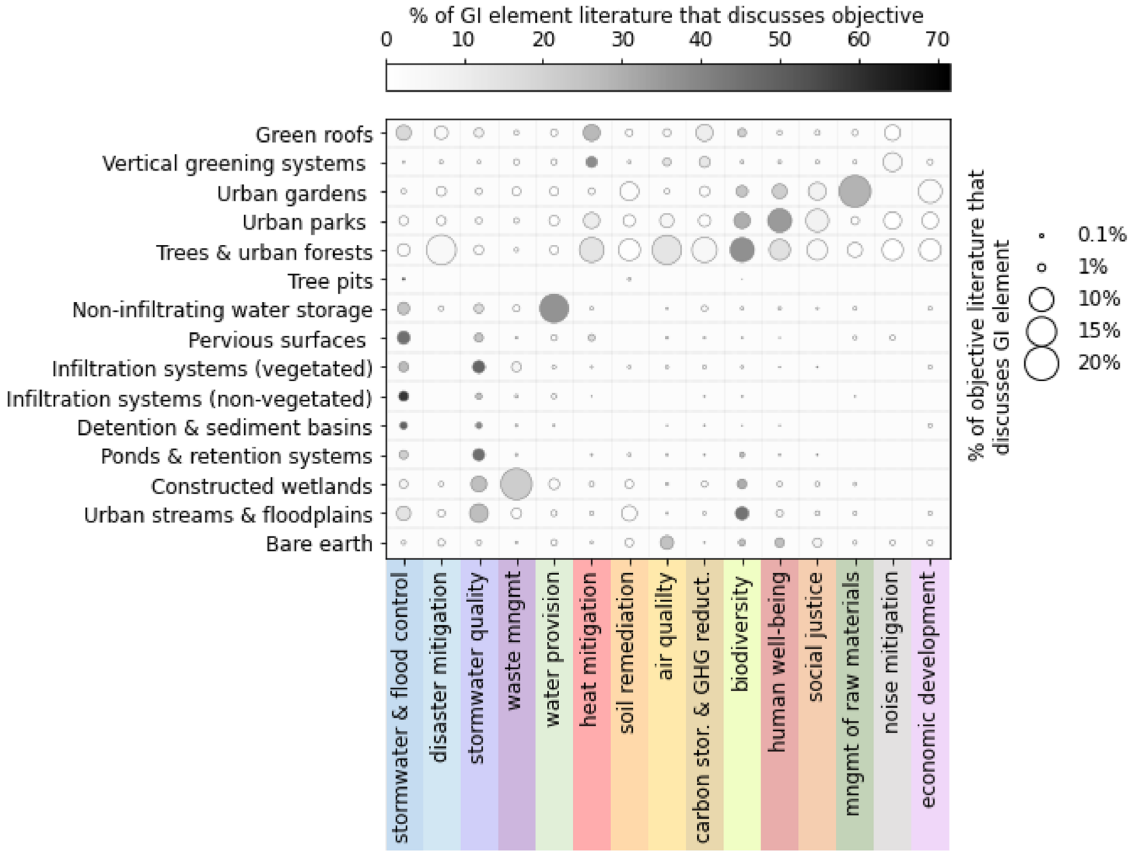

Fig. 4 | The matrix of green infrastructure elements and objectives (E/O). The E/O matrix quantifies the relationship between elements and objectives found in the literature. The occurrence of 15 different GI elements (rows; aggregated based on Fig. 2, Supplementary Table 1) as associated with the 15 objectives (columns; compiled based on Fig. 3, Supplementary Table 2) is shown as described in "Methods." Greyscale represents the objectives that dominate across a GI element, calculated by counting the total number of publications for each element and objective divided by total count for element. Circle size represents the GI elements that dominate across an objective, calculated by counting the total number of publications for each element and objective divided by the total count for objective.

In Fig. 4, the greyscale (read horizontally) represents the percentage of the literature related to GI elements that discuss the objective, while the size (read vertically) represents the percentage of the objective literature discussing the element. The former is calculated by normalizing the publication count for each element and objective (Table 1) by element (total divided by publication count for the element; see the last row in Tables 1 and 2). Dark gray means an objective dominates the literature of a GI element, while a row of the same color means objectives are equally distributed across the literature for a GI element. For example, for vertical greening systems, the heat mitigation objective is darkest, meaning a majority of literature related to these systems focuses on heat. The percent of the objective literature that refers to a GI element (circle size) is calculated by normalizing total publication count by objective (see last column in Tables 1 and 3). A large circle means that a GI element dominates the discussion of the literature for an objective. For example, non-infiltrating water storage dominates the discussion of water provision. It should be noted that one study could appear in multiple categories and thus the sum used to calculate the percentages could include the same study more than once.

If all elements and objectives were equally represented throughout the literature (all circles with the same size and color), this would be an indication that multifunctional GI had been largely embraced within the academic community. However, the results show that silos within literature remain. Literature about "engineered" GI (e.g., non-infiltrated water storage, pervious surfaces, vegetated and non-vegetated infiltration systems, detention basins, and ponds/retention systems) tends to only discuss water-related objectives (stormwater and flood control, stormwater quality, waste(water) management, and water provision) and ignore many others. At the same time, the literature surrounding GI elements that are less often "engineered," including urban gardens, parks, trees, and bare earth, tend to leave out these water-related objectives. Literature pertaining to these non-engineered elements instead tends to focus on biodiversity and human well-being, and to a lesser extent, heat mitigation. Some of the objectives clearly dominate the discussion for a particular GI element (heat mitigation dominates vertical greening systems; human well-being dominates urban parks; biodiversity dominates trees). Literature related to urban streams/floodplain restoration and green roofs tends to be the most inclusive of both water and non-water-related objectives (several darker circles across the row).

There is also an uneven discussion of GI elements across the objective literature. In some cases, one GI element clearly dominates the literature for a certain objective, such as trees for disaster mitigation, non-infiltrating water storage for water provision, constructed wetlands for wastewater treatment, and urban gardens for management of raw materials. Trees are repeatedly the most or second most discussed element across all objectives, in particular for the objectives not related to water. Only literature pertaining to stormwater management and biodiversity has discussed all of the 15 GI elements (a circle is present in every row), while some elements are largely missing from the literature for certain objectives (e.g., infiltration systems for non-water related objectives).

Overall, it is clear that silos between objectives and elements remain (e.g., management of raw materials and urban farms). Some elements/objectives largely dominate the discussion (e.g., trees), while others are left out. Most underrepresented in the literature are objectives such as social justice and noise mitigation, as well as, elements related to water storage, such as tree pits and non-vegetated infiltration systems.

Discussion

The siloes shown in the E/O matrix (Fig. 4) hinder coordination of multifunctional GI systems on the ground. Our results show a divide between the types of elements discussed in water-related literature (such as engineered, infiltrating systems) and those prevalent in non-water-related literature (including parks and trees). In particular, there is an opportunity among "engineered" GI elements to expand into multiple objectives. For instance, vegetated infiltration systems can be carbon sinks, reduce air pollution, and mitigate heat, yet our results show a dearth of literature in these areas.

Different entities control the elements and objectives within the matrix presented in Fig. 4 as well as the associated implementation and maintenance budgets. As a result, the gaps and information shown there can also provide practitioners with an understanding of where there are opportunities for innovation and coordination[92]. For this to occur, entities or initiatives that target a single objective, e.g., stormwater quality and volume, will need to allow for inclusion of other objectives. As funding of interdisciplinary projects continues to increase, there is an opportunity for further coordination among academic disciplines linked to the E/O matrix. Future analyses should reevaluate these silos over time to see if they are diminished by interdisciplinary funding mechanisms. Overall, a transition to systems thinking that facilitates coordination of multiple objectives during the planning, design, and maintenance stages of GI elements is needed[1,15,31,86,93,94].

There is increasing consensus that planners and managers of the built environment must balance the needs of social-ecological-technological systems[95,96] beyond those of the elements and objectives within the matrix presented here. First, not all objectives are well quantified, which impedes the ability to appropriately value and monetize the objectives and incorporate them into cost-benefit analyses, along with justifying financing of these systems. This lack of quantification makes it difficult to coordinate GI decisions, including understanding tradeoffs, before implementation. We will need to account for potential disservices, limitations, or tradeoffs that result from implementing a particular GI for a specific objective[25]. For instance, attenuating peak flows using ponds or wetlands can lead to increased downstream water temperatures, affecting local microclimate. Moreover, maintenance costs, which are frequently higher than expected, add to the complexity. These costs vary depending on GI element type, location, construction, maintenance frequency, and site access[92].

Another glaring challenge is accounting for the extreme weather events associated with climate change, such as high-intensity rainfall, drought, and heat spells. Following calls to ensure resilience of infrastructure systems, individual GI elements will need to be adapted to climate change to withstand future conditions[97,98]. Maintaining performance in a changing climate only adds to the challenge of multifunctional GI planning, design, and maintenance and the need for coordination. Overall, with a large and ever-growing number of aspects to consider, implementing and sustaining a multifunctional GI system could become a paradox of choice and equity.

As suggested by Hansen and Pauleit[31], managing the complexity of designing across multiple GI objectives and elements could come as part of a "multifunctionality assessment" that evaluates multifunctionality hotspots, trade-offs, and synergies, as well as, stakeholder preferences in order to identify the relevant parts of the E/O matrix to consider in the design and installation of GI. This multifunctionality assessment could draw from the steps of Multicriteria Decision Analysis (MCDA)[99–101] to first recognize and structure the decision space according to the components in the E/O matrix, and then prioritize objectives according to decision-maker preferences. Since these assessments will be project-specific, leading to different GI elements and objectives that will be suitable in each case, policies are needed to facilitate this assessment, as it will require additional time, effort, and transdisciplinary expertise.

The uptake of new technical and policy mechanisms supporting multifunctionality will take time and may only slow implementation. Acknowledging that the need for multifunctional GI is now, there are a number of established practices that can allow for the implementation of GI while consistent with multifunctionality goals. For example, principles of adaptive/flexible design, where infrastructure is designed flexibly so they can be adapted in the future[102], in this case, to incorporate more objectives and synergies of multifunctionality. Similarly, the principles of performance-based design can also be applied, where the performance of objectives is tracked over time in order to inform future multifunctional GI[103,104]. As we develop the tools and align the resources needed for multifunctional GI, monitoring, evaluation, and flexibility of current systems will be key to fine-tuning designs that ensure multifunctionality.

The matrix of GI elements and objectives presented in this study may be used as a guide to structure GI decisions across a range of scales, yet future research is needed to develop tools for the multifunctionality assessment that determines the optimal number of design objectives for a particular site, given the system of GI in the surrounding region that are achieving a range of objectives. Thus, a systems approach is beneficial for guiding GI planning and design among landscape and local scales to achieve multifunctionality within a locality. Unintentional or passive multifunctionality will need to transition to active and integrated planning and design decisions coordinated across sectors and scales. Ideally, this assessment could be used by any entity managing a component of the E/O matrix and used to support policy development. Naturally, trans and interdisciplinary research and collaborations[105,106] are needed, and it will be important to appropriately engage stakeholders and manage their data, especially as issues of data privacy, uncertainty, and nomenclature arise.

In conclusion, this study provides evidence from the literature proving that we must do more to address multifunctionality across a range of GI elements and objectives. The E/O matrix presented here can inform both researchers and practitioners about the 15 elements and 15 objectives to jointly consider during planning, design, and implementation of GI, which will ultimately facilitate systems thinking and coordination across this system.

Methods

Querying peer-reviewed literature for GI elements and objectives

Web of Science was used to query literature across a range of 15 GI elements (or types) and 15 objectives, and queries were completed during January 21–22, 2023. The search terms used for each of the 15 GI elements and 15 objectives are shown in the Supplementary Information in Supplementary Table 1 and Supplementary Table 2, respectively. By querying each objective for each element type, this resulted in 225 total queries. The searches were conducted across All Databases and All Collections, with document types limited to articles or review articles. Thus, the analysis reflects peer-reviewed literature. Since the focus of the analysis is for urban areas, all queries also included a topic search (i.e., title, abstract, or author keyword) using the following urban keywords: "urban" or "built environment" or "city" or "cities" or "metropoli*" or "megapolis". The asterisk indicates a wildcard, e.g., metropolitan or metropolis would both be a match for metropoli*.

Summarizing the literature query results

Table 1 shows a summary of these query results. The second to last column, labeled as "sum of columns" is a summation of the studies within each row of objectives, e.g., 1154 stormwater attenuation and flood control studies (from the 15 queried GI elements). Similarly, the last row of Table 1 ("sum of rows") shows the summed values for each column of elements, e.g., 1042 green roof studies (from the 15 queried GI objectives). These summed values could include duplicate publications within a column or row and thus do not represent "true" totals; rather, they were used for normalization for elements and objectives to represent relative weight within an element or objective. Table 2 shows the percentage of publications for an objective represented in the GI element literature, calculated as the total publication count for an objective and element normalized by the sum of rows for the element shown in Table 1. Similarly, Table 3 shows the percentage of publications for an element that is represented in the objective literature, calculated as the total publication count for an objective and element normalized by the sum of columns for the objective shown in Table 1. The percentages in Fig. 4 represent the values shown in Tables 2 and 3.

Table 1 | Summary of publication counts for each of the Web of Science (WoS) queries

	Green roofs	Vertical greening systems	Urban gardens	Urban parks & green space	Trees & urban forests	Tree pits	Non-infiltrating water storage	Pervious surfaces	Infiltration systems (veg.)	Infiltration sys. (non-veg.)	Detention & sediment basins	Ponds & retention sys.	Constructed wetlands	Urban streams & floodplains	Bare earth	Sum of columns
Stormwater attenuation & flood control	187	3	18	69	128	5	118	134	78	79	42	59	55	165	14	1154
Disaster mitigation (excl. flood control)	39	3	21	19	197	0	6	0	0	0	0	0	5	12	11	313
Stormwater quality	79	10	39	37	84	0	82	73	140	34	33	130	226	310	25	1302
Waste management	4	6	14	5	3	0	9	1	18	2	1	1	186	20	1	271
Water provision	10	7	16	22	16	0	174	8	3	5	1	0	24	7	8	301
Heat mitigation	289	123	46	267	647	0	13	50	5	1	0	4	26	17	9	1497
Soil remediation	5	1	36	15	49	1	0	0	1	0	0	1	7	24	7	147
Air quality	42	45	18	145	635	0	3	5	7	0	1	3	6	3	133	1046
Carbon storage & greenhouse gas (GHG) reduction	99	41	36	50	220	0	13	2	5	1	1	1	13	4	1	487
Biodiversity	220	36	403	794	1793	1	33	10	25	10	3	76	265	523	137	4329
Human well-being	32	18	353	901	702	0	16	2	3	0	2	5	38	76	136	2284
Social justice	10	5	125	206	168	0	2	0	1	0	0	1	8	8	32	566
Management of raw materials	17	7	481	32	105	0	7	8	0	1	0	0	5	7	8	678
Noise mitigation	9	13	0	11	16	0	0	1	0	0	0	0	0	0	1	51
Economic development	0	2	38	19	33	0	1	0	1	0	1	0	0	1	2	98
Sum of rows	1042	320	1644	2592	4796	7	477	294	287	133	85	281	864	1177	525	

Table 2 | Percentage of publications for an objective that is represented in the element literature (total publication count for an objective and element normalized by the total for the element)

	Green roofs	Vertical greening systems	Urban gardens	Urban parks & green space	Trees & urban forests	Tree pits	Non-infiltrating water storage	Pervious surfaces	Infiltration systems (veg.)	Infiltration sys. (non-veg.)	Detention & sediment basins	Ponds & retention sys.	Constructed wetlands	Urban streams & floodplains	Bare earth
Stormwater attenuation & flood control	17.9%	0.9%	1.1%	2.7%	2.7%	71.4%	24.7%	45.6%	27.2%	59.4%	49.4%	21.0%	6.4%	14.0%	2.7%
Disaster mitigation (excl. flood control)	3.7%	0.9%	1.3%	0.7%	4.1%	0.0%	1.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.6%	1.0%	2.1%
Stormwater quality	7.6%	3.1%	2.4%	1.4%	1.8%	0.0%	17.2%	24.8%	48.8%	25.6%	38.8%	46.3%	26.2%	26.3%	4.8%
Waste management	0.4%	1.9%	0.9%	0.2%	0.1%	0.0%	1.9%	0.3%	6.3%	1.5%	1.2%	0.4%	21.5%	1.7%	0.2%
Water provision	1.0%	2.2%	1.0%	0.8%	0.3%	0.0%	36.5%	2.7%	1.0%	3.8%	1.2%	0.0%	2.8%	0.6%	1.5%
Heat mitigation	27.7%	38.4%	2.8%	10.3%	13.5%	0.0%	2.7%	17.0%	1.7%	0.8%	0.0%	1.4%	3.0%	1.4%	1.7%
Soil remediation	0.5%	0.3%	2.2%	0.6%	1.0%	14.3%	0.0%	0.0%	0.3%	0.0%	0.0%	0.4%	0.8%	2.0%	1.3%
Air quality	4.0%	14.1%	1.1%	5.6%	13.2%	0.0%	0.6%	1.7%	2.4%	0.0%	1.2%	1.1%	0.7%	0.3%	25.3%
Carbon storage & greenhouse gas (GHG) reduction	9.5%	12.8%	2.2%	1.9%	4.6%	0.0%	2.7%	0.7%	1.7%	0.8%	1.2%	0.4%	1.5%	0.3%	0.2%
Biodiversity	21.1%	11.3%	24.5%	30.6%	37.4%	14.3%	6.9%	3.4%	8.7%	7.5%	3.5%	27.0%	30.7%	44.4%	26.1%
Human well-being	3.1%	5.6%	21.5%	34.8%	14.6%	0.0%	3.4%	0.7%	1.0%	0.0%	2.4%	1.8%	4.4%	6.5%	25.9%
Social justice	1.0%	1.6%	7.6%	7.9%	3.5%	0.0%	0.4%	0.0%	0.3%	0.0%	0.0%	0.4%	0.9%	0.7%	6.1%
Management of raw materials	1.6%	2.2%	29.3%	1.2%	2.2%	0.0%	1.5%	2.7%	0.0%	0.8%	0.0%	0.0%	0.6%	0.6%	1.5%
Noise mitigation	0.9%	4.1%	0.0%	0.4%	0.3%	0.0%	0.0%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%
Economic development	0.0%	0.6%	2.3%	0.7%	0.7%	0.0%	0.2%	0.0%	0.3%	0.0%	1.2%	0.0%	0.0%	0.1%	0.4%
Sum of columns	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table 3 | Percentage of publications for an element that are represented in the objective literature (total publication count for an objective and element normalized by the total for the objective)

	Green roofs	Vertical greening systems	Urban gardens	Urban parks & green space	Trees & urban forests	Tree pits	Non-infiltrating water storage	Pervious surfaces	Infiltration systems (veg.)	Infiltration sys. (non-veg.)	Detention & sediment basins	Ponds & retention sys.	Constructed wetlands	Urban streams & floodplains	Bare earth	Sum of rows
Stormwater Attenuation & flood control	16.2%	0.3%	1.6%	6.0%	11.1%	0.4%	10.2%	11.6%	6.8%	6.8%	3.6%	5.1%	4.8%	14.3%	1.2%	1
Disaster mitiga-tion (excl. flood control)	12.5%	1.0%	6.7%	6.1%	62.9%	0.0%	1.9%	0.0%	0.0%	0.0%	0.0%	0.0%	1.6%	3.8%	3.5%	1
Stormwater quality	6.1%	0.8%	3.0%	2.8%	6.5%	0.0%	6.3%	5.6%	10.8%	2.6%	2.5%	10.0%	17.4%	23.8%	1.9%	1
Waste management	1.5%	2.2%	5.2%	1.8%	1.1%	0.0%	3.3%	0.4%	6.6%	0.7%	0.4%	0.4%	68.6%	7.4%	0.4%	1
Water provision	3.3%	2.3%	5.3%	7.3%	5.3%	0.0%	57.8%	2.7%	1.0%	1.7%	0.3%	0.0%	8.0%	2.3%	2.7%	1
Heat mitigation	19.3%	8.2%	3.1%	17.8%	43.2%	0.0%	0.9%	3.3%	0.3%	0.1%	0.0%	0.3%	1.7%	1.1%	0.6%	1
Soil remediation	3.4%	0.7%	24.5%	10.2%	33.3%	0.7%	0.0%	0.0%	0.7%	0.0%	0.0%	0.7%	4.8%	16.3%	4.8%	1
Air quality	4.0%	4.3%	1.7%	13.9%	60.7%	0.0%	0.3%	0.5%	0.7%	0.0%	0.1%	0.3%	0.6%	0.3%	12.7%	1
Carbon storage & greenhouse gas (GHG) reduction	20.3%	8.4%	7.4%	10.3%	45.2%	0.0%	2.7%	0.4%	1.0%	0.2%	0.2%	0.2%	2.7%	0.8%	0.2%	1
Biodiversity	5.1%	0.8%	9.3%	18.3%	41.4%	0.0%	0.8%	0.2%	0.6%	0.2%	0.1%	1.8%	6.1%	12.1%	3.2%	1
Human well-being	1.4%	0.8%	15.5%	39.4%	30.7%	0.0%	0.7%	0.1%	0.1%	0.0%	0.1%	0.2%	1.7%	3.3%	6.0%	1
Social justice	1.8%	0.9%	22.1%	36.4%	29.7%	0.0%	0.4%	0.0%	0.2%	0.0%	0.0%	0.2%	1.4%	1.4%	5.7%	1
Management of raw materials	2.5%	1.0%	70.9%	4.7%	15.5%	0.0%	1.0%	1.2%	0.0%	0.1%	0.0%	0.0%	0.7%	1.0%	1.2%	1
Noise mitigation	17.6%	25.5%	0.0%	21.6%	31.4%	0.0%	0.0%	2.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2.0%	1
Economic development	0.0%	2.0%	38.8%	19.4%	33.7%	0.0%	1.0%	0.0%	1.0%	0.0%	1.0%	0.0%	0.0%	1.0%	2.0%	1

Reporting summary
Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability
The datasets used during the current study are available from the corresponding author upon reasonable request.

Code availability
The underlying code for this study is not publicly available but may be made available to qualified researchers on reasonable request from the corresponding author.

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Author contributions
L.C. led the study, while K.G. compiled and ran literature queries. L.C., K.G. and V.S. led the research design, results interpretation, and manuscript drafting. L.C. developed Figs. 1, 2, 3 and 4 and V.S. edited Fig. 1. M.M., P.K., B.W. and R.T. provided disciplinary perspectives, contributed to the research design, commented on intermediate drafts, and provided additional edits. All authors read and approved the final manuscript and ensure the integrity of the research.

Competing interests
The authors declare no competing interests.

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