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RESEARCH ARTICLE

How reliable – and (net) beneficial – is the green in green infrastructure

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Abstract

The idea of green infrastructure (GI) has generated great interest and creativity in addressing a range of challenging and expensive environmental problems, from coastal resilience to control of combined sewer overflows (CSOs). The appeal of GI stems from its cost savings compared to traditional "gray" infrastructure and the multiple benefits it provides, including biodiversity, aesthetics, and carbon sequestration. For example, a "green" approach to controlling CSOs in New York City saved \$1.5 billion compared to a "gray" approach. Despite these advantages, GI still does not have detailed design and reliability specifications as compared to engineered gray infrastructure, potentially hindering its adoption. In this paper, we review some of the potential applications of GI in modern environmental science and discuss how reliability and associated (un)certainty in net benefits need to be addressed to realize the potential of this new approach.

Keywords: ecosystem services; extreme events; green infrastructure; urban ecosystems

Introduction

Green infrastructure (GI) is an exciting topic at the interface between science, design, governance, management, and social justice. The use of hybrid natural and engineered features to provide a wide range of environmental benefits (ecosystem services) requires understanding of environmental (plant, soil, hydrology), engineering, economic, and social sciences. As a cross cutting boundary concept and interdisciplinary field of study, GI research can provide useful insights in many areas of sustainability and resilience science.

As GI research and practice rapidly evolve, we must address many uncertainties and unresolved issues. Foremost among these is the variation and confusion about how GI is defined, designed, implemented, and evaluated. This variation and confusion extends across the multiple disciplines researching GI (Matsler, Miller, and Groffman 2021), as well as the many ways it is planned for by cities (Grabowski et al. 2022). This uncertainty propagates through concerns about the reliability of ecological processes (e.g., plants) relative to engineered features (e.g., pipes), sources and sustainability of financing for projects, and the equity of benefits from these projects. There remains an urgent need for interdisciplinary and applied collaborations to examine how various forms of GI affect the costs of reliably providing key infrastructure services in different built environment and social contexts.

In recent years, ecologists sometimes feel like "the dog who caught the mail truck" that they have been chasing for many years. We have long advocated for the use of natural features and processes to replace engineered systems in environmental applications. Now we have been tasked with providing GI to improve water and air quality, biodiversity, and human mental and physical health. What if it does not work? How reliable are the plants and soils that underlie the function of GI? What types of ongoing interventions and maintenance do they require to maintain function and meet aesthetic expectations? As nature-based solutions become a mainstream solution to addressing climate resilience challenges – as evidenced by large federal investments (White House 2022), how will ecosystems, and their myriad social relationships, be reshaped to function as infrastructure? While it is straightforward to develop design and performance standards for traditional "gray" infrastructure, for example, levees and culverts, with existing tools, and metrics, how can this be done for biological and ecological features? What are the institutional arrangements required to evolve gray systems to integrate green elements? Is the long-term performance of a wall more predictable than that of a tree? Should trees be asked to perform like walls, or do social expectations around what infrastructure is and does need to change? These questions expose how infrastructure systems are manifestations of larger social goals and aspirations that require systems of expertise and skilled labor for planning, development, and evaluation.

In this paper, we discuss "what is green infrastructure" with a focus on a new definition encompassing its multiple biophysical and social components and interactions with built systems. We then present examples of evaluations of GI's effectiveness, highlighting some emergent challenges and uncertainties, along with identifying approaches for long-term evaluation. We apply these considerations in the case study of New York City (NYC), where we present a path forward for evaluating the role of GI in mitigating damage from extreme weather events like 2012's Superstorm Sandy.

What is GI: A new definition

Cities have always struggled with the need for green amenities. One can imagine Nebuchadnezzar realizing the need for some vegetation to keep Babylon cool, absorb air and water pollutants, and provide aesthetic services, and deciding to create the Hanging Gardens of Babylon that included exotic plants as well as constructed streams and topographic features (Polinger Foster 1998). Cities worldwide have always integrated green and ecological elements into their core fabrics, like the wetland agricultural systems of chinampas in Mexico City (Merlín-Uribe et al. 2013), and extensive systems of landscape alteration in Peru (Tomateo 2021). The challenge of combining the benefits of dense urban form while maintaining pleasant and high-quality environments has long attracted creative and ambitious thinkers such as Nebuchadnezzar. A more modern example is the work of landscape designers and urban planners such as Frederick Law Olmstead and Ebenezer Howard working in the 19th century to provide green amenities to rapidly developing cities in Europe and the USA (Eisenman 2013). Struggles have emerged as these green visions intersected with hierarchical and unequal planning processes, like those that resulted in the displacement of a predominantly Black community during the realization of Olmstead and Calvert Vaux's vision for New York's Central Park. These processes have led to numerous intersecting concerns around the equity of GI strategies (Grabowski, McPhearson, and Pickett 2023). As urban development accelerated over the last century, and the challenges of maintaining green features in cities became more evident, conceptualizations of GI evolved to integrate human-engineered infrastructure systems with more "natural" ecosystems and processes.

A major change occurred in 2007 when the US Environmental Protection Agency (EPA) began encouraging the use of GI for compliance with the Clean Water Act's National Pollutant Discharge Elimination System (NPDES) regulations. NPDES was designed in part to mitigate the damaging effects of stormwater runoff from impervious surfaces on the physical, chemical, and biological properties of receiving waters by regulating the outfalls of separated stormwater sewers and combined sewers (in which sanitary sewage and stormwater runoff are conveyed in the same pipes) as point sources of pollution. Of particular concern is the prevention of combined sewer overflows (CSOs) which occurs when a combined sewer systems capacity is exceeded during heavy rainfall events and raw sewage overflows directly into lakes and rivers. Because GI facilities can slow, store, and treat stormwater before it enters either sewer system type, it can help mitigate point source pollution discharge stemming from both combined and separated sewer systems. EPA's acceptance of GI stimulated the development of numerous hybrid stormwater control measures in cities across the USA working to obtain NPDES permits (McPhillips and Matsler 2018).

The explosion of interest in GI features to slow, store, and treat stormwater in the USA underpinned the formalization of green stormwater infrastructure (GSI) approaches defined under Section 502 of the Clean Water Act as "...the range of measures that use plant or soil systems, permeable pavement or other permeable surfaces or substrates, stormwater harvest and reuse, or landscaping to store, infiltrate, or evapotranspirate stormwater and reduce flows to sewer systems or to surface waters." These features reduce and treat stormwater where it is produced, while at the same time delivering ancillary environmental, social, and economic benefits. There is a clear contrast between these features and "gray" stormwater infrastructure including conventional piped drainage and water treatment systems designed to move stormwater away from urban features. GSI can save money. For example, the NYC Department of Environmental Protection estimated that by pursuing land conservation instead of treatment plant construction in the Catskill and Delaware watersheds they avoided over $8.5 billion dollars in costs (New York City Department of Environmental Protection 2010). Within the city itself, NYC DEP estimated that the use of GSI for controlling CSOs would save $1.5 billion compared to a straight gray approach (New York City Department of Environmental Protection 2010).

The clear and distinct interests in GI for general urban greening and for stormwater control create confusion and a GI paradox (Grabowski et al. 2022). In an analysis of over 122 plans from 20 cities in the USA, Grabowski et al. (2022) found over 140 unique definitions of GI in diverse types of city plans (comprehensive, watershed, sustainability, etc.). These definitions fit within three distinct conceptual orientations of GI: approaches focused on landscape conservation, stormwater management, or a broader integration of built systems with the natural environment. These concepts were somewhat aligned with specific plan types, as many cities use different definitions of GI in different types of plans. In some instances, a GI paradox emerged, whereby the adoption of a stormwater-focused concept prevented the implementation of broader landscape conservation approaches, exacerbating tensions between city agencies managing different aspects

Figure 1. The eco-techno spectrum of green infrastructure organizes facilities by the proportion of the facility that consists of living, biological components vs human-made, technological components. From Matsler et al. (2021).

of a city's GI. To facilitate a more robust interdisciplinary and inter-sectoral dialog, Grabowski et al. (2022) proposed a new definition of GI as " . . . a system of interconnected ecosystems, ecological–technological hybrids, and built infrastructures providing contextual social, environmental, and technological functions and benefits. As a planning concept, green infrastructure brings attention to how diverse types of urban ecosystems and built infrastructures function in relation to one another to meet socially negotiated goals." This definition motivates consideration of multiple types, functions, and benefits of GI and could provide an integrative point of departure for planning, design, and implementation of GI strategies in cities, encompassing built infrastructure systems providing stormwater, transportation, energy, and housing as well as broader urban greening objectives.

A key component of this definition involves viewing different features along a spectrum from almost entirely natural ecosystems such as relict forests and wetlands at one end to highly engineered features such as porous pavement at the other end, with features such as bioswales and green roofs in between (Figure 1). This "eco-techno spectrum" (Matsler, Miller, and Groffman 2021) is useful for conceptualizing the range of GI features in a city. More fundamentally, it is useful as a basis for evaluation and analysis of the services provided by these features. There are multiple coherent patterns that fall out along this spectrum, including direct and indirect community interactions with different types of facilities, varied jurisdiction over the design, implementation, and maintenance of these features by different agencies with different missions, and differing sources of finance across the types of features. Information about this variation is critical if we are to evaluate the effectiveness of GI, as it will be evaluated on its effectiveness and efficiency at providing specific infrastructural services (Hoover et al. 2021; Meerow and Newell 2017; Herreros-Cantis and McPhearson 2021).

Does GI work?

Evaluations of the effectiveness of GI features must be interdisciplinary and multiscalar. They need to consider the wide range of functions that are provided by these features at highly local (individual site) and larger (neighborhood, watershed, city) scales. Evaluations need to consider the wide range of stakeholders that are affected by the features, with a focus on the equitable distribution of amenities and disamenities.

Evaluation of GI has been a major focus of the Urban Resilience to Extremes Sustainability and Resilience Network (UREx-SRN) funded by the US National Science Foundation (McPhearson et al. 2022; McPhillips and Matsler 2018). This network views cities and their components such as GI as social-ecological-technological systems (SETS), which facilities multidisciplinary and multiscalar evaluations. UREx-SRN focused on 10 cities in the USA and Latin America, covering an extensive range of climate, governance, and socio-demographic characteristics.

Interdisciplinary analyses of GI in these 10 cities found five challenges to the realization of comprehensive GI benefits (McPhearson et al. 2022). The first challenge was a lack of cohesive GI design and implementation guidelines and standards across different "silos" within cities. The use of GI has stimulated a great flowering of creative design and strategies, but a lack of guidelines and standards creates variation in implementation and challenges for evaluation. This variation underlies the second challenge, that is, the need for regionally specific codes and standards (Matsler, Grabowski, and Elder 2021). Guidelines and standards for dry cities in Latin America (e.g., Mexico City) need to be different than those that apply in wet temperate cities (e.g., Baltimore). Development of these guidelines and standards should be adaptive and flexible however, as new forms and approaches develop. They must all be comprehensive and encompass the wide range of social and ecological issues affected.

A third challenge is a lack of attention to environmental justice and equity (Cousins 2021). There are frequent disconnects between the populations and communities that benefit from and appreciate the amenities of GI and the communities that suffer disservices and burdens associated with GI (Hoover et al. 2021; Heck 2021; Walker 2021). Environmental justice is a great challenge across cities, and there is hope that a SETS-based approach to evaluate GI can provide an approach for addressing inequity in other areas (McPhearson et al. 2022).

A more disciplinary challenge is the fact that design metrics for GI do not consider extreme events and implications for sustained performance and support of human well-being. This omission is especially important for GSI features that are designed to process runoff from small- or medium-size storms. Extreme events are often responsible for the majority of environmental damages and negative social outcomes and are increasing with climate change (Rosenzweig et al. 2019).

A final cross-cutting challenge identified by the UREx-SRN analysis was a lack of streamlined financing mechanisms. Many groups (municipalities, real estate developers, nonprofits) are interested in GI, but a source of funds for design, implementation, and interdisciplinary and multi-scale evaluation is often lacking. And while many municipalities have extensive experience with estimating costs and potential bids for other infrastructure projects, the cost uncertainty of GI strategies hinders the creation of dedicated budgets (Dickson et al. 2018). There is a clear need for research about marketing methods to stimulate provision of the missing funding through private action or government taxation powers.

While the UREx-SRN analysis identified general challenges facing the function of GI, there has also been extensive analysis of the performance of individual sites in specific neighborhoods. For example, work in NYC addressed concerns about accumulation of petroleum hydrocarbons and heavy metals in GI features connected to streets (Figure 2). This work showed that features more directly connected to streets, for example, with curb cuts, have higher levels of contamination. However, these features still maintained high levels of microbial function relevant to water quality (Figure 3). There is a need to consider how long high levels of microbial function will be sustained if contaminants continue to accumulate. These results highlight the clear need for ongoing, detailed evaluations that consider how ecological function affects or serves human well-being.

A major site-scale concern is maintenance. Informal surveys of GI features in many cities reveal accumulation of trash, clogging of flow paths, and degradation of biological features, for example, plants (Figure 4). Maintenance issues can often be seen in underserved neighborhoods, which combined with expectations that volunteers maintain facilities and can create further environmental justice issues (Hager et al. 2013; Hoover et al. 2021; Riedman 2021).

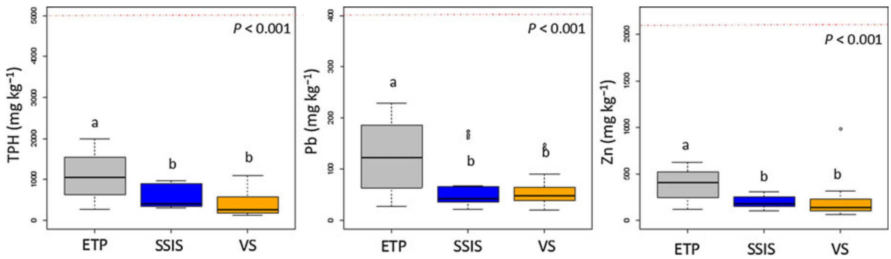

Figure 2. Boxplots showing the effect of green infrastructure designs: enhanced tree pits (ETP), street-side infiltration swales (SSIS), and vegetation swale (VS), on total petroleum hydrocarbon (TPH), lead (Pb), and zinc (Zn), respectively. The middle bar is the median, the box extends from the 25% to the 75% quartile, and horizontal bars show minimum and maximum values. Significant differences ($P < 0.05$) are indicated by different letters. Dashed line is the contamination threshold ($n = 12, 15, 33$ for ETP, SSIS, and VS, respectively). The level of "connectivity" to the street is ETP > SSIS > VS. From Deeb et al. (2018).

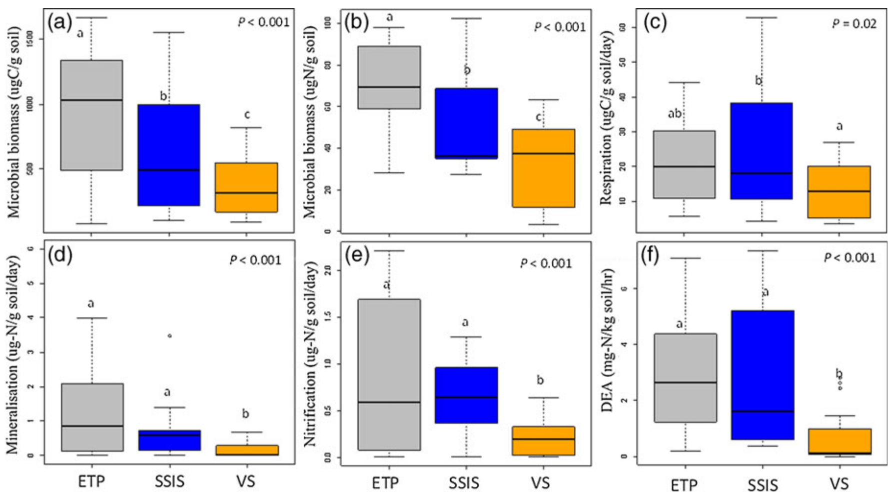

Figure 3. Boxplots showing the effect of green infrastructure designs: enhanced tree pits (ETP), street-side infiltration swales (SSIS), and vegetation swale (VS), on soil microbial biomass carbon and nitrogen (N) content, microbial respiration, potential net N mineralization and nitrification, and denitrification potential (DEA), respectively. The middle bar is the median, the box extends from the 25% to the 75% quartile, and horizontal bars show minimum and maximum values. Significant differences ($P < 0.05$) are indicated by different letters ($n = 12, 15, 33$ for ETP, SSIS, and VS, respectively). The level of "connectivity" to the street is ETP > SSIS > VS. From Deeb et al. (2018).

How can we tell if GI is working?

The above discussion about just how well GI functions highlights the need for interdisciplinary and multiscalar evaluation systems. These systems must account for the wide range of biophysical and social components of GI and must be valid for the wide range of features and locations where these features occur. Further, to meet the needs and demands of multiple stakeholders, they must be technologically and scientifically valid, efficient to carry out, and understandable to a wide range of stakeholder audiences.

Figure 4. A green infrastructure feature in an underserved neighborhood in Baltimore, MD, USA. This feature is designed to reduce runoff to receiving waters well outside this neighborhood, which loses parking spaces. The feature has accumulated trash, despite a "please don't litter" sign and plant material has degraded. Photo by Neil Bettez.

For example, an evaluation system to monitor natural and nature-based shorelines was produced recently in New York State in the USA (Wijsman et al. 2021). The state was making large investments in natural and nature-based shorelines to increase resilience to large storms such as Hurricane Sandy. These investments created a strong need for a framework capable of evaluating the full range of these features, which is similar to the range of features along the eco-techno spectrum (Figure 1). These features are deployed across the highly diverse shorelines of New York State, that is, Atlantic Ocean, Hudson River, and Great Lakes. The framework needed to have a strong scientific and technical foundation and be relevant to and understandable by agencies, practitioners, and civic groups. Most importantly, the framework had to encompass the multiple functions and effects of these features; hazard mitigation, structural integrity, ecological processes, and socio-economic and community resilience. Wijsman et al. (2021) describe the development of this framework with scientific working groups, interactions with stakeholders across the state, and field testing. The framework is currently being applied and further tested with the hope that it will serve as an example that will be useful over the long term, in many locations.

Sandy is coming back: What are we going to do about it?

In October 2012, Hurricane Sandy flooded streets, inundated tunnels, and caused power outages across NYC. There were 44 fatalities in the city and an estimated $19 billion in damage and lost economic activity (https://www1.nyc.gov/site/cdbgdr/about/About%20Hurricane%20Sandy). Due to oceanographic and geological factors, NYC occupies a sea level rise hotspot (Sallenger, Doran, and Howd 2012) and will be subject to increasing intensities of localized extreme precipitation events (New York City Department of Environmental Protection 2017). Although there is considerable uncertainty about increases in the intensity of coastal hurricanes and extratropical cyclones (Garner et al. 2017), there is a strong sense that more Sandy-like superstorms are on the way. How cities like New York will prepare for these storms, and other intersecting climate-related hazards is perhaps the most important question facing coastal cities over the next 100 years (Orton et al. 2019).

A crucial decision point in preparing for major storms is the use of gray versus GI. This decision can be framed as a contrast between "fail-safe" and "safe-to-fail" approaches to hazard management (Kim et al. 2017). In the traditional fail-safe approach, large walls, concrete channels, and other engineered structures are used to protect human settlements. If these structures fail, for example as they did during Hurricane Katrina in New Orleans in 2005, the damage can be catastrophic. Concern about these failures is increasing as both the climate and the structure and function of cities becomes harder to predict. This concern has led to the consideration of safe-to-fail approaches that prioritize protection of key services, minimizing the consequences of extreme events and facilitating rapid recovery and resumption of services. Safe-to-fail approaches are often less centralized than fail-safe approaches and require interdisciplinary approaches to develop. Of particular interest is the need to "design for exceedance" or undergo a process of examining the consequences of systems' experiencing conditions exceeding their design thresholds, necessitating advancements in systems modeling approaches that incorporate gray and green elements. These systems models could be combined with economic analyses of the costs, benefits, synergies, and trade-offs to provide a more balanced estimate of the net benefits and costs associated with different GI strategies.

To ecologists, safe-to-fail approaches are extremely appealing as they are deeply rooted in ideas about resilience and diversity that have emerged from the study of natural ecosystems. But how will this "play out in the real world"? Will decentralized GI features work as well as large flood walls during a large storm? Perhaps more importantly, will people have confidence in these features as they make decisions about where to live and invest? Will the features be distributed equitably, for example, which neighborhoods will get esthetically pleasing GI versus unsightly earthen berms? Can significant greening investments provide local resilience benefits but displace current residents to more risky areas (Gould and Lewis 2016)? What role should planned retreat play in making space for extreme events? For example, one approach to increasing flood resilience may be "buy-outs" of land in floodplains which will require difficult decisions requiring significant attention to the social dynamics of planning such interventions. As a new Federal Technical Working Group on the costs and benefits of nature-based solutions takes shape in the USA (White House 2022), we must remain attendant to the social preferences that influence the valuation of different types of infrastructure systems supporting distinct patterns of development and economic activity.

In NYC, the decision point between fail-safe and safe-to-fail approaches involves trade-offs between a series of enormous flood barriers and construction of a large number of natural and nature-based features across the City (Aerts et al. 2013). Making these decisions will require extensive scientific and technical expertise and interaction with a large and diverse group of stakeholders (McPhearson, Hamstead, and Kremer 2014). A heated debate continues over the desirability and feasibility of planned retreat as part of making space for extreme weather and GI in NYC and other coastal cities worldwide, which largely appears to only be feasible after disasters are experienced (Braamskamp and Penning-Rowsell 2018). Hopefully, the advances in design, planning, and evaluation that we discuss here will be useful for a more anticipatory process in New York and other coastal cities.

Conclusions

Now is an exciting, important, and somewhat nerve-racking time in environmental and natural resources sciences. The threats to natural and human infrastructure from climate and other components of human-accelerated environmental change have never been greater. At the same time, conceptual thinking about how to address these threats has matured, and a burst of creative engineering and design has led to the availability of potentially effective and exciting solutions. Advocates for GI and other solutions based on biological features and processes are "the dog who has caught the mail truck." Now we need to figure out what to do with it.

The next few years and decades will allow for an assessment of if the potential for these conceptual and practical advances can be realized. Will new "soft" GI features work as well, or better, than the "hard" engineering solutions that have traditionally been applied in climate hazard management? What evaluative criteria allow for comprehensive and robust comparative assessment of different infrastructure pathways? Will a wide range of stakeholders, from community groups to regulators, insurance companies, and real estate investors have confidence in these new approaches? Will we be able to develop and apply assessment methodologies that encompass the wide range of functions and services that these features need to provide?

These assessments will be taking place as GI is poised to become a mainstream solution to addressing climate resilience challenges, facilitated by large federal investments (White House 2022). The stakes of this assessment are high for both science and society. Climate hazards are a real and increasing multi-dimensional threat to the health and well-being of billions of people across the planet. If we fail to address these hazards, the costs in human suffering will be high. On the other hand, success will help us adapt to a constantly changing planet, improve overall quality of life, and help scientists, decision makers, and practitioners build credibility with stakeholders as we address these and other challenges.

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