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Contributions of green infrastructure to enhancing urban resilience

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Abstract

After briefly reviewing key resilience engineering perspectives and summarising some green infrastructure (GI) tools, we present the contributions that GI can make to enhancing urban resilience and maintaining critical system functionality across complex integrated social–ecological and technical systems. We then examine five key challenges for the effective implementation of GI that include (1) standards; (2) regulation; (3) socio-economic factors; (4) financeability; and (5) innovation. We highlight ways in which these challenges are being dealt with around the world, particularly through the use of approaches that are both context appropriate and socially inclusive. Although progress surmounting these challenges has been made, more needs to be done to ensure that GI approaches are inclusive and appropriate and feature equally alongside more traditional 'grey' infrastructure in the future of urban resilience planning. This research was undertaken for the Resilience Shift initiative to shift the approach to resilience in practice for critical infrastructure sectors. The programme aims to help practitioners involved in critical infrastructure to make decisions differently, contributing to a safer and better world.

Keywords Appropriateness · Challenges · Green infrastructure · Inclusiveness · Resilience

1 Introduction

With 70% of the world's population likely to be living in urban areas by 2050 and with climate change making weather and natural resource distributions more volatile, reducing risks and enhancing resilience of vital infrastructures in our increasingly densely populated urban environments is of crucial concern everywhere (Ahern 2011; Staddon 2010). From the many definitions currently in circulation (Windle 2010; Goldstein et al. 2013; Southwick et al. 2014; Butler et al. 2016; McEwen et al. 2017), we adopt the well-known Rockefeller Foundation formulation that sees urban resilience as *the capacity of individuals, communities, institutions, businesses, and systems within a city to survive, adapt, and grow no matter what kinds of chronic stresses and acute shocks they experience* (100 Resilient Cities[1]). In the face of these stresses, shocks and threats, which may relate to internal organisational vulnerabilities or external hazards such as natural disasters, it becomes crucial to model and implement existing scenarios and prospective interventions to improve urban resilience in practice as quickly and efficiently as possible (Hamilton et al. 2013; Sweetapple et al. 2018). One intervention pathway relates to what are called 'nature-based solutions' or 'green infrastructure' (GI), understood as *the creative combination of natural and artificial (green + grey) structures intended to achieve specific resilience goals (e.g. flood impact mitigation, public health protection and enhancement, etc.) with broad public support and attention to the principles of appropriate technology*. Such approaches have also been conceptualised as 'hybrid socio-technical engineered systems',[2] involving as they do the engineering of both new ("grey") systems and their integration with re-discovered "green" systems, which

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[1] http://www.100resilientcities.org/.

[2] As in the Lloyd's Register Foundation Foresight Review of Resilience Engineering (2014, 33).

may themselves be re-imagined and re-engineered (Staddon et al. 2017). So, for example, urban storm water management schemes (in the UK called "Sustainable Urban Drainage Schemes"—SUDS) now frequently employ a mix of 'grey' and 'green' approaches to boost flood resilience. However, because resilience is a social phenomenon as well as a physical one, and because cities are often places of manifest distributional inequality (Harvey 2009; Gould and Lewis 2017), it is also critically important to ensure that schemes incorporate sensitivity to social as well as physical impacts and, ideally, plan in social inclusion and equity during design and operation of these hybrid socio-technical systems.

Lessons from the *Pitt Review* into the English floods of summer 2007 highlight the finding that improving overall infrastructural resilience will require attention to the specific dimension of social resilience as well as the resilient engineering of 'things' (Pitt 2008). In other words, resilience is not just about the structures—grey, green, grey–green, etc.—that are intentionally designed or engineered, but also *how* these are conceived, (co)created and integrated within complex socio-ecological–technical systems. Resilience emerges out of 'why' things are done (to resolve an identified issue), 'how' things are done (can an intervention resolve multiple issues simultaneously?) and 'who' they are done with (direct and indirect beneficiaries or stakeholders) as well as 'what' things are done (the intervention itself) (Staddon et al. 2017). Those working to make our cities more resilient places are increasingly focussing on the contribution of GI to *socio-economic resilience*; on citizens' empowerment (particularly women, children and disadvantaged communities), on the encouragement of adaptive behaviours at all scales and on improving decision-making through active engagement of citizens with GI (e.g. through initiatives such as Climathon[3]). We argue that calls for integrated systems approaches to major engineering projects need also to include integration of social factors and impacts as well as integration of more transparent and open design, optioneering and decision processes. Better inclusion of social impact analysis and stakeholder engagement can also render resilience valuation exercises more robust and help ensure that value is realised through the project life cycle. It will also make it easier to map GI benefits onto the emerging "planetary health agenda" through, according to a recent *Lancet* article by Whitmee et al. (2015, p. 2006) "[i]ntegration of health and environmental goals… [which] will result in reduced costs and environmental impacts and improved health".

However, despite growing interest in the potential of GI to positively contribute to urban resilience, there is growing recognition that there are considerable challenges associated with its mainstreaming. For example, evidence suggests that poorly planned GI can in fact lead to greater social inequality, with—in the worst cases—people from disadvantaged backgrounds forced to relocate or being otherwise precluded from enjoying the benefits of improved ecosystem services (Abercrombie et al. 2008; Byrne 2012; Wolch et al. 2014). Additionally, GI has also received criticism for the part it plays in the 'green movement paradigm', a sort of 'green washing' that superficially appears to be linked to the public good but which in fact can result in socially-asymmetric outcomes (Paul et al. 2014). A clear example, often repeated around the world, are urban greening strategies that depend on dislocating poor or marginalised communities or which systematically prioritise more affluent areas of the city.

With these issues in mind, and as part of the series of ten resilience engineering scoping studies commissioned by The Resilience Shift in the U.K. (five of which are presented in this special issue), the authors explored the contributions of GI to urban resilience (Staddon et al. 2017). Using the other scoping studies presented in this special issue, the literature available on GI and an analysis of a series of global case studies, we undertook a synthesis that illustrates the main challenges of GI implementation. Our analysis indicated that there are five key challenge areas for the effective mainstreaming of GI in cities across the world. These include (1) design standards; (2) regulatory pathways; (3) socio-economic factors; (4) financeability; and (5) innovation. The paper proceeds as follows. The next section summarises common approaches to GI that emerged through our 2017 global review. The following section explores the five challenge domains and shares global experiences in overcoming them to enable successful contributions to be made to enhancing urban resilience through GI implementation. Reference is made to some of the more than 20 detailed case studies compiled during and after the "Desk Study" phase, which was completed by July 2017. In the concluding section, we point to some key "next steps" that we contend are necessary to facilitate the mainstreaming of GI and hybrid "green–grey" approaches to enhancing urban resilience.

2 Green infrastructure: common platforms and approaches

Different GI elements will perform differently in different contexts, just as different grey infrastructure elements are more appropriate in some locations over others and in resolving some water supply and stormwater challenges than others (Hoang and Fenner 2016). As Staddon (2010) points out, water infrastructures are always also social

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[3] Climathon is a global 24-h event where citizens, students, start-ups, entrepreneurs, big thinkers and technical experts meet to come up with innovative solutions to climate challenges in cities. Retrieved from https://climathon.climate-kic.org/ (last accessed 12 June 2017).

Table 1 Examples of GI elements, their purpose and case study implementation locations in the USA. (Reproduced with permission from Staddon et al. 2017)

GI element	Description	Cities/countries that have incentive programs
Downspout disconnection	Rerouting of rooftop drainage from going into the sewer to going into a rain garden, cistern or porous pavement	Los Angeles Downspout Disconnection Program Milwaukee Downspout Disconnection Portland Downspout Disconnection Program
Rainwater harvesting	Systems that slow and reduce stormwater runoff and collect rainwater for later use in rain barrels/cisterns	New York City Rain Giveaway Program
Rain garden/bioretention/biofiltration cells/infiltration trenches/settling ponds	Shallow vegetated basins that store and infiltrate runoff from rooftops, streets and sidewalks	Brunsville, Minnesota Rain Gardens in Puget Sound, Washington
Planter boxes	Rain gardens used in urban dense areas that have vertical walls and either closed or open bottoms	Michigan Ave. Streetscape Philadelphia Water Department
Bioswales/filter strips	Xeriscapes, mulched or vegetated channels that treat and retain stormwater as it moves by slowing, infiltrating and filtering the flow	Madison, Wisconsin
Permeable pavements	Surfaces that infiltrate, treat and collect stormwater where it falls. Materials include porous asphalt, pervious concrete or interlocking pavers	Sultan, Washington Shoreville, Minnesota Scotland
Green streets	Streets that integrate GI elements into their designs including permeable pavements, bioswales, planter boxes and trees	Seattle Public Utilities GSI Projects Syracuse Green Street Los Angeles Green Street Chicago Green Alley
Green parking	Parking lots that integrate GI elements including permeable pavements, rain gardens and bioswales in perimeter and medians	Ipswich River Watershed Demonstration Project
Green roofs/walls	Building roofs that are covered with growing media and vegetation	King County, Washington
Urban tree canopy	Trees intercept precipitation and slow stormwater runoff	Chicago Trees Initiative Philadelphia Stormwater Tree Trench
Land conservation	Protection of open space and sensitive natural areas (e.g. riparian areas, steep slopes, wetlands) within or adjacent to cities	Green Seams Flood Management in Milwaukee, Wisconsin GI Investment Program in Alachua County, Florida
Concrete inflow structures	Areas surrounding GI that are impermeable but have the necessary slope to direct stormwater to GI	Syracuse, New York
Curbside extensions/chicanes	GI that is located in areas extended into the road	Tucson, Arizona
Traffic circles	GI located in traffic circles that slow traffic and provide area for rain gardens	Tucson, Arizona

infrastructures. For example, the stormwater management capacity of GI can depend as much on social context (location, context and the physical characteristics of the surrounding landscape and community) as on the physical–structural characteristics of the GI itself (Vogel et al. 2015). GI includes trees, forests, swales, rain gardens, green roofs, wetlands, retention ponds (temporary storage), detention basins (permanent storage), rainwater storage tanks (water butts, rain barrels, rainwater harvesting systems), permeable paving and other pervious outdoor surface coverings. Such measures use soils (and other substrates) and vegetation, as well as man-made tanks to infiltrate, evapotranspirate and/or recycle rainwater, surface water and stormwaters (USEPA 2009), but also depend on some level of acceptance and "use acquiescence" by surrounding communities which they may also impact differentially.

Table 1 summarises some common GI configurations directly promoted through incentive programmes in the USA and elsewhere. GI elements may be "front of pipe", where water is slowed, infiltrated, evaporated and/or reused, or "end of pipe", where they receive and treat the flow after it has been transported via a conveyance system, e.g. to a wetland (Staddon et al. 2017). For a typology of GI, sustainable drainage systems, best management practices, low impact development elements and others, refer to Fletcher et al. (2015) and for a more extensive collection of examples (beyond the scope of this paper to detail them all here) refer to Staddon et al. (2017). The Institute for Sustainable Infrastructure has also recently released a revised version of its

"Envison" resource: a decision tool that planners, designers and engineers during the infrastructure design-build process.

As well as stormwater management benefits, GI has been recognised as driving other sorts of multiple co-benefits such as improving health outcomes, providing additional leisure amenities, enriching biodiversity and new cultural opportunities, such as in the Cheong Gye Cheon linear water park in Seoul, South Korea and the Dragon-shaped River and Lake on the Beijing Olympics site (Watkins and Charlesworth 2014; Zhou et al. 2017). At a smaller scale, the Avalon Green Alley Network in Los Angeles (USA) took a similar approach, using infiltration and attenuation trenches to treat and infiltrate an average of 7.7 kilolitres of stormwater annually, as well as including murals, vines, trees, paving and lighting, enhancing liveability for the existing residents of the area, who were not displaced as sometimes happens during such schemes (Staddon et al. 2017). In respect to this latter point, social inclusivity and appropriateness can be key elements of successful GI initiatives, where it has been shown that community buy-in to such GI schemes drives down costs, increases sustainability and community satisfaction and, ultimately, boosts resilience. An example of driving down the cost of wastewater treatment, integrated constructed wetlands, typically cost 10–50% of the capital cost of grey options (e.g. activated sludge systems) and are likely to incur only 10–25% of the operating costs of grey alternatives (Zhou et al. 2009). However, it can be difficult to demonstrate how GI performs in relation to such themes, which can present challenges that are discussed in depth in the following section.

A common sense approach to evidence-based optioneering of green (or hybrid) solutions for sustainable infrastructure involves adducing life-cycle "point" values to competing options and then to use an optimisation process to select optimal techniques and applications. This is the logic at the heart of the ASCE's "Envision" tool, whose recently released third iteration specifically allocates credits for design elements fostering greater social justice and inclusion. A similar, UK-based, tool called "Building with Nature" was launched in 2017 by a consortium including the University of the West of England and the Gloucestershire Wildlife Trust. Building with Nature brings together available evidence and existing good practice guidance, creating a set of principles that planners and developers can work towards to more effectively and consistently deliver high-quality green infrastructure (Jerome et al. 2017). Other systems that are similar include LEED and Goldstar, though these do not explicitly include social equity and their approach to life-cycle valuation of design choices appears not to be as advanced as Envision.

3 Green infrastructure contributions and challenges for urban resilience

Contributions of GI to our broader definition (following the Rockefeller Foundation 100 Resilient Cities Initiative) of urban resilience are becoming more readily documented in the literature as mainstreaming occurs in an ever increasing number of regions across the globe. We have found that GI can be a transformative technology that can facilitate critical system functionality. For example, environmental managers in Krueger National Park (KNP), South Africa use constructed wetlands as nature-based wastewater treatment infrastructure, treating and returning 365 megalitres to the natural environment annually. The wetlands are both ecologically sympathetic to the area and compliant with the Department of Water and Sanitation Regulations for the release of treated water into aquatic ecosystems (Staddon et al. 2017).

A review of other recent case studies identified that GI can create mutually reinforcing interdependencies amongst water, food, transportation, energy, health and other aspects of integrated social–ecological–technical systems, with benefits of GI including improved (Staddon et al. 2017):

- Stormwater management;
- Flood mitigation due to stormwater reduction;
- River water quality through combined sewer overflow reductions;
- Water efficiency through rainwater harvesting;
- Air quality through pollution removal;
- Odour and noise control;
- Biodiversity through increased habitats/refuges for different species;
- Urban aesthetics and perception of neighbourhood quality;
- Environmental justice (reduction of issues in comparison with grey infrastructure projects);
- Urban agriculture, pollination and grazing ecosystem services;
- Urban heat island effect through temperature reduction;
- Climate change mitigation through carbon sequestration/storage and reduced greenhouse gas production (over grey infrastructure projects);
- Traffic calming and use of public transport;
- Energy savings and energy efficiency in buildings;
- Recreational opportunities and social cohesion;
- Social–ecological connectivity and socio-economic cost–benefit (compared to grey infrastructure projects);
- Educational opportunities and stress management.

These improvements can foster urban resilience by facilitating critical system functionality and reducing the magnitude and duration (as well as frequency) of impacts and consequences associated with threats, stresses or system failures, which enables integrated social–ecological–technical systems to respond and recover in a more positive way (Casal-Campos et al. 2016). Perhaps there is no better example at present of an integrated approach to resilience at the urban-regional scale than the government-led 'sponge cities' initiative, which is being piloted across 16 Chinese cities including Wuhan, the capital of central China's Hubei province (Jiang et al. 2017; Li et al. 2017). Wuhan has a complex urban environment, ideally suited to stress-test the design and implementation of multiple intersecting GI systems at an early stage, so that lessons learned can be applied elsewhere in China and globally. Using a whole-city approach to urban water management, the strategic aim is to see excess water as a resource that can be used in novel ways rather than as a hazard, a public health risk and an inhibitor of economic growth. Life-enhancing public spaces absorb storm water, making the city simultaneously more liveable and more resilient to climate change. Performance, value and success are measured through the six monitoring categories of water ecology, water environment, sponge facilities, water safety, system construction and visibility; within each category there are 18 monitoring criteria (Staddon et al. 2017).

However, although GI can provide the outlined multiple benefits in differing combinations and degrees, there are limitations and challenges for implementation and mainstreaming. These can be attributed to physical characteristics such as soil type (impacts infiltration potential) and depth of aquifer (e.g. if too shallow can cause groundwater mounding). Features of the GI may also increase risks; for example, open waters may encourage vector-borne diseases by inadvertently providing mosquito breeding grounds (a concern in the US especially due to rising prevalence of West Nile, Zika and other mosquito-vectored illnesses), or catalyse other risks such as wildfires, allergens, toxic/poisonous plants/animals (e.g. snakes), increased vegetative debris and increased costs for maintenance and/or cleaning (Bhaskar et al. 2016; Hoang and Fenner 2016; Wong and Jim 2017). These limitations can be minimised with good design and planning, collaboration, co-creation and communication, which can be catalysed by responding to institutional, technical and perceptual challenges as recognised by the US National Research Council (2009). Such challenges may include political instability, inconsistency in planning regimes, capacity deficits, fear of change, uncertainty in process and performance and societal understanding and acceptability. In expanding our consideration of the literature, scoping studies and case studies, we further considered and focused on what we perceive to be the key challenge domains, to contribute to the continued evolution of frameworks and processes for valuing resilience to ensure value is realised through the GI project life cycle. For example, in the case of the UK's first 'eco-town' in Bicester, England, GI assisted in the delivery of social, commercial and environmental infrastructure across a development of 6000 new homes (the first phase consisted of 393 zero carbon homes). Government policy (e.g. 'Planning Policy Statement 1: Delivering Sustainable Development') required that 40% of the total site area (406 ha) should be allocated as green space, including GI and linked to wider countryside. In this case, the GI project lifecycle value of resilience was not only crucial for GI functioning, but for the resilience of the entire development and beyond. This was quantified using a method developed by Arcadis based on the Natural Capital Protocol, the Construction Industry Research and Information Association's Benefits of Sustainable Drainage Tool (BeST) and a government report on approaches to ecosystem valuation (Staddon et al. 2017).

However, not in all cases is such success achieved. In the following brief subsections, we summarise five challenges that emerged from our synthesis of the scoping study and case studies: the standards challenge, regulatory challenge, socio-economic challenge, financeability challenge and innovation challenge. After briefly outlining each challenge, we then discuss some examples of where they are beginning to be resolved.

3.1 Standards challenge

A range of factors have contributed to a current absence of globally acknowledged standards for GI. After all, it is not a 'one size fits all' intervention that can simply be plucked uncritically from a shelf, depending as it does on a close appreciation of local conditions which can be enhanced (or harmed) through sensitive green and grey–green engineering (Parr et al. 2016). Additionally, inadequate design, insufficient performance data (particularly across different climatic extremes) and lack of maintenance can all stem from a lack of standards, resulting in negative perceptions and reluctance to develop individual solutions from the growing GI toolkit (refer to Sect. 2) (Charlesworth et al. 2014; Baptiste et al. 2015; Campbell et al. 2016). Insufficient quantitative and qualitative data on provision of ecosystem services related to GI design can also hinder mainstreaming, implementation and adoption after construction, as it is difficult to demonstrate exactly how critical system functionality is maintained through GI approaches (Tayouga and Gagné 2016; Kremer et al. 2016). The situation is changing, however, with standards beginning to emerge from different contexts. For example, in the cold desert regions of the Western USA, Houdeshel and Pomeroy (2014) developed customised GI configurations resulting in GI standards to enable native vegetation to flourish. In the UK, Gloucestershire Wildlife Trust in partnership with planners from the University of the West of England developed the 'Building with Nature' GI design standard (Sinnett et al. 2017, 2018). Building with Nature aims to define what 'good green infrastructure' is in housing developments, providing certification via benchmarking activities, addressing three main themes: (1) health and well-being—easily accessed by people, (2) water management—stormwater management and reduction of flooding risk, and (3) wildlife or nature conservation—connected habitat for species (Sinnett et al. 2017). Such achievements may have a capacity building dimension too if clearly embedded with programmes of engineering and urban design education.

3.2 Regulatory challenge

On top of and relating to the standards challenge is the regulatory challenge—where an absence of or inadequate provision for governance, regulation, policy or law relating to GI places emphasis on voluntary adoption and self-regulation in urban developments, rather than referring to a common regulatory platform, as for example, for fire safety (Dhakal and Chevalier 2016). There may also be a preponderance of regulation relating to grey infrastructure that is not directly applicable to or adaptable for GI (Liu et al. 2016). In the UK, a key issue in this domain is related to "SuDS adoption" and determination of exactly who the relevant regulator is for these hybrid grey-green assets and how they are to act. Additionally, there may be overlap between stormwater management legislation and clean water/water supply legislation, leading to polycentric, but not necessarily harmonious, governance of greenspace (Kremer et al. 2016). This can work for as well as against GI, as in the case of the USA where GI assists in compliance with coastal zone and endangered species objectives (Martin-Mikle et al. 2015). Dhakal and Chevalier (2016) and Ward and Butler (2016) assert that such decentralised polycentric governance can be crucial to the success of GI, rainwater harvesting in the case of the latter, as such interventions require co-creation within communities to ensure their optimal design, planning and operation across integrated complex systems. A combination of top-down and bottom-up approaches seems to ensure greater success as in the Australian case where GI was introduced at the grassroots level but specifically mandated in national guidelines, followed by official programmes and then performance targets were enacted—although this embedding took place across a time span of nearly 50 years (Vogel et al. 2015). In the UK, GI techniques were first programmatically recommended in the Flood and Water Management Act of 2010 to alleviate flooding, but there is still controversy and debate over many aspects of mainstreaming (Charlesworth et al. 2014). Top-down examples where GI is mandated or strongly recommended are emerging, usually in response to a major event, though policies can vary from city to city and region to region within the same country. The City of Toronto, Canada mandates that all new city-owned buildings have 50–75% green roof coverage; Basel, Switzerland mandates that all new developments must have over 500 m^2 of green roofs; Minneapolis, USA passed a zoning ordinance mandating greenspace in new properties; in Portland, USA the "Grey to Green Initiative" promotes the development and maintenance of GI; and the City of Berlin adopted the Green Area Ratio policy that mandates the adoption of GI in new development (Vogel et al. 2015; Tayouga and Gagné 2016). In all these cases GI is used to enhance urban resilience in a value-driven as well as performance-driven manner appropriately encoded in regulatory standards.

3.3 Socio-economic challenge

Recent studies have argued that the evidence for socially positive effects from GI is still relatively weak, as well as evidencing that inadequately planned GI can lead to greater social inequality, with people from disadvantaged backgrounds forced to relocate, or being locked out from enjoying the benefits of improved ecosystem services (Abercrombie et al. 2008; Byrne 2012; Wolch et al. 2014; Frantzeskaki et al. 2017; Haase et al. 2017). A critical assessment of the implications of GI for resilience considering well-being and social equality must apply to any planned intervention, especially as low-income communities often have disproportionately limited access to greenspace and can be casualties of green gentrification (Hoang and Fenner 2016; Gould and Lewis 2017). Consequently, inclusion of all citizens in public deliberation processes (especially those of minority group status through disability, cultural, ethnic, religious, socio-economic and psychological circumstances) and co-creation of design and implementation becomes crucial to the mainstreaming and critical functioning of GI—as does the production of appropriate GI, which should be tailored to local needs and capacities, rather than merely imposed (Gould and Lewis 2017; Staddon et al. 2017). Excellent engineering, whether grey or green, is absolutely necessary but is not, by itself, sufficient to yield the needed step change in urban resilience thinking and outcomes. In the promotion of GI, there needs to be awareness that considers social context and perception of place, as well as socio-economic factors, when establishing the value of benefits of ecosystem services to citizens (Kremer et al. 2016). Examples of where this has happened include the cities of Bristol and Mexico under the 100 Resilient Cities programme, where citizen-led processes have been notably successful in delivering resilience strategies that are inclusive of previously disenfranchised residents, as well as stressing the importance of all citizens at all levels of society in policy making, respectively (as also mentioned in relation to the Green Alley initiative, refer to Sect. 2 above). Such cases highlight the need to consider urban resilience across complex integrated social–ecological–technical systems.

3.4 Financeability challenge

While floods and other impacts of hazards, threats and stresses can result in significant financial implications [e.g. the USA spends on average $2 billion per year in response to floods (Subramanian 2016)], determining the socio-economic benefits of GI above grey infrastructure can be challenging, resulting in challenges in justifying its financeability. As previously discussed, GI is not one size fits all and therefore each scheme requires assessment of whether it is cheaper than grey infrastructure, whether it provides additional benefits for limited or no extra cost, how such cost–benefit analysis is performed (some less tangible criteria are problematic to monetise) and whether there is a willingness to pay for them (and if so, by whom?). Levy et al. (2014) provide an excellent example of such assessment in relation to constructed wetlands, which were cheaper to construct than grey infrastructure, but where there was uncertainty in performance in relation to water quality objectives, resulting in debate over both financeability and standards compliance (refer to challenge 1 in Sect. 3.1). Wang et al. (2017) also highlighted that a bioretention basin displayed the least climate change impact and financial cost for cleaning water, but separate storm systems consumed the least energy for cleaning water (Jeong et al. 2016). Hoang and Fenner (2016) also found that GI can actually increase life cycle costs, especially for maintenance and cleaning. Consequently, financial instruments to promote GI mainstreaming are considered in some contexts, such as in Cleveland where free or reduced cost rain barrels and technical assistance for installing rain gardens are provided (Baptiste et al. 2015). In the City of Chicago, a grant programme was launched for the adoption of green roofs that benefited 20 projects with a cost of $100,000 (Tayouga and Gagné 2016). However, as the case of alternative energy supply systems (photovoltaics in particular) in the UK illustrates, when such subsides and support programmes are scaled back or withdrawn, there can be a devastating effect on the supply chain and stalled further uptake of green approaches—especially where willingness to pay is not met by the market and then must potentially be underwritten by the state or public authorities (Sweetnam et al. 2013). Articulation of new financial mechanisms for funding green or grey–green approaches to urban resilience are vitally important.

3.5 Innovation challenge

Perhaps the most poignant innovation challenge to overcome is innovation in governance, business models and new ways of thinking about urban infrastructure for resilience (Ward and Butler 2016). The GI toolkit has evolved in different forms and guises for decades, but mainstreaming within organisations, institutions and governance processes requires significant innovation in frameworks both from the top-down and bottom-up. This is a collaborative challenge as well as an technical challenge as GI necessitates scientists, engineers, planners, developers and politicians to co-create designs and interventions with citizens through extensive deliberative and participatory processes (Tayouga and Gagné 2016). Additionally, intersections with other infrastructures, such as those for energy provision or ICT, mean that interdependencies between different technical subsystems should be considered, which is often particularly difficult (Kremer et al. 2016). The City of Lima, Peru provides an interesting case study for such innovation. As part of the Future Megacities research programme sponsored by the German Ministry of Education and Research, scientists from the Institute for Landscape Planning and Ecology (ILPÖ) at the University of Stuttgart developed the Lima Ecological Infrastructure Strategy (LEIS) as part of the LiWa project (Sustainable Water and Wastewater Management in Urban Growth Centers Coping with Climate Change—Concepts for Metropolitan Lima, Peru) (Eisenberg et al. 2014). LEIS is a planning and approach for GI. The plan integrates urban ecosystems, rivers and valleys, mountains, wetlands and the coastline. LEIS is a comprehensive design and planning tool that integrates several scales through three main products: principles, tools, and manual and includes a participatory process. This has strengthened relationships and collaboration between local stakeholders, academics and authorities, integrating urban water management and wastewater treatment into the design of open spaces, where parks serve multiple functions (through constructed wetlands), while providing recreation opportunities to the residents (Eisenberg et al. 2014).

4 Conclusion

In this paper, we have provided a high-level global overview of the contributions of GI to urban resilience and the challenges that are beginning to be overcome to further enhance and value this pathway to resilience throughout integrated social–ecological–technical systems approaches. Different GI elements can facilitate critical system functionalities, but perform differently in different contexts, depending as much on geographical and social context as physical characteristics and configurations. GI can include trees, forests, swales, rain gardens, green roofs, wetlands, retention ponds, detention basins, rainwater storage, permeable paving and other pervious surfaces. Documented improved ecosystem services with respect to urban resilience resulting from GI include flood mitigation due to stormwater reduction, water efficiency through rainwater harvesting, air quality through pollution removal, biodiversity through increased habitats/refuges for different species, urban agriculture, climate change mitigation through carbon sequestration/storage, reduced greenhouse gas production (over grey infrastructure projects), leisure and recreational opportunities and greater social cohesion. However, there are still challenges on the path to greater mainstreaming though these relate less to the physical GI structures themselves, as most interventions have been tried and tested for decades. Rather, the challenges that emerged from our research relate to standards, regulation, socio-economic factors, financeability and innovation. Through a range of examples from around the world, it has been possible to illustrate that some headway is being made in responding to these challenges, but that sustained effort by a range of professionals at a range of levels (from government to educators) with different responsibilities within different social, ecological and technical systems in urban environments is crucial for the continued the process of mainstreaming GI for enhanced urban resilience.

Many of the challenges identified in this paper are increasingly being addressed through new and revised certification systems, especially the “Envision” (USA) and “Building with Nature” (UK) schemes that allocate points for attention to an increasingly broad spectrum of GI-related benefits including social inclusivity and full life-cycle assessment of environmental costs and benefits. Clearly there is a challenge for other existing schemes, which are often regionally prominent (e.g. LEED in the UK and Goldstar in South Africa) to also expand to incorporate additional environmental and social co-benefits of their points-based schemes. Notwithstanding these advances, there is a common global challenge relating to financing GI. Our review showed that it remains the case that the most common finance mechanisms for GI are still CSR or public investment. Further work on monetisation of GI assets will open up new financing opportunities, though may also increase risk of “value capture” by other actors in the urban sphere. Thus, there is a need for clear and strong regulation of GI as it becomes progressively mainstreamed in cities around the world.

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