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The role of trees in urban stormwater management

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Abstract

Urban impervious surfaces convert precipitation to stormwater runoff, which causes water quality and quantity problems. While traditional stormwater management has relied on gray infrastructure such as piped conveyances to collect and convey stormwater to wastewater treatment facilities or into surface waters, cities are exploring green infrastructure to manage stormwater at its source. Decentralized green infrastructure leverages the capabilities of soil and vegetation to infiltrate, redistribute, and otherwise store stormwater volume, with the potential to realize ancillary environmental, social, and economic benefits. To date, green infrastructure science and practice have largely focused on infiltration-based technologies that include rain gardens, bioswales, and permeable pavements. However, a narrow focus on infiltration overlooks other losses from the hydrologic cycle, and we propose that arboriculture – the cultivation of trees and other woody plants – deserves additional consideration as a stormwater control measure. Trees interact with the urban hydrologic cycle by intercepting incoming precipitation, removing water from the soil via transpiration, enhancing infiltration, and bolstering the performance of other green infrastructure technologies. However, many of these interactions are inadequately understood, particularly at spatial and temporal scales relevant to stormwater management. As such, the reliable use of trees for stormwater control depends on improved understanding of how and to what extent trees

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interact with stormwater, and the context-specific consideration of optimal arboricultural practices and institutional frameworks to maximize the stormwater benefits trees can provide.

1. Urban stormwater runoff and green infrastructure

Modified hydrological regimes are an important byproduct of rapid global expansion and intensification of urban areas (Grimm et al., 2008). The proliferation of urban impervious surfaces such as streets, parking lots, and rooftops has created interconnected networks of hardscapes. Impervious surfaces on the built landscape reduce the number and extent of hydrologic losses (infiltration, transpiration, etc.) as compared to non-urban landscapes. Consequently, stormwater runoff is initiated at a lower threshold, and storm flow volumes are routed across the landscape into centralized wastewater collection systems. Large volumes of runoff may lead to flooding, sewer system malfunction, and impairment of surface and subsurface water resources (Roy et al., 2014). Traditionally, the management of storm flows has relied on pipes and sewers, termed gray infrastructure, to convey stormwater to treatment facilities or into surface waters.

Gray infrastructure wastewater collection systems are typically grouped into two categories – combined and separate. Combined sewer systems carry stormwater and wastewater from residential, commercial, and industrial sources in the same conveyance structure. Due to limited storage capacity, these systems are susceptible to overflowing during storm events wherein a mixture of stormwater and untreated sewage is discharged directly into surface water bodies. Combined sewer overflow volumes can be substantial; for example, combined sewers in Cincinnati, Ohio, USA, discharge approximately 43.5 billion liters (11.5 billion gallons) of mixed raw sewage and stormwater into surrounding streams and rivers each year (Project Groundwork, n.d.). Separate sewer systems are generally found in suburban areas and recently renovated urban centers. These sewers convey stormwater and sanitary sewage in separate pipes. Yet, untreated stormwater is sent to receiving streams, and excessive soil moisture and rising shallow groundwater tables post-storm can flow into sewers, reducing system capacity and leading to septic, combined, or both types of sewer overflows.

Legal measures have been taken to reduce the negative impacts of urban stormwater runoff; see Nickel et al. (2014) and Roy et al. (2008) for policy perspectives from Germany and the US/Australia, respectively. In the US, cities are obligated to control sewer overflows under the Clean Water Act, and a part of this process is to manage stormwater runoff. Cities with separate sewer systems must implement stormwater management programs and obtain discharge permits. Cities with particularly problematic combined sewers negotiate binding legal agreements under which improvements must be made to reduce combined sewer overflows. For example, a consent decree in Cleveland, Ohio, USA, led to the formation of the Project Clean Lake program, which stipulates \$3 billion in spending over 25 years to lower annual discharges of mixed raw sewage and stormwater from 17.0 billion liters (4.5 billion gallons) to 1.9 billion liters (494 million gallons) (Project Clean Lake, 2016). The high costs of sewer system management are exacerbated by attempts to repair, replace, and upgrade gray infrastructure, and these costs are usually passed on to ratepayers who experience steep increases in water service fees.

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Unfortunately, improvements to gray infrastructure systems may only partially solve problems associated with excessive stormwater runoff, because the hydraulics of wastewater collection and conveyance systems are not straightforward. The oldest parts of the collection-conveyance system are usually original to the city, accept the greatest amounts of flow from ongoing connections to new development, and have layers of additions, extensions, and repairs that have created backwaters and transient storages within the system. One outcome of such conditions is that different parts of the system do not respond to quantity management on a one-to-one basis. For example, in Cleveland, Ohio, models suggest that perhaps 29 liters (7.6 gallons) of stormwater runoff volume must be prevented from entering the collection system to obtain a decrease of 4 liters (1 gallon) in combined sewer overflow volume (Project Clean Lake, 2016). Where improvements to gray infrastructure are prohibitively expensive or not effective at mitigating sewer malfunctions attributable to excessive stormwater runoff, there is an opportunity to decentralize stormwater management practices throughout the system. In such cases, green infrastructure may be a viable means of reducing the volume of water reaching centralized collection-conveyance systems.

Green infrastructure, which historically refers to larger green spaces linked together in a contiguous manner (Benedict & McMahon, 2006), has more recently emerged as a set of wastewater and stormwater management strategies that act as a complement to gray infrastructure (Fletcher et al., 2015). Green infrastructure (also termed green stormwater infrastructure) leverages the properties of soil and vegetation to enhance watershed or sewershed detention capacity, and in this way, manages stormwater volume. Examples of green infrastructure include rain gardens or bioretention areas, permeable pavements, bioswales, green roofs, stormwater curb cutouts to collect and route street runoff into detention areas, rainwater harvesting with rain barrels or cisterns for later use, and disconnection of roof downspouts from storm sewers. Part of the appeal of green infrastructure is that these practices may provide ancillary economic, social, and environmental benefits in addition to stormwater control functions (Center for Neighborhood Technology, 2010). On the other hand, gray infrastructure is purpose-built and is not interactive with the broader, aboveground socio-ecological cityscape. While it is generally recognized that green infrastructure cannot completely replace gray infrastructure, urban areas can be retrofitted with green infrastructure to reduce the burden on gray infrastructure systems (Shuster, Morrison, & Webb, 2008). Cities that are planning or undertaking green infrastructure efforts are working to understand the costs of stormwater control using green infrastructure, because it is still an open-ended question with regard to cost effectiveness among gray and green infrastructures built with equivalent design capacities (Montalto, Behr, & Yu, 2012).

In recent years, green infrastructure science and practice have largely focused on technologies designed to facilitate stormwater infiltration (e.g., rain gardens, bioswales, and permeable pavements). However, infiltration must be done with sufficient planning and care, as conditions must be appropriate to allow the movement of rainfall or runoff into soils. Infiltrated water can raise water tables and can cause groundwater mounding, which may subsequently cause residential flooding, sewer backups, and unwanted return flow into collection system pipes (Endreny & Collins, 2009). More importantly, the focus on infiltration alone overlooks ensuing pathways for losses from the urban hydrologic cycle that can help reduce runoff volumes. These other losses (termed abstractions) include evapotranspiration, deep percolation, recharge, and redistribution. Increasing evapotranspiration in cities, for example, will promote a closer reflection of historical conditions, particularly on landscapes that were forested prior to development. Indeed, trees are an obvious candidate for increasing losses from the urban hydrologic cycle because they can provide relatively dense vegetation in a small footprint, and their extensive canopies and subsurface root systems are capable of capturing and pumping substantial amounts of water. Thus, there is a need to direct more attention to understanding the role of urban trees as a stormwater control measure.

To summarize the problem, stormwater runoff must be managed to protect human health and environmental quality, and in many situations, to aid in compliance with legal requirements. Green infrastructure shows promise as a complement to gray infrastructure that may also deliver ancillary ecosystem services. However, green infrastructure strategies focused narrowly on infiltrating and/or detaining stormwater have practical limits and may not be the most cost-effective option. On the other hand, it is possible that trees can effectively complement other green and gray infrastructure approaches to help meet stormwater control targets. In this article, we draw on existing research to describe how trees can provide alternative pathways for urban stormwater via a broader range of losses from the urban hydrologic cycle, and note opportunities to pair trees with other green infrastructure technologies. We then discuss the outlook for using trees as elements of green infrastructure to achieve reliable stormwater control, and conclude by identifying challenges and research gaps related to quantifying the performance of trees as stormwater control measures and ensuring growth and longevity of urban trees. We focus largely on the interactions between trees and the urban hydrologic cycle, but as stormwater management is an inherently socio-ecological problem, we also describe administrative challenges including economic and policy issues. Literature is drawn from peer-reviewed research and government reports from around the world as available, but readers will note that the majority of studies have taken place within the US, and empirical research has covered a limited selection of tree species, landscape contexts, and geographical settings.

2. Trees as elements of green infrastructure for stormwater management

As defined here, the urban forest includes all trees within a delineated urban area. Trees are found throughout urban areas on public land (e.g., parks, in the right-of-way along streets) and private land (e.g., residential and commercial properties). The urban forest is comprised of both planted and naturally established trees, across a spectrum of species and sizes, and located in various settings ranging from the urban core to remnant forests. The functions and value of the urban forest have received increased attention in recent decades as urban ecology and ecosystem services have become prominent areas of research (e.g., McPherson et al., 1997; Sander, Polasky, & Haight, 2010). In fact, researchers have been interested in the impacts of trees on urban stormwater runoff for at least three decades (Sanders, 1986). However, research on the interaction between the urban forest and stormwater has been relatively understudied compared to other topics such as air quality and carbon sequestration benefits (Roy, Byrne, & Pickering, 2012; Xiao & McPherson, 2016).

In urban systems where runoff volume is challenging to manage, trees serve as green infrastructure by routing rainfall to various components of the hydrologic cycle. Losses can occur via canopy interception loss, transpiration, improved infiltration, and possible benefits with regard to deeper percolation along root channels and water table management. These losses occur on different time scales; for example, canopy interception loss is relevant during and immediately after a storm event, while transpiration plays a role in managing soil moisture in the days or weeks between storm events. In the following sections, we review research on the interactions between the urban forest and management of stormwater runoff volumes.

2.1. Canopy interception loss

The capacity for abstraction of precipitation on tree surfaces is initiated at the onset of a storm event. Canopy interception loss is the sum of water stored in tree canopies and evaporated from tree surfaces. Interception loss can be measured indirectly by subtracting stemflow and throughfall from gross precipitation falling on a tree. Stemflow is water that runs down a tree’s stem or bole to the ground surface, and throughfall is water that passes through a tree’s canopy or drips off tree surfaces onto the ground. Stemflow and throughfall are either infiltrated into the soil or runoff is initiated if they are delivered faster than the infiltration rate. Canopy interception loss protects water quality by reducing the volume of stormwater runoff and by reducing soil erosion and pollutant washout (Asadian & Weiler, 2009).

Forest type is a key determinant of canopy interception rates. In closed-canopy forests around the world, interception loss has been quantified at approximately 18–29% of total precipitation for hardwood forests, and approximately 18–45% for coniferous forests depending on the stand characteristics (Carlyle-Moses & Gash, 2011). As compared to closed-canopy forests, landscape-wide interception loss is substantially lower in urban areas where tree canopies cover a smaller proportion of the landscape, even though individual trees within an urban area may intercept more precipitation than their rural counterparts (Asadian & Weiler, 2009). For example, interception on residential properties with relatively high canopy cover in North Carolina, USA, was measured at 19.9–21.4% of total precipitation, based on averages of mean observations from 14 storms (Inkiläinen, McHale, Blank, James, & Nikinmaa, 2013). Xiao, McPherson, Simpson, and Ustin (1998) estimated that the urban forest in Sacramento, California, USA, intercepts 1.8% of gross annual precipitation citywide. However, canopy cover is relatively low in Sacramento (14%) compared to other US cities (Nowak et al., 1996), and regardless of differences in tree species composition and storm regimes, citywide interception loss would likely be substantially higher in cities with high canopy cover such as Baton Rouge, Louisiana (55% canopy cover), or Portland, Oregon (42% canopy cover).

Canopy interception loss varies according to tree attributes, phenology, and meteorological conditions (Table 1). In terms of tree attributes, interception loss varies sharply within species based on tree size and health, and among species based on differences in mature size, leaf canopy architecture, leaf area, leaf and branch angles, leaf smoothness, and bark thickness and roughness (Van Stan, Levia, & Jenkins, 2015; Xiao & McPherson, 2011, 2016; Xiao, McPherson, Ustin, Grismer, & Simpson, 2000). Xiao et al. (2000) attributed differences in percent interception loss among species primarily to tree surface area and surface storage capacity (measured as average depth of water stored on leaf and stem surfaces). In a study of twenty tree species, Xiao and McPherson (2016) found that conifers generally stored more water on plant surfaces than broadleaf trees, and leaf surfaces had larger capacities to store rainfall than stem surfaces. Van Stan et al. (2015) observed important differences in interception loss by species with different structural characteristics, with *Fagus grandifolia* (American beech) intercepting an average of approximately 500 L per storm event (21.5% interception) compared to approximately 650 L per event (27.8% interception) for similarly-sized *Liriodendron tulipifera* (tulip tree). Interspecies variability is important even within the same genus, as Livesley, Baudinette, and Glover (2014) noted interception rates of 29% vs. 44% of annual rainfall for two different *Eucalyptus* species. Phenology impacts interception loss more for deciduous than evergreen trees (e.g., conifers), as interception is much higher during leaf-on months compared to leaf-off months (Van Stan et al., 2015; Xiao & McPherson, 2011). Increased planting of broadleaf evergreens and conifers has been proposed to maintain higher levels of canopy interception during leaf-off periods for deciduous trees (Clapp, Ryan, Harper, & Bloniarz, 2014; Xiao et al., 2000).

The intensity, duration, and time between storms affects the extent to which a tree can detain or store water (Inkiläinen et al., 2013). Interception loss is higher during the wet-up period in the early stages of a precipitation event, and it decreases after tree surfaces become saturated with water (Van Stan et al., 2015; Xiao et al., 2000). A higher proportion of rainfall is lost to interception when rainfall events produce less rain, over a longer period of time, and with longer times between rain events (Xiao & McPherson, 2011). For this reason, Xiao et al. (1998) suggested that trees could provide more benefits associated with water quality protection than with flood control, because smaller rain events are responsible for the majority of pollutant washout. Xiao & McPherson (2016) provide a recent empirical assessment of canopy interception by studying differences in surface water storage capacity according to rainfall intensity, duration, and tree species. In their study, water storage on tree surfaces increased with rainfall intensity up to about 80 $mm \cdot hr^{-1}$, and storage leveled off at higher intensities. As empirical research has only been conducted in limited settings, more research is needed to fully characterize differences in performance among species, and to understand the extent to which canopy interception loss mitigates stormwater runoff problems at the scale of watersheds or sewersheds. Yet, we can anticipate that canopy interception losses can contribute to the protection of water quality by appreciably reducing the volume of stormwater runoff and by reducing soil erosion and pollutant washout.

2.2. Evapotranspiration

Evapotranspiration (ET) is a key loss in the urban hydrologic cycle comprised of evaporation from plant and landscape surfaces, and transpiration wherein water is moved along the soil-plant-atmosphere continuum as soil water is taken up by plants and subsequently lost through leaf surfaces to the atmosphere. While we are not aware of studies that specifically document the extent to which ET affects soil moisture and storage capacity with respect to managing urban stormwater, research has documented the importance of ET in the urban hydrologic cycle. Cleugh, Bui, Simon, Xi, and Mitchell (2005) used a calibrated urban water cycle model in Woden Valley, Australia, and observed that urban ET was the largest output term (81% of rainfall at 510 mm·yr^{-1}) among all relevant variables. Köhler, Schmidt, Grimme, and Laar (2002) showed that water cycling on green roofs yielded an ET rate between 60–79% of annual precipitation. Given its importance in water cycling, ET can play a critical role in urban management decisions regarding reduction of stormwater runoff, water resource use, and mitigation of urban heat islands via evaporative cooling (Peters, Hiller, & McFadden, 2011). However, while ET often represents the largest loss in water balance equations, relatively little attention has been paid to the role of ET by urban hydrologists. Indeed, few studies quantify ET in urban areas (Cleugh et al., 2005), provide in situ measurements of urban forest transpiration (Pataki, McCarthy, Litvak, & Pincetl, 2011), or measure ET in rain gardens and other green infrastructure installations (Wadzuk, Hickman, & Traver, 2014). Furthermore, quantifying seasonal or annual ET rates does not necessarily capture ET effects at temporal scales relevant to processes central to stormwater management, such as modulation of soil moisture between storm events.

Whereas estimates of gross evaporation rates are useful for investigating total landscape water budgets and energy balance, they provide minimal information about the direct contribution of water use by trees, or how the uptake of soil water may vary among taxa. The accurate estimation of ET in urban areas is clearly a precursor to maximizing the effectiveness of green infrastructure in stormwater management. Collectively, studies of urban water balance from cities representing different climates, geographic regions, and land development types demonstrate that urban areas vary in magnitude and seasonality of ET due to differences in climate, soil moisture status, irrigation, and vegetation cover (Balogun et al., 2009; Grimmond & Oke, 1999; Moriwaki & Kanda, 2004; Offerle, Grimmond, Fortuniak, & Pawlak, 2006; Peters et al., 2011). Yet, acquiring accurate ET or transpiration estimates is generally complex and time consuming. Evaporation of intercepted precipitation is affected by meteorological factors such as temperature, cloud cover, relative humidity, and wind speed (Staelens, De Schrijver, Verheyen, & Verhoest et al., 2008; Xiao & McPherson, 2011). Moreover, the spatial heterogeneity of urban landscapes greatly complicates extrapolation of water flux measurements to other cities, as soil moisture, albedo, and vegetation composition and proportional cover vary widely within and between urban areas (Peters et al., 2011). Even under the same climatic and meteorological conditions, actual ET may exhibit high spatial variability as a function of different vegetation types and land covers that are patchy at fine scales (<10 m) within urban landscapes (Liu et al., 2010).

On vegetated urban land, transpiration rates are an important factor in overall water flux. However, transpiration rates can be difficult to quantify because they reflect plant-specific information that will vary within and among species according to tree size, age, health, and soil moisture conditions. Pataki et al. (2011) surveyed urban forest transpiration rates during August in the Los Angeles, California, USA, metropolitan region and observed substantial differences among species, with estimates ranging from 3.2 ± 2.3 kg·tree^{-1}·d^{-1} in *Pinus canariensis* (Canary Island pine), a slower-growing coniferous tree, to 176.9 ± 75.2 kg·tree^{-1}·d^{-1} in *Platanus hybrida* (London plane tree), a faster-growing deciduous tree. McCarthy, Pataki, and Jenerette (2011), who also investigated transpiration rates of the urban forest in Los Angeles, reported transpiration rates varying from <5.0 × 10^{3} kg·yr^{-1} for *Brachychiton populneus* (Kurrajong) to ~2.5 × 10^{4} kg·yr^{-1} for *Gleditsia triacanthos* (honeylocust). They also observed considerable intraspecific variation, such that transpiration rates of *G. triacanthos* varied from <2.0 × 10^4 to >3.0 × 10^4 kg·yr^{-1} (McCarthy et al., 2011). An increased emphasis on urban ecohydrology studies, which include explicit ecophysiological measurements for urban-grown trees, is needed to make informed decisions about urban water management (Pataki et al., 2011).

Distinguishing among plant functional types may enable partitioning seasonal patterns of urban evapotranspiration (Peters et al., 2011). Evergreen needleleaf trees tend to have lower leaf transpiration rates than deciduous broadleaf trees (Givnish, 2002), yet both functional types tend to be more deeply rooted, and thus able to access deeper water sources, than cool season turfgrasses (Ludwig, Dawson, Prins, Berendse, & de Kroon, 2004). There are distinct seasonal patterns in physiological activity or phenology across plant functional types and among species. For instance, cool season turfgrasses show higher physiological activity in the spring and fall (Zhang et al., 2007) while deciduous broadleaf trees and evergreen coniferous trees demonstrate peak activity in midsummer (Givnish, 2002). Additionally, evergreen needleleaf trees remain physiologically active year-round compared to shorter growing season activity of either deciduous broadleaf trees or cool season turfgrasses (Catovsky, Holbrook, & Bazzaz, 2002; Givnish, 2002). Thus, a green infrastructure design that incorporates a mixture of plant functional types may be preferred for providing year-round cycling of stormwater volume inputs in urban landscapes.

Monitoring sap flux density can also provide valuable information about seasonality of transpiration rates. Studies quantifying sap flux density have become commonplace for non-urban forests, but are just beginning to emerge for urban forests (Pataki et al., 2011). For example, Wang et al. (2011) observed strong seasonality in daily sap flux density of urban trees in Beijing, China, with the highest sap flux density observed in summer. Higher daily sap flux density in summer coincides with the season of rapid growth, increased solar radiance, and abundant soil-water availability (Wang et al., 2011), which are typical conditions for treed settings in temperate and tropical ecosystems (Zeppel, Yunusa, & Eamus, 2006). In environments where soil moisture is restricted during the growing season, urban trees are maintained by irrigation, resulting in a unique mixture of biotic and abiotic conditions that make it challenging to predict urban tree transpiration *a priori* (Pataki et al., 2011). For instance, regular irrigation would provide a more homogenous soil-water profile, while sporadic irrigation would lend heterogeneity to the distribution and duration of soil water content. The concept of least limiting water range – a multifactor index of soil physical quality that integrates soil strength, aeration, and water supply to roots – may be a useful guide for managing soils to promote appropriate water availability to the root system of the tree (da Silva, Kay, & Perfect, 1994).

In the soil-plant-atmosphere continuum, latent energy fluxes are driven by atmospheric evaporative demand and limited by soil water availability (Jovanovic & Israel, 2012). Therefore, maintaining adequate soil moisture sustains the highest levels of ET. Recent studies have shown that trees may have lower ET rates than turfgrass per unit land area (Kotani & Sugita, 2005; Peters et al., 2011). Peters et al. (2011) observed that turfgrasses represented a higher contribution to annual ET than trees in recreational (77% higher) and residential (33% higher) land use types. Relative contribution of turfgrass and trees to total

ET was driven by both fractional cover and plant functional type differences in daily water use (Peters et al., 2011). Moreover, transpiration rates of trees may vary widely depending on where and how densely trees are planted. For instance, transpiration rates are 30% higher for trees grown over asphalt compared to trees grown over turfgrass (Kjelgren & Montague, 1998). Densely planted trees also transpire at rates two to three times lower than sparsely planted trees (Hagishima, Narita, & Tanimoto, 2007). While turfgrasses may typically exhibit higher total ET than trees, optimal tree planting strategies can minimize measured differences in ET, and in addition capitalize on large canopy interception losses from trees. As such, cities in mesic regions experiencing frequent rainfall events may place higher value on maintaining large-canopied trees rather than turfgrasses because trees provide co-benefits of canopy interception and water cycling via ET (Wang, Endreny, & Nowak, 2008). As with canopy interception, ET is an integral component of the urban hydrologic cycle, but more research is needed to address knowledge gaps and accurately quantify how ET losses translate to volumetric reductions in stormwater runoff across urban regions and under variable storm intensities, durations, and frequencies.

2.3. Trees improve infiltration

Incorporating trees into urban landscapes can substantially reduce stormwater runoff by improving infiltration. In experimental plots in Manchester, UK, tree pits containing small trees reduced runoff from asphalt control plots by 62%, and this reduction was largely attributed to infiltration into the tree pit (Armson, Stringer, & Ennos, 2013). So even though small trees themselves have limited capacity to capture stormwater, integrating structures like tree pits into the urban landscape for the express purpose of planting trees can increase opportunities to capture stormwater via infiltration. While canopy interception loss and transpiration may be the primary means by which trees provide direct stormwater control, trees may improve infiltration by modulating the soil ecosystem via root growth and senescence (which can create contiguous macropores), higher organic matter inputs, higher microbial activity, and stabilization or formation of soil structure. Studies in forest ecosystems have shown that stemflow leads to infiltration of precipitation within close proximity to the tree’s trunk (e.g., Tanaka, Taniguchi, & Tsujimura, 1996). Stemflow attenuates rainfall intensity, effectively slowing the delivery of water to the soil surface. The expansion of roots is especially important for generating channels in the soil to facilitate infiltration. In one greenhouse experiment, tree roots penetrated subsoils that were compacted to mimic soil conditions in urban settings, and the presence of trees increased infiltration by 63% on average compared to treeless controls (Bartens, Day, Harris, Dove, & Wynn, 2008). However, many urban trees grow on convex or mounded landscape settings that encourage runoff rather than detention and infiltration. As practiced with rain gardens and most other types of green infrastructure designed to detain and infiltrate stormwater, planting water-tolerant tree species in shallow, concave settings may be a good option for collecting runoff and allowing natural drawdown. Where soils slope away from the tree, the influence of tree morphology may be important to slow stemflow and throughfall to maximize infiltration, or to reduce ponding and subsequent erosion around the base of the tree.

2.4. Integrating trees with other green infrastructure technologies

Due in part to their unique morphology and hydrologic capacities, trees are already included in many designs for stormwater controls such as rain gardens and stormwater curb cutouts. While there is limited empirical evidence that trees improve the performance of green infrastructure installations, Scharenbroch, Morgenroth, and Maule (2016) found that tree transpiration was the primary water output from a bioswale receiving runoff from a parking lot, accounting for 46–72% of the system's water outputs. Trees may enhance the reliability and capacity of rain gardens and other infiltration- or storage-based green infrastructures by aiding in the regulation of soil moisture content (Shuster, Gehring, & Gerken, 2007). In the dry periods between storms, soil moisture redistribution is regulated by subsoil texture, layering, and its specific hydraulics. Tree root systems extend the prospects for pumping moisture out of the soil profile as transpiration. The resulting dry pore spaces provide capacity for volume inputs from subsequent storms. Trees grown in green infrastructure installations can also improve the function of these systems with regards to water quality. For instance, Denman, May, and Moore (2016) grew four street tree species in experimental rain gardens, and the trees reduced nutrient concentrations in water leaching from the systems.

Researchers have noted good health among trees integrated into infiltration-based green infrastructure systems (Denman et al., 2016; Scharenbroch et al., 2016), so trees may survive longer and grow larger in these settings compared to more stressful urban sites like tree pits along streets. Furthermore, innovative green infrastructure technologies are emerging to simultaneously reduce stormwater runoff and promote tree growth and longevity. For example, a new technique to reduce soil compaction by rebuilding urban soil profiles to a depth of 60 cm (as compared to 10–15 cm in common practice) appeared to promote growth of newly planted trees (Layman et al., 2016). Structural soils, a mixture of mineral soil and coarse stone or gravel, are an increasingly popular option for reducing conflicts between roots and infrastructure that can have stormwater management benefits (Bartens, Day, Harris, Wynn, & Dove, 2009). Planting trees in structural soils can allow greater rooting volume and infiltration capacity under paved urban surfaces as compared to typical tree pit designs (Bassuk, Grabosky, & Trowbridge, 2005; Day & Dickinson, 2008). These installations can accept and manage stormwater runoff from surrounding impervious surfaces while avoiding severe soil compaction seen in other urban tree pits, and they lead to enhanced tree growth and transpiration (Bartens et al., 2009).

Structural soils are not the only engineered system designed to reduce soil compaction and increase infiltration and tree performance. A slightly different approach employs modular structures to support aboveground pavement while providing ample uncompacted soil belowground in the void spaces of the structures (e.g., Silva Cells™, http://www.deeproot.com/products/silva-cell/overview). In these systems, the uncompacted soil can infiltrate more stormwater than a typical urban soil, and trees may exploit larger rooting volume, leading to increased tree growth, longevity, and ultimately increased hydrologic functions such as canopy interception and transpiration. Another engineered system provides an alternative to traditional tree pits, which may exhibit high soil compaction, limited rooting volume, and poor tree growth and survivorship (Bassuk et al., 2005; Day &

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Dickinson, 2008). These systems (e.g., StormTree™, http://www.storm-tree.com) rely on innovative stormwater collection systems and engineered soil media to provide improved stormwater control and enhanced tree health. As these systems for managing stormwater and improving growing conditions for trees continue to emerge and evolve, long-term monitoring is needed to understand which approaches are most appropriate in a particular setting.

The technologies described in the previous paragraphs may not be appropriate in all situations because they can be costly and may require installation of sizeable structures. As such, they may only be feasible to install during road construction and other major projects. When financial budgets are particularly tight, disconnecting rain gutter downspouts from combined sewer lines is perhaps the simplest way to reduce stormwater flow to sewer systems in residential areas. In these cases, stormwater can be routed through flow spreaders to encourage shallow sheet flow, and to protect surface soils from erosive forces. Then water should pass through vegetative ground cover that grows to at least the height of maximum anticipated flow. Finally, this stormwater can be directed toward tree species with relatively high transpiration rates (e.g., *Acer rubrum*, *Nyssa sylvatica*; Wullschleger, Hanson, & Todd, 2001) to effectively cycle the water to the atmosphere and mitigate against groundwater mounding.

2.5. Ancillary benefits increase the appeal of trees

Trees are an especially attractive stormwater control measure because they provide a suite of ancillary social, economic, and environmental benefits (Escobedo, Kroeger, & Wagner, 2011; Mullaney, Lucke, & Trueman, 2015; Nowak & Dwyer, 2007). It is already common for municipalities and private landowners to plant and manage trees for a variety of reasons including aesthetics, shade provision, increased property values, and noise reduction (Mullaney et al., 2015). Trees are also employed to mitigate pollution in the soil and groundwater through the process of phytoremediation (Pulford & Watson, 2003). Local context is an important consideration for maximizing the benefits from trees, and for reducing disservices such as overconsumption of water in semiarid regions and the release of allergens or biogenic volatile organic compounds (Escobedo et al., 2011).

Continuing to plant trees in the urban environment – but with explicit focus on strategic placement and design to reduce stormwater runoff – will promote stormwater control as well as the other ecosystem services we already rely on trees to provide. In this vein, it is important to note that we already receive stormwater benefits from existing trees (Berland & Hopton, 2014; Xiao & McPherson, 2002). Newly planted trees specifically implemented as stormwater control measures will enhance the benefits provided by the urban forest, especially if the trees are integrated using optimal site-specific designs to maximize stormwater control. For guidance on green infrastructure design tailored to specific US regions, refer to US EPA (2016). As many communities have plans to expand their tree canopy cover, there may be ample opportunities to design explicitly for stormwater control. At the same time, stormwater runoff problems are exacerbated by tree losses due to pests, inadequate tree care, structural failure, urban development, and other factors that must be considered when assessing the outlook for trees as an urban stormwater control measure.

3. Outlook and barriers to implementation

3.1. Encouraging signs

Our literature review indicates that trees interact with substantial volumes of stormwater (particularly through the processes of canopy interception and ET), suggesting that urban trees can provide appreciable stormwater control. In addition, trees have been shown to be compatible with green infrastructure technologies designed to infiltrate stormwater, and trees may improve the function of these installations especially through ET and by improving infiltration. The research community is increasingly active at the intersections of urban forestry/arboriculture, green infrastructure, and stormwater management. This includes both empirical research and modeling of vegetation impacts on stormwater (e.g., i-Tree, 2016). Continued dialogue among the empirical and modeling research communities will improve our ability to simulate the consequences of tree planting and other management practices for stormwater control.

There has been a tremendous commitment to tree planting in cities across the US and beyond. For example, New York City (Million Trees NYC, 2015), Los Angeles (City Plants, 2015), and Philadelphia (TreePhilly, n.d.) have all adopted ambitious plans to increase tree canopy in part to help alleviate stormwater problems. Understanding the effects of these programs on stormwater runoff through research and monitoring can provide invaluable broad-scale insights into the performance of trees as a stormwater control measure. At the same time, lessons learned from these programs will help guide future efforts to maximize stormwater control using urban trees and related green infrastructure technologies such as bioswales and structural soils.

3.2. Unknowns, barriers, and research priorities

Despite growing interest surrounding the use of trees for stormwater control, we recognize that several research gaps or uncertainties warrant further consideration. In our view, these can be organized into three major categories related to (1) the performance of trees as a stormwater control measure, (2) arboricultural challenges, and (3) institutional and organizational challenges. We describe key uncertainties and challenges for each of these themes below.

3.2.1. Tree performance as a stormwater control measure—To date, field studies have demonstrated the promise of trees as a viable stormwater control measure, but only in limited settings. Additional research is needed to more fully understand how trees interact with stormwater across a wider array of tree species, in different landscape contexts and geographic settings, and over longer periods of time (Table 1). The complex interactions among trees, soil, the atmosphere and meteorological conditions, and the characteristics of the surrounding landscape make this an especially daunting task (Figure 1). The urban forest is comprised of dozens of species, and characteristics that impact stormwater control (e.g., tree morphology, transpiration rates) vary sharply among species (Van Stan et al., 2015; Xiao & McPherson, 2011), even for species within the same genus (Livesley et al., 2014). Some initial recommendations have been proposed for trees that perform well as stormwater controls. In Davis, California, USA, coniferous evergreens (e.g., *Picea pungens*, blue spruce)

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had substantially higher capacities for surface water storage than broadleaf deciduous (e.g., *Pyrus calleryana*, Callery pear; *Ginkgo biloba*, ginkgo) or broadleaf evergreen (e.g., *Eucalyptus globulus,* blue gum) trees (Xiao & McPherson, 2016). Trees with large mature sizes and high stomatal conductance (e.g., *Quercus macrocarpa,* bur oak) were shown to markedly improve the function of bioswales (Scharenbroch et al., 2016). Bartens et al. (2009) recommended species that can tolerate wet soils and high pH such as *Quercus bicolor* (swamp white oak) and *Acer rubrum* (red maple) for a structural soil system. Additional comparisons of species performance in multiple urban settings (e.g., residential yards, tree pits, bioswales) are needed to develop research-based guidelines for species selection.

Along with lacking information about how most urban tree species perform as stormwater control measures, we need to improve the understanding across geographic space and over time. Existing studies are limited to a few individual trees from a small set of species, and these trees were studied for short time periods (less than one year up to several years) in a single geographic location per study. While the practical realities of the research process (i.e., limited funding, time, and labor) necessitate limited project scopes, we do not know how well the results of a few studies can be generalized broadly to guide management practices. For example, the use of deciduous trees for urban stormwater control may not translate well to the Pacific Northwest US, where the majority of rainfall is received during winter months (leaf-off period for deciduous trees) when trees intercept less precipitation (Clapp et al., 2014; Xiao & McPherson, 2016). Similarly, the difficulty in scaling up from measurements at individual trees to management-relevant spatial units like cities or watersheds presents a particular challenge for quantifying the degree to which trees contribute to urban stormwater management.

Even in places like the eastern US where the majority of rainfall is received during the leaf-on period, we need to improve the characterization of how trees interact with stormwater in different types of storm events, and how this in turn impacts stormwater runoff and combined sewer overflow events. Consistent with other forms of green and gray infrastructure, trees are best suited to directly capturing the majority of rainfall depth produced in smaller storms, which occur more frequently than large storms (Xiao et al., 2000). It is clear that canopy interception rates diminish once tree surfaces are saturated with precipitation (Van Stan et al., 2015; Xiao et al., 2000). It is also apparent that the heaviest and most intense precipitation events generate the worst stormwater runoff events. If trees are to serve as a valuable stormwater control measure in our cities, we need to better understand the effectiveness of trees in mitigating stormwater runoff during large precipitation events, and how this compares to the performance of other green and gray infrastructure technologies. It is possible that the research community is understating the importance of trees for managing soil moisture between storms and providing additional landscape-level capacity to make water available to meet evaporative demand. In this vein, research should focus on quantifying how ET between storms contributes to volumetric reductions in runoff produced by storms.

Continuing to research the role of trees in urban stormwater management will lead to improved modeling tools. At present, i-Tree (2016) offers perhaps the best models to estimate the impacts of trees on stormwater runoff at city or watershed scales. Nevertheless, even these models contain simplifying assumptions that have been largely untested in the field (Nowak et al., 2008). New data products are emerging to facilitate model refinement at the species level. For example, McPherson, van Doorn, and Peper (2016) used empirical data from across the US to develop species-level allometric equations for metrics such as crown diameter and leaf surface area that are relevant to stormwater management. Ongoing conversation between the empirical research and modeling communities can drive the development and refinement of modeling tools. The end goal should be to provide models that can be verified, validated, and calibrated with field data, and used at the local level to reliably estimate the impacts of existing and planned tree plantings on stormwater runoff. This depends on robust model parameterization according to factors such as canopy interception loss and transpiration at the species level, in various growing environments (e.g., tree lawns, tree pits, parks), at spatial and temporal scales relevant to applied stormwater management, with consideration of local soils and topography, and in the context of precipitation seasonality, frequency, and intensity in a changing climate.

3.2.2. Arboricultural challenges—Fostering the long-term growth and survival of trees in the urban environment is difficult due to a wide variety of factors (Koeser, Hauer, Norris, & Krouse, 2013). Urban trees face challenges from both environmental conditions (e.g., water stress, inadequate soil volume, severe weather) and human activities (e.g., improper pruning techniques, vandalism, root disturbance during construction). In addition, invasive pests and pathogens are a primary threat to urban trees. For example, the emerald ash borer outbreak in North America has highlighted the need for taxonomic diversity in the urban forest (Subburayalu & Sydnor, 2012) while simultaneously removing ash, a highly successful urban tree, from the list of candidates for new plantings (at least for the time being). So urban foresters are tasked with maintaining or increasing tree canopy cover (see the examples of Los Angeles, New York City, and Philadelphia above), but they must achieve those targets while considering goals for tree diversity, a tree's likelihood to thrive in a particular setting, citizen preferences, and more. If cities implement explicit plans to control a certain quantity of stormwater with their trees, the urban forester will be under increased pressure to maintain consistent canopy cover regardless of tree losses to urban expansion, the arrival of new invasive pests and pathogens, and less predictable storm regimes, all of which can reasonably be expected to occur in future decades. These issues are more unsettling when considering temporal lags in tree growth – the stormwater benefits lost due to the death of one large tree cannot be replaced for decades, even if multiple trees are planted to replace the tree that was lost. Given that storms and pest outbreaks tend to cause rapid, widespread tree losses across a city, strategies must be in place to minimize disruption in stormwater control from trees in the event that many mature trees are lost during a disaster.

3.2.3. Institutional and organizational challenges—Due to their long-standing pervasiveness in the urban environment, urban trees hold advantages over other green infrastructure in terms of public acceptance and institutionalization. Urban citizens generally hold favorable opinions of trees (Lohr, Pearson-Mims, Tarnai, & Dillman, 2004). Over 3,000 US communities participate in the Tree City USA program (Berland, Herrmann, & Hopton, 2016), which requires communities to specify a legal framework and direct funding toward their urban forestry programs. Moreover, it is increasingly common for cities to set urban forestry goals and implement monitoring programs using remotely sensed imagery (e.g., USDA Forest Service, 2014) or ground-based assessments (e.g., i-Tree, 2016). Thus, cities commonly have the basic public support and organizational structures in place to conduct proactive tree planting and management, but some challenges related to management practices and economic considerations deserve mention.

Managing urban trees for stormwater control is complicated by multiple formal and informal organizations operating in cities that may have conflicting agendas (Conway, Shakeel, & Atallah, 2011). Informal and formal organizations are in the practice of managing trees in many cities, but are not accustomed to coordinating their activities (Pincetl, 2010). Institutional differences among cities pose an additional confounding factor for the management of trees, as municipal zoning is local in nature and leads to further heterogeneity in tree policies (Conway & Urbani, 2007). In the US, local ordinances prevail when dealing with city planning and zoning regulations. Thus, the management strategy for urban trees can vary widely from city to city, even those abutting one another. Furthermore, tree management policies often vary within a city depending on whether the land is publicly or privately owned. Conway and Urbani (2007) found that municipal tree policies in metropolitan Toronto, Canada, frequently did not address private properties, which is notable because the majority of urban trees are located on private land.

Successful management of urban trees for stormwater control will require improved coordination between organizations with overlapping jurisdictions (e.g., neighborhood groups and municipal departments). This creates challenges for coordinated tree management due to cross-jurisdictional interactions (Green et al., 2015). In order for improved coordination of tree planting and management for stormwater control to occur, communication and information sharing will have to be fostered between formal and informal organizations involved in street tree management (Green et al., 2015; Young & McPherson, 2013). Because there are issues with coordination for the management of urban trees, a hybrid approach that taps traditional, informal, and market mechanisms will likely be an effective way to coordinate tree management in metropolitan areas (van de Meene, Brown, & Farrelly, 2011).

Fundamental uncertainties about the costs and short- and long-term performance of green infrastructure with respect to controlling stormwater runoff is one barrier to freer innovation and implementation. Beyond addressing scientific uncertainties, an appropriate economic framework must be in place to encourage the optimal combination of trees, other green infrastructure technologies, and gray infrastructure. In economic systems that rely heavily on markets to determine the mix of goods and services produced, ecosystem services such as canopy interception and evapotranspiration will always be degraded because no property rights have been established for them, and therefore they cannot be exchanged in markets. One of the functions of markets is to impute scarcity values to scarce resources. So even though several studies have demonstrated the stormwater benefits produced by trees (Berland & Hopton, 2014; Soares et al., 2011; Xiao & McPherson, 2002), existing markets will always assign these benefits zero value. This is one form of market failure that could be corrected with a stormwater retention trading system, a program of cap and trade for stormwater management (Goddard, 2012). Stormwater retention trading would be based on a cap on legally permitted runoff from all land parcels, providing an incentive to install green infrastructure to retain stormwater and/or to purchase the right to discharge stormwater from other parcel owners in a watershed. Such a program could greatly increase the demand for tree planting on private parcels, thus stimulating movement toward restoring predevelopment tree canopy cover and associated ecosystem services, providing a base on which to predicate expanded research on optimal species selection and spacing (Goddard, 2012). Cities like Minneapolis, MN, USA (City of Minneapolis, 2016) and Philadelphia, PA, USA (City of Philadelphia, n.d.) are implementing programs that allow landowners to reduce their stormwater fees by installing green infrastructure. Lessons learned from these innovative programs can provide guidance for other cities interested in taking similar measures to mitigate excessive stormwater runoff volumes.

4. Conclusions

Action is required to reduce urban stormwater runoff to protect human health and environmental quality. As green infrastructure becomes more prominent in stormwater management, it is increasingly important to understand how trees interact with stormwater. Research has shown that trees can play a substantial role in reducing stormwater runoff via canopy interception loss, transpiration, facilitating infiltration, and by coupling trees with other green infrastructure technologies such as bioswales and structural soils. This is promising because trees are already a major and widely distributed component of the urban environment, they have broad public appeal, and they can be planted in a relatively small footprint. At present, these desirable characteristics give trees some advantages over emerging green infrastructure technologies that occupy larger footprints, may take longer to earn public support, and have rapidly evolving designs for which the long-term performance is uncertain.

Although trees appear to hold great potential in strategic urban stormwater management, additional research is needed in four major areas: (1) documenting the performance of trees as a stormwater control with respect to species and life stage; (2) considering the influences of local soil, atmospheric, and landscape conditions when determining the applicability of trees for stormwater control; (3) navigating arboricultural challenges to situate stormwater control in the context of other urban forestry goals, for example, by maintaining diverse tree assemblages while choosing species that maximize stormwater control, and maintaining tree cover in the face of factors like tree pests and urban expansion; and (4) developing policy and economic mechanisms that encourage strategic tree planting and maintenance on public and private lands to promote cost effective management of stormwater runoff.

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Highlights (*3–5 required, 85 characters each including spaces*)

- Green infrastructure (GI) is an emerging management practice for stormwater control
- GI approaches based on infiltration overlook functions performed by trees
- Trees have a place in the future of urban stormwater management

Addressing science and policy challenges will promote successful implementation

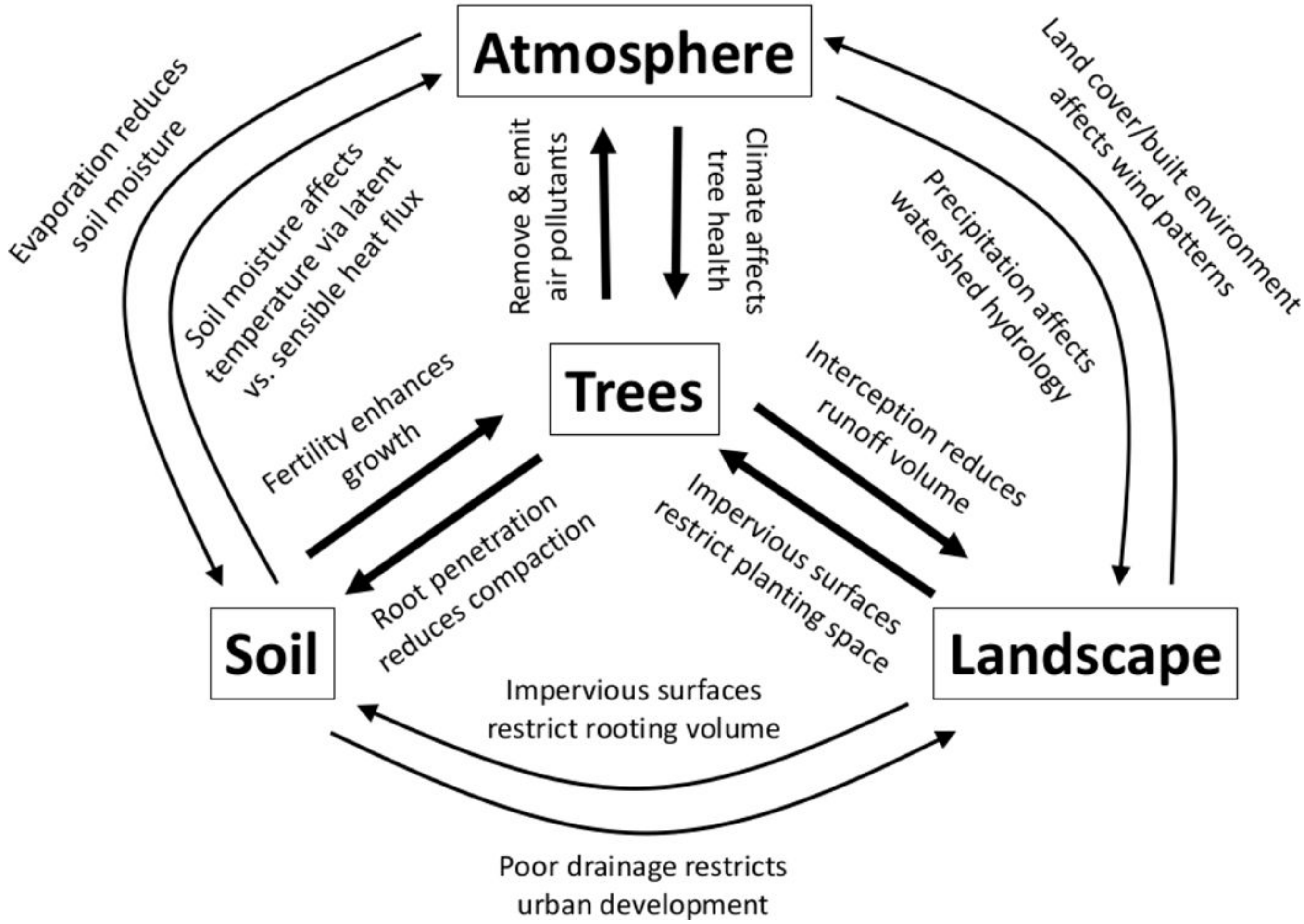

Figure 1.

Examples of interactions among trees, soil, the atmosphere, and the surrounding urban landscape. Better understanding of such interactions will facilitate improved quantification of urban hydrology, particularly with respect to the performance of trees as a stormwater control measure.

Table 1.

Major factors influencing the performance of trees as a stormwater control measure. This is not an exhaustive list. The research community should determine which factors must be quantified to reliably model the stormwater benefits expected from a tree. Key references are cited for each topic.

Tree[1]	Atmosphere[2]	Soil[3]	Landscape[4]
Evergreen/deciduous Species Phenology (leaf-on period) Size / age Health Leaf area index Leaf morphology Branch angle Bark texture Evapotranspiration rate Root structure/depth	Climate zone Annual precipitation Precipitation intensity Precipitation duration Precipitation frequency Time between storm events Temperature Evaporative demand Wind	Rooting volume Water holding capacity Fertility Compaction Drainage Green infrastructure installations (e.g., structural soils) Least limiting water range	Surrounding land cover Impervious surfaces Watershed position Pollution (air, water, soil) Tree density Open grown vs. overlapping crowns Ground cover (e.g., shrubs, turfgrass, bare ground) Slope/aspect

[1] Asadian & Weiler, 2009; Clapp et al., 2014; Givnish, 2002; Inkiläinen et al., 2013; Livesley et al., 2014; McCarthy et al., 2011; Pataki et al., 2011; Scharenbroch et al., 2016; Van Stan et al., 2015; Wullschleger et al., 2001; Xiao & McPherson, 2002; Xiao & McPherson, 2011; Xiao & McPherson, 2016

[2] Moriwaki & Kanda, 2004; Staelens et al., 2008; Van Stan et al., 2015; Wadzuk et al., 2014; Wang et al., 2011; Xiao & McPherson, 2011; Xiao & McPherson, 2016; Xiao et al., 1998

[3] Bartens et al., 2008, 2009; Bassuk et al., 2005; Day & Dickinson, 2008; Denman et al., 2016; Layman et al., 2016; Scharenbroch et al., 2016

[4] Armson et al., 2013, Hagishima et al., 2007; Inkiläinen et al., 2013; Kjelgren & Montague, 1998; Peters et al., 2011; Wang et al., 2001; Wang et al., 2008; Xiao et al., 1998