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Developing a framework for stormwater management: leveraging ancillary benefits from urban greenspace

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Abstract

Managing stormwater and wastewater has been a priority for cities for millennia, but has become increasingly complicated as urban areas grow and develop. Since the mid-1800s, cities often relied on an integrated system of underground pipes, pumps, and other built infrastructure (termed gray infrastructure) to convey stormwater away from developed areas. Unfortunately, this gray infrastructure is aging and often exceeds its designed capacity. In an effort to alleviate issues related to excess stormwater, many urban areas across the United States are interested in using green infrastructure as a stopgap or supplement to inadequate gray infrastructure. Green infrastructure and other greenspace promote interception and/or infiltration of stormwater by using the natural hydrologic properties of soil and vegetation. Furthermore, there are numerous ancillary benefits, in addition to stormwater benefits, that make the use of greenspace desirable. Collectively, these ecosystem services can benefit multiple aspects of a community by providing benefits in a targeted manner. In this paper, we present a framework for balancing stormwater management against ancillary benefits of urban greenspace. The framework is structured around the Millennium Ecosystem Assessment ecosystem service categories: provisioning, cultural, regulatory, and supporting services. The purpose is to help communities better manage their systems by 1) allowing stakeholders to prioritize and address their needs and concerns within a community, and 2) maximize the ecosystem service benefits received from urban greenspace.

Keywords

green infrastructure; ecosystem services; stormwater management; greenspace; framework

Introduction

For millennia, cities have developed a number of technologies to control and manage the movement of water or sewage (Burian et al. 1999; Angelakis et al. 2005; De Feo et al. 2014). For example, ancient Greek communities developed extensive hydrologic systems to transport stormwater for irrigation, or flushing sewage out of buildings (Angelakis et al.

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2005). As communities developed and increased the amount of impermeable surfaces, they increasingly implemented engineered/single purpose technologies such as gray infrastructure (e.g., pipes, pumps, and storage tanks) (Hopton et al. 2015; Lim and Welty 2017) to treat, store, direct, or slow stormwater runoff.

As cities mature, often they add new technologies or expand existing technologies to keep up with population growth and increased demand, relying on gray infrastructure to manage stormwater (Maidment 1993). Since the mid-1800s, cities primarily have used one of two gray infrastructure options to manage stormwater—keep it separate from, or combine it with, wastewater (e.g., Burian et al. 1999). Thousands of cities operate under either a municipal separate storm sewer system (MS4)—a system of pipes, drainage systems, and gutters to transport and hold stormwater for treatment and processing; or a combined sewer system (CSS)—a wastewater collection system that transports sanitary waste with stormwater in shared pipes and drainage network (Burian et al. 1999; National Research Council 2009). Because stormwater and wastewater are combined, minor storm events can overwhelm the treatment facilities' capacity to treat the waste stream, forcing the release of untreated sewage into surface waters—a problem known as a combined sewer overflow (CSO) event (Berland et al. 2017).

Effectively managing stormwater has become difficult due to aging infrastructure coupled with increasing population density and development (USEPA 2013). The result is many older communities have wastewater systems operating at or near capacity and many are unable to ensure safe and healthy waterways or meet their regulatory requirements (USEPA 2013). Untreated stormwater contains pollutants (e.g., nutrients and heavy metals) and biological contaminants (e.g., *Escherichia coli*, *Legionella spp.*, *Enterococcus spp.*), that degrade habitats, contaminate surface and groundwater sources, and ultimately, impact human health (USEPA 2013; Ahmed et al. 2018; Steele et al. 2018). Thus, communities across the U.S. are forced to remediate overwhelmed and outdated wastewater infrastructure to better manage excess stormwater runoff (National Research Council 2009; Hopton et al. 2015).

Before communities employed highly engineered solutions, they used natural processes of the hydrologic cycle to manage stormwater (Burian et al. 1999; Angelakis et al. 2005). Today, this purposeful use of soil, vegetation, and constructed technological applications to help manage stormwater is termed green infrastructure (GI) and, in this context, is often used interchangeably with other terms such as stormwater control measures, best management practices, and more recently urban green infrastructure (Fletcher et al. 2015). GI works by slowing the movement of stormwater through interception, infiltration, retention, and/or detention (Hopton et al. 2015). Green infrastructure can be comprised of vegetation (e.g., rain gardens, bioswales) or manufactured materials (e.g., permeable surfaces, rain barrels) and should be distributed across the watershed/sewershed to be functional (Makropoulos and Butler 2010; Green et al. 2012). Particularly because gray infrastructure can be expensive to install, repair, or replace, not to mention disruptive in existing development, and has not adequately protected receiving waters—an effective way to lessen stormwater runoff in these systems is to integrate GI. An additional advantage of installing GI are the ancillary benefits associated with the installation of vegetation (Berland

and Hopton 2014; Shuster and Garmestani 2014; Shuster et al. 2017; Nivala et al. 2018). These benefits are termed ecosystem services and refer to any benefit(s) humans receive from nature (Millennium Ecosystem Assessment 2005; Green et al. 2015). These benefits are more commonly associated with general greenspace (e.g., parks, lakes, forests), but research suggests these benefits are also applicable to GI.

Goal and Objectives

First, we contend any greenspace installed for the primary purpose of managing stormwater be considered a type of GI (e.g., passive GI), and use the term greenspace going forward in this paper. Hence, we assume all greenspace provides measurable and non-measurable benefits for a community. Furthermore, we propose greenspace, when situated thoughtfully, may help communities address social, environmental, and economic issues through careful consideration of where to install greenspace to help manage stormwater. Because the literature is somewhat sparse with studies that integrate data and concepts across disciplines (e.g., social sciences, ecology, or engineering), or fails to consider interactions between services (Prudencio and Null 2018), our goal is to identify demonstrated (i.e., quantified) ecosystem services provided by urban greenspace, linking both stormwater and ancillary benefits. Finally, we present a conceptual framework that uses greenspace to help communities maximize ecosystem services received by determining where to place greenspace based on their identified needs and concerns.

Quantified ecosystem services from urban greenspace

The concept of ecosystem services as a research field was established in the early 2000's (deGroot et al. 2002), and in 2005, the Millennium Ecosystem Assessment (MEA) published a framework for ecosystems and human health (Millennium Ecosystem Assessment 2005). MEA classifies ecosystem services as provisioning, regulating, supporting, and cultural, and we follow their categorization to build a framework (Millennium Ecosystem Assessment 2005). Properly functioning human-based systems should incorporate all of these services to be a healthy and sustainable (Tzoulas et al. 2007; Bieling et al. 2014; Coutts and Hahn 2015). Unfortunately, planners do not always consider ecosystem services, particularly in concert with stormwater management, and the scientific literature quantifying such benefits is limited. There are, however, many benefits recognized from greenspace, and common themes within the ecosystem services/urban greenspace scientific literature relevant to stormwater management

The relationship between human health, behavior, and environment is documented in disciplines such as behavioral psychology and anthropology; numerous studies observed a relationship between human health, well-being, and access to urban greenspace (Maas et al. 2006; Nutsford et al. 2013; Astell-Burt et al. 2014; Bixby et al. 2015; Dennis and James 2016; Egorov et al. 2017; Ekkel and de Vries 2017; Feng and Astell-Burt 2017; Hoyle et al. 2017; Taylor et al. 2017; Banzhaf et al. 2018; Wu et al. 2018). Social behavior research examining the relationship between greenspace and reported crime (e.g., break-ins, robberies, drug use), found decreased rates and reports of crime in areas with higher vegetation cover, and in areas closer to greenspace (Kuo and Sullivan 2008; Kondo et al.

2015). For example, Kondo et al. (2015) showed statistically significant reductions in narcotics possession, narcotic production, and burglaries within a 0.1–0.8 km buffer from greenspace in Philadelphia. Relationships between greenspace and community participation, volunteerism, and activism have also been studied (e.g., Dennis and James 2016; Camps-Calvet et al. 2016; Langemeyer et al. 2018). Several papers highlight the importance of having well-tended greenspace in neighborhoods to improve social cohesion (Wagner and Gobster 2007; Camps-Calvet et al. 2016; de la Barrera et al. 2016; Lapham et al. 2016; Banzhaf et al. 2018), where social cohesion connects one's sense of place and belonging in a community. A strong sense of place yields social bonds that can empower collaboration around environmental or social change (Tuan 1975).

Greenspace can provide economic benefits, such as increased employment opportunities and property values (Campisano et al. 2017; Song et al. 2018). Czembrowski and Kronenberg (2016) examined residential home sales prices and found a 1% increase in visible greenery increased home sale prices, whereas a 1% increase in distance from forested land led to a 3% decrease in price per square meter of a home. Mazzotta et al. (2014) conducted a meta-analysis on the effect of low-impact development (LID) on property values, identifying 35 studies valuing open spaces similar to, or associated with, LIDs (e.g., wetlands, buffers, or trees). They reported an increase in willingness-to-pay for tree and buffer type LIDs, and increases in mean property values of 1.3–3.7% per home within a 250 m and 250–500 m buffer zone (Mazzotta et al. 2014). A review by Song et al. (2018) showed benefits received from urban trees and forests included improved property values and environmental health outweighed the costs of tree planting. Greenspace can, for example, affect the urban microclimate, filter water or air, or provide a local food source. Shade provided by trees, or buildings equipped with green roofs, can reduce energy consumption by lowering heating/cooling bills (e.g., Francis and Jensen 2017), not to mention street trees reduce air-borne particulate matter by 23% (Yli-Pelkonen et al. 2017b), and reduce NO₂ and O₃ concentrations (Reid et al. 2017; Yli-Pelkonen et al. 2017a). A literature review by Francis and Jensen (2017) estimated annual energy savings of 7–70% dependent on the existing insulation of the building, cooling effects of 0.03^o–3^oC, and an additional benefit of removal of particulate pollution (PM₁₀). Nikodinoska et al. (2018) assessed the monetary value of carbon sequestration from urban parks and trees to be \$263 USD per hectare, and concluded urban greenspaces have the highest economic value per hectare, even compared to non-urban forested or agricultural lands (Nikodinoska et al. 2018).

The protection, conservation, or increase of habitat to support native flora and fauna is a potential outcome from increased greenspace and is particularly important to biological diversity (Berland and Hopton 2016). A literature review by Hand et al. (2016) concluded species richness and habitat type were the most important predictors of biodiversity. Unfortunately, the literature is limited regarding effects of greenspace supporting species richness, diversity, abundance, or other metrics of biological diversity within an urban landscape (Mikenas 2017; Mexia et al. 2018)—many studies mention the benefits of increased biodiversity from these types of habitats, but few are empirical (Knapp et al. 2018). For example, one empirical study reported an increase in bird species richness and diversity with increased greenspace size, water area, and habitat heterogeneity (Shih 2017), but this remains an area lacking in stormwater-related research.

Additional processes from greenspace provide direct and indirect benefits to people. Evapotranspiration or soil formation are examples of these services and are well researched. For example, Egerer et al. (2018) observed an increase in soil fertility and nutrient cycling, based on soil and water samples from raised garden beds. Other studies measured carbon and nitrogen cycling to evaluate soil management (Ning et al. 2017), and leaf litter decomposition in urban forests (Melliger et al. 2017). Rainfall interception from trees, runoff infiltration, or decreased peak flows can be the result of urban forests, street trees, rain gardens, and bioswales alike (U.S. Department of Agriculture 1986; Berland and Hopton 2014; Berland et al. 2017; Gonzalez-Sosa et al. 2017; Palla et al. 2017; Shuster et al. 2017).

Creating a framework for ecosystem services and stormwater

Incorporating these various benefits into stormwater management and greenspace placement is challenging (Keeley et al. 2013). Most available frameworks and decision-support tools focus on leveraging stormwater control metrics (e.g., total discharge, peaks-over-threshold, water quality) (e.g., Ellis 2013), climate change, or hazard mitigation (e.g., Gill et al 2007), or do not include a discussion of ecosystem services in the context of stormwater management (e.g., Hansen and Pauleit 2014). Lindley et al. (2018) reviewed concepts and frameworks in ecosystem services and greenspace specific to African cities. They found health and wellness were frequently ignored services, and provided recommendations for a framework incorporating flexibility, adaptability, with top-down and bottom-up processing (Lindley et al. 2018). Dagenais et al. (2016) developed a participatory decision support tool for placing greenspace based on 12 potential secondary benefits. They proposed social, environmental, and aesthetic benefits, and included potential hazards and vulnerabilities (Dagenais et al. 2016). Whereas their goals were similar to ours, they selected ecosystem services from city documents instead of empirical scientific literature, excluding a large number of potential benefits. For these reasons, we emphasized empirically-based ecosystem services, and construct our framework by maximizing ecosystem services with stormwater management across the landscape (Fig. 1).

Methods

Developing the conceptual framework

To develop the framework, first we conducted a literature review of studies on ecosystem services from greenspace specific to stormwater management. Results from the review provide a resource from which communities can select confirmed ecosystem services they want to acquire or increase. Using Google Scholar® search engine (e.g., Mazzotta et al. 2014; Nesbitt et al. 2018), we searched scientific literature for research on urban greenspace and ecosystem services, restricting our search to papers published 2009–2018. Boolean search terms included: greenspace, green infrastructure, health, socio-ecological, socio-economic, stormwater management, ecosystem services, rain garden, green roof, bioswale, and tree. In addition, papers cited by those in the initial search results (e.g., primary and secondary results) that emphasized ecosystem services provided by greenspace, were included in our results and examined. Note this was not meant to be an exhaustive

compilation of every available paper discussing ecosystem services, or a review of every known ecosystem service, but a way to assemble current thought on *measured* ecosystem services provided by greenspace. Because our search focused on empirical studies, non-empirical papers on stormwater policy, governance, or modelling were not included. Our search results reveal gaps in the ecosystem services literature as is evident in the rather limited list of empirical studies.

Because much of the ecosystem service language differed across disciplines, our first step was to interpret terms found in the resulting literature and establish common terminology. We used a hierarchical system (Fig. 2) to categorize the ecosystem services/benefits examined and issues addressed in each paper. The primary issue examined by the researcher(s) (e.g., poverty, carbon emissions, etc.) was identified first, followed by the ecosystem service provided (e.g., biodiversity, recreation, etc.), then we grouped the ecosystem service into one of nine sub-categories (community building, economic, well-being, consumer products, habitat, mediated processes, stormwater, ameliorative services, ecosystem functions; Appendix 3). Finally, each subcategory was binned into one of four types of ecosystem services corresponding to MEA categories. Although there is some overlap in the classification of ecosystem services (e.g., air quality is both a provisioning and regulating service), each service was assigned to a single classification based on the literature assignment or our interpretation.

The nomenclature is meant to increase access and participation in stormwater planning by providing ecosystem service terms in a way a user finds most helpful, at the same time enabling communication across stakeholder interests, agendas, and different disciplines. This gives stakeholders the ability to select the ecosystem service, the issue of interest, or one of the MEA categories that will provide the types of benefits they are interested in receiving. Each ecosystem service has one or more indicators that can be used to evaluate or measure the service. For example, decreased crime is an ecosystem service from urban greenspace, and example indicators used to measure this service include quantifying the total number of police reports filed for petty, burglary, assault, or other crimes over time. By understanding how these characteristics are distributed spatially, and identifying suitable locations for installation of greenspace, greenspace can be located to increase and focus the benefits desired. Stakeholders can monitor the affect greenspace is having on the system over time. Therefore, in this study, we defined an indicator as a trait or attribute to measure or monitor to determine how well the greenspace is performing at providing the desired ecosystem service(s). The intent of our framework is to enable stakeholders to incorporate the process of identifying services, indicators, and priorities affecting their community, and merging these needs with identified stormwater-related issues (e.g., flooding, managing stormwater runoff, etc.).

Results

Ecosystem services from urban greenspace

Our search identified 105 original research articles, 18 review-only articles, and eight additional pre-2009 papers cited in the review articles, for a total of 131 peer-reviewed articles examining ecosystem services provided by urban greenspace. Ecosystem services

identified in the review papers were included in our list of ecosystem services (Table 1), but were excluded from the literature review summary. Of the 131 papers, 35 different ecosystem services were identified and classified in our hierarchy. Half of the studies involved urban forests, trees, parks, and several types of gardens (rain, botanical, urban agriculture), and they examined ecosystem services including stormwater retention and storage (15%), biodiversity (13%), air quality (11%), and social cohesion (11%). Prudencio and Null (2018) conducted an extensive literature review on stormwater, ecosystem services, and greenspace. They found 170 papers, but >60% of them focused on regulating or provisioning ecosystem services. This contrasts with our search that resulted in papers that primarily investigated cultural and regulating services. However, our literature search and resulting review differed from their study in a number of ways. First, Prudencio and Null's search period covered 1823 to 2017, and they restricted their search to abstracts in Thomson ISI Web of Science, Water Resources Abstracts, Sustainability Science Abstracts, and Scopus. We included in our search journals from behavioral and social sciences, and excluded modelling and policy papers related to ecosystem services, which Prudencio and Null included in their results. These distinctions account for the majority of discrepancies between their review and our results.

Proximity to Greenspace—One notable explanatory variable from our literature review was proximity to greenspace. Distance from greenspace was an important variable in providing ecosystem services in many of the papers. For example, Nutsford et al. (2013) examined the relationship between treatment counts reported for anxiety/mood disorders and greenspace (< 500m²) and found a significant decrease in the number of treatment counts for such disorders at a distance of 3km or less from greenspace. Specifically, number of individuals treated for anxiety and mood disorder decreased 3% for every 100m decrease in distance to the nearest greenspace within the 3km zone (Nutsford et al. 2013). Similarly, Egorov et al. (2017) showed biomarkers commonly attributed to depression significantly decreased in residents within a 450–500 m radius from a greenspace. Other papers contained similar findings, identifying a positive relationship between proximity of greenspace and human health (Maas et al. 2006; Reid et al. 2017). Interestingly, despite greater health benefits closer to a greenspace, there is evidence that an individual's positive perception of a greenspace is inversely related. Bijker and Sijtsma (2017) showed an increase in ratings of attractiveness (aesthetic value) for greenspace farther away from the resident's home versus greenspaces that were closer to the home. Hence, it is important stakeholders fully understand the benefits possible.

Ecosystem Disservices—Although not the focus of this paper, it is important to note there are negative effects from greenspace (e.g., allergic reactions to pollen), that should be considered against the benefits. For example, Ren et al. (2017) found some tree species were responsible for 78% of measured emissions of biogenic volatile organic compounds (BVOCs), an air pollutant and indicator of poor water quality. Berland and Hopton (2016) suggest that increasing street tree diversity may decrease the ability of an urban forest to resist certain types of introduced or invasive pests. Wolch et al. (2014) found increasing property values resulting from urban greenspace can displace residents in the neighborhood where the greenspace was placed (i.e., gentrification). Fortunately, some disservices may be

reduced by understanding social systems, and preparing for externalities as best as possible by examining beneficiaries of greenspace practices (Cole et al. 2017). Recognizing possible disservices that accompany ecosystem services may help inform decision makers when selecting which issues to address and which solutions to implement.

Conceptual Framework for Stormwater and Community Planning

We propose a framework for placing greenspace that speaks to overall system resilience and sustainability by considering social, economic, and environmental issues and encourages stakeholder engagement, all in the context of managing stormwater. The framework allows stakeholders to prioritize their interests, wishes, or concerns (e.g., stormwater, economic, social, cultural, etc.) to find the location(s) that increase desired benefits based on their priorities. The framework consists of the following elements:

- Identify suitable location(s) for installing greenspace for stormwater management.
- Identify social, economic, and environmental concerns or issues the community wants to address and identify their spatial distribution (Table 1). Stakeholder involvement is critical at this stage.
- Select the measurable ecosystem services shown to address identified needs and issues (Table 1).
- Determine areas of overlap between identified issues and stormwater management needs (Fig. 3), and at the same time consider available space, existing land use, etc., appropriate for considered solutions.
- Identify type(s) of greenspace suitable for selected locations and capable of providing desired benefits.
- Install greenspace at the location(s) identified.
- Measure and monitor the system using indicators to quantify changes.

Discussion

Implementing the framework at the community level

This framework can be applied through low- or high-tech methods (e.g., paper maps, participatory mapping (e.g., Plieninger et al. 2013), geographic information system (GIS) software, etc.). To illustrate this process, we will walk through an example where a community wants to manage stormwater in addition to addressing poor quality of life among residents. Once a community decides to manage stormwater using greenspace, they need to identify parcels suitable for installation. At the same time, the community identifies the spatial distribution of social, economic, and environmental issues, and determines those important to the community and in need of attention (e.g., a desire to improve individual well-being). The community must identify how to achieve improvements to well-being (e.g., decreasing crime rates, improving health, and increasing recreation opportunities) and select indicators to monitor the status of those improvements. By comparing the spatial distribution of the selected social, economic, or environmental issues to areas where greenspace can help

address stormwater management, and identifying areas of overlap, the community can select a type of greenspace (e.g., rain gardens, street trees, urban parks, etc.) capable of providing recognized benefits (e.g., crime reduction, improved mental health, etc.), and select locations for greenspace to maximize stormwater management needs (e.g., runoff reductions) and ancillary benefits. Finally, the installed greenspace and surrounding community should be monitored over time to determine its effectiveness at providing stormwater and ancillary benefits, by identifying and tracking change in indicators of well-being (e.g., reports of crime, asthma rates, hospital visits, etc.) over time.

This framework encourages users to understand the spatial distribution of social, economic, and environmental characteristics in a community appropriate for effective management (e.g., neighborhood, city, region, etc.), or level of government, by including stakeholders in decision-making processes. It is important to select indicators that quantify characteristics relevant to the community's issues of interest and services desired, and the indicators should be monitored over time to determine if benefits are being realized. Although not necessary, GIS can help facilitate identifying areas of overlap within this framework to assist further in implementation. Lastly, availability of funding and incurred costs or expenses should be considered when selecting the type, size, and location of greenspace and type of greenspace implemented.

Conclusions

Cities have been managing stormwater and sewage using gray infrastructure for more than century. However, an increase in impervious surfaces, aging infrastructure, and increasing population have placed many of these systems at or above capacity. GI often is proposed as a solution to take some pressure off existing gray infrastructure to help manage stormwater. Using greenspace for stormwater management provides additional ecosystem services such as air and water filtration, microclimate regulation, and improvements to human health, which may not be provided by highly engineered solutions. Using existing empirical based studies on ecosystem services, stormwater management, and greenspace, we developed a framework to help communities leverage benefits of greenspace while managing stormwater. Decision-makers interested in using greenspace to help manage stormwater can leverage ancillary benefits by identifying areas of known social, economic, and environmental issues and consider these areas as potential sites for installing greenspace. The framework involves a process of identifying spatial overlap between stormwater and economic, social, and/or environmental needs and concerns to place greenspace strategically to maximize benefits received. By applying this framework, communities can receive benefits from greenspace in addition to those related to stormwater, and, potentially, improve the quality of life for residents.

A better understanding (i.e., additional research) of the provision of ecosystem services from urban greenspace is needed to help community planners, decision makers, and stakeholders build more resilient systems, and gain insight in terms of stormwater infrastructure and leveraging social, economic, environmental benefits.

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Appendix 1.

Table 2.

List of ecosystem services identified from described greenspace and green infrastructure in empirical-based studies. Ecosystem services, associated categories, greenspace type and issues that can be addressed, based on literature review of papers from 2009–2018. MEA = Millennium Ecosystem Assessment. References are those returned from the search and numbers correspond to Appendix 2.

Greenspace/Green Infrastructure	MEA Category	Sub-categories	Ecosystem Service	Issues Addressed	References
Parks/trees/forest, median strips	Cultural	Community Building	Resilience	lack of protected natural areas	31, 79, 90, 102
Urban agriculture, community gardens, orchards, rain barrels, parks	Cultural	Community Building	Social Activity	few social interactions, lack of community cohesion or activism	9, 14, 15, 43, 64, 67, 69
Trees, Community gardens, urban agriculture, rain gardens, rain barrels	Cultural	Community Building	Social Capital	low community networks and resources	9, 14, 53, 68, 70
Trees, grass, community gardens, urban agriculture, orchards, rain barrels, parks, brownfields	Cultural	Community Building	Social Cohesion	lack of unity and solidarity across neighbors	14, 15, 43, 49, 50, 65, 69, 73, 78, 102
Parks/trees/forests/shrubs, greenway trails, grassed areas	Cultural	Community Building	Improved Equity	environmental injustice or unequal provision of services	2, 16, 52, 54, 55, 56, 57, 59, 60, 62, 63, 64, 66, 89, 91
Parks/trees/forests	Cultural	Economic	Improved Aesthetics	lack of landscaping, lack of neighborhood appeal	4, 18, 37, 49, 69, 71, 72, 73, 81
Forests	Cultural	Economic	Median Household Income	poverty	2, 16, 52, 56, 59, 60, 61, 62, 63, 66, 82
Parks/trees/forest, Green roofs	Cultural	Economic	Tourism	lack of sustainable business, jobs	93, 94
Parks/trees/forests	Cultural	Economic	Increased Property Value	low socioeconomic status	16, 18, 42, 54, 55, 57, 65, 81, 82, 84, 104
Parks/trees/forests, urban agriculture	Cultural	Well-being	Physical Health	obesity or hypertension	9, 12
Parks/trees/forest	Cultural	Well-being	Death reduction	high suicide rate or sudden death	3, 8
Parks/Trees, Vacant lot greening (grass)	Cultural	Well-being	Crime reduction	high number of robberies or narcotic possession	74, 75, 76
Parks/trees/forests	Cultural	Well-being	Improved Mental Health	high rates of depression, anxiety, or stress	1, 7, 10, 12, 50
Parks/trees/forests	Cultural	Well-being	Improved Quality of Life	negative behaviors such as attention deficit disorder, anger, low satisfaction, happiness	2, 5, 11, 19, 51
Community gardens, urban agriculture, trees/forests, nature conservatory spaces, private gardens	Cultural	Well-being	Perceived Health	negative attitudes or feelings about one's health	4, 6, 12, 17, 43, 69, 77

Greenspace/Green Infrastructure	MEA Category	Sub-categories	Ecosystem Service	Issues Addressed	References
Community gardens, urban agriculture, vacant lots, garden parks, any natural perceived place	Cultural	Well-being	Recreation	lack of access to trails/walking paths, or areas for picnics	43, 49, 71, 73, 90
Green Roofs	Provisioning	Consumer Products	Energy Consumption	high building energy costs or fossil fuel consumption	13, 46, 58, 94, 95
Community Gardens, urban agriculture, vacant lots	Provisioning	Consumer Products	Food Supply	lack of fresh produce or food scarcity	9, 15, 43, 90, 105
Rain Barrels	Provisioning	Consumer Products	Water Quantity	available water for landscape plants	27, 28, 86
Parks/trees/forests, Green roofs	Provisioning	Habitat	Biodiversity	low species or biological diversity	20, 21, 22, 23, 39, 41, 42, 46, 60, 72, 74, 87, 90, 94, 98
Parks/trees/forests	Provisioning	Habitat	Carbon Sequestration/Storage	high carbon emissions	9, 18, 36, 37, 41, 42, 62, 81, 90, 92, 93, 100, 101
Parks/trees/forests, Green roofs	Regulating	Mediated Processes	Microclimate Regulation	high urban temperatures	13, 25, 37, 42, 88, 90
Community gardens, urban agriculture, vegetated area	Regulating	Mediated Processes	Pollination	low plant propagation, low biodiversity	14, 31
Rain Gardens	Regulating	Mediated Processes	Pollutant Filtration	high total suspended solids, high turbidity	35
Forests	Regulating	Stormwater	Improved Infiltration	surface ponding or excessive runoff	17, 34, 35, 80, 96, 90
Parks/trees/forests, Green roofs	Regulating	Stormwater	Peak Flow Reduction	stream flashiness or flooding	16, 35, 40, 45, 47, 97
Parks/trees/forests, Green roofs	Regulating	Stormwater	Stormwater Storage/Retention	combined sewer overflow events, stormwater backups in streets or homes	17, 32, 33, 35, 36, 40, 42, 44, 45, 46, 47, 48, 62, 81, 85, 94, 95, 97, 103
Parks/trees/forests, Green roofs	Regulating	Stormwater	Reduced time to travel through the watershed (Time of Concentration)	stream flashiness or flooding	35, 40, 45
Green Roofs	Regulating	Stormwater	Improved Water Quality	harmful algal blooms, <i>Escherichia coli</i> exposure	27, 80, 83, 95, 99
Parks/trees/forests, Green roofs	Regulating	Ameliorative Services	Improved Air Quality	high asthma rates, allergies	13, 17, 24, 25, 26, 29, 30, 38, 40, 60, 62, 95, 90, 94
Trees	Regulating	Ameliorative Services	Noise Reduction	high traffic noise	31
Various green infrastructure	Regulating	Ameliorative Services	Disease Reduction	high incidence of West Nile virus, water borne illnesses	7, 9
Trees	Regulating	Ameliorative Services	Pest Management	high mosquito population	39
Green Roofs	Supporting	Ecosystem Functions	Evapotranspiration	urban heat island effect, excess soil moisture	34, 35, 46, 48
Parks/trees/forests, Community Gardens, urban agriculture	Supporting	Ecosystem Functions	Soil Management (fertility, nutrient cycling)	poor nitrogen cycling, soil porosity	14, 42, 87

Appendix 2. Results of literature search using the Google Scholar® search engine—we searched the scientific literature for research on urban greenspace and ecosystem services, restricting our search to papers published within the last ten years (2009–2018). Numbers correspond to reference column (Appendix 1, Table 2).

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Appendix 3. Glossary of terms and authors’ definition for consistency and clarity of how they are used in paper.

Ameliorative Services are benefits received by improving for humans the quality of ecosystem components or processes through management of regulating services. Examples of these services include removing particulates from air, and reducing infectious diseases or pests.

Community Building Services are cultural services that provide benefits to a community, or groups of people. This sub-category includes services that create a sense of place, social bonds with neighbors, and community cohesion or activism.

Consumer Products are provisioning services that provide a good related to purchasing or selling. Examples of this are reducing energy consumption from strategically placed greenspace or harvesting agricultural products from an urban garden.

Cultural Services are non-material goods people obtain or receive from the ecosystem, such as a sense of community, recreation, or education.

Economic Services are cultural services that benefit an individual's social and economic status or personal finances. These include indicators such as increased property value, income, and education.

Ecosystem Functions are supporting processes that provide direct and indirect benefits to people. Whereas these functions are vital to human well-being, they occur with or without the presence of people (e.g., water and nutrient cycling and energy flow). Evapotranspiration, a component of the water cycle, can help regulate water infiltration and improve microclimate regulation in cities.

Ecosystem Services are benefits or goods derived from nature. These services are categorized as regulating, provisioning, cultural, or supporting.

Habitat Services are provisioning services that provide a benefit related to the ecosystem. Increased biodiversity, areas suitable to support wildlife or carbon sequestration are examples of habitat-provisioning services as they are providing measurable, physical goods that directly and indirectly benefit humans.

Mediated Process Services are regulatory services that capture ecological processes other than stormwater. Decreased air temperature from the urban forest (e.g., street trees) can help alleviate the urban heat island effect is one example.

Provisioning Services are physical products or goods that are obtained from the ecosystem. Examples include food from a garden, plant derived medicines, or a source of fuel (e.g., wood or solar energy).

Regulating Services are benefits received from maintaining the quality of ecosystem components (e.g., air, water) or processes (e.g., flood control, pollination). These might include microclimate regulation (e.g., reducing the urban heat island effect), or improved water quality.

Stormwater Services are regulatory services specific to stormwater and urban hydrologic metrics. These include benefits such reduced peak flows, stormwater runoff, and time to concentration, or increased stormwater retention capabilities.

Supporting Services are benefits that enable or promote the production of ecosystem goods by providing ecosystem functions, and support the ecosystem so it can provide cultural, provisioning, and regulating services. Examples of supporting services are the production of oxygen and nutrient cycling. Note that there can be overlap between a supporting service and a regulating service.

Well-being Services are cultural services that impact an individual's physical, emotional, psychological, or spiritual health; this sub-category also includes quality of life indicators (e.g., access to recreation).

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Fig. 1.

Under the framework, multiple spatial variables are examined and overlain to identify locations suitable for stormwater management and areas in need of receiving ancillary benefits. Identifying areas of overlap between stormwater needs and community issues can result in maximizing greenspace benefits. Above are but a few examples that could be included in the framework.

Fig. 2.

Items/issues (a) were categorized hierarchically by services identified (b) in the literature and grouped into sub-categories (c) before being placed into a Millennium Ecosystem Assessment category (d). All services are connected to environmental, social, and economic issues they are purported alleviate or improve.

Fig. 3.

A Venn diagram of the Millennium Ecosystem Assessment categories illustrates the framework concept. Each oval represents a provided category of ecosystem services and can be thought of in a spatial context. Greenspace can provide many of the four categories of ecosystem services, depending where it is installed. For example, greenspace can be installed at point 1 but it only provides primarily stormwater benefits. The framework helps communities locate greenspace by considering areas that could benefit from receiving additional ecosystem services (point 2 or 3). In this example, moving from position 1 to 3 might add another type of benefit, in addition to stormwater management, whereas moving greenspace from position 1 to 2 might add three or four additional benefits in addition to the stormwater benefits.

Table 1

Examples of ecosystem services, associated categories, greenspace type and issues that can be addressed, based on our literature review of papers from 2009–2018. *Provisioning services* are products obtained from ecosystems such as food, medicine, or drinking water; *regulating services* represent benefits from the regulation of processes such as clean air and water, or climate regulation; *cultural services* include non-material items such as spiritual enrichment, learning, or increased recreation; and *supporting services* are those necessary to support the ecosystem and keep it functioning (e.g., nutrient cycling or soil formation) (Millennium Ecosystem Assessment 2005). MEA = Millennium Ecosystem Assessment. The complete results of our search are available in supplementary materials (Appendix 1), including the list of references (Appendix 2) and a glossary of terms (Appendix 3).

Greenspace/Green Infrastructure	MEA Category	Sub-categories	Ecosystem Service	Issues Addressed	References
Parks/Trees, Vacant lot greening (grass)	Cultural	Well-being	Crime reduction	high number of robberies or narcotic possession	Kuo et al. (2008); Kondo et al. (2015); Lapham et al. (2016)
Parks/trees/forests, Green roofs	Provisioning	Habitat	Biodiversity	Low species or biological diversity	McPherson et al. (2005); McDonnell et al. (2013); Kondo et al. (2015); Berland and Hopton (2016); Conway (2016); Hand et al. (2016); Pulighe et al. (2016); Bryant et al. (2017); Mikenas (2017); Ning et al. (2017); Melliger et al. (2017); Shih (2017); Knapp et al. (2018); Mexia et al. (2018); Watkins and Gerrish (2018)
Parks/trees/forests, Green roofs	Regulating	Stormwater	Reduced time to travel through the watershed	stream flashiness or flooding	Locatelli et al. (2014); Gonzalez-Sosa et al. (2017); Shuster et al. (2017)
Parks/trees/forests, Community Gardens, urban agriculture	Supporting	Ecosystem Functions	Soil Management (fertility, nutrient cycling)	poor nitrogen cycling, soil porosity	Melliger et al. (2017); Ning et al. (2017); Egerer et al. (2018);