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REVIEW ARTICLE

Quantifying the benefits of urban forest systems as a component of the green infrastructure stormwater treatment network

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Abstract

The use of green infrastructure for reducing stormwater runoff is increasingly common. One under-studied component of the green infrastructure network is the urban forest system. Trees can play an important role as the "first line of defense" for restoring more natural hydrologic regimes in urban watersheds by intercepting rainfall, delaying runoff, infiltrating, and transpiring captured stormwater. However, inadequate research quantifying the urban tree contribution to rainfall/runoff processes limits their promotion by stormwater managers. The purpose of this literature review is to highlight the limited research performed, document areas of need for quantifying the benefits of urban trees for stormwater management, and provide a basis for providing credits for trees in stormwater designs. Recent research has shown that urban trees can retain a sizable volume of annual rainfall in their crowns, delay the flow of stormwater runoff, substantially increase the infiltration capacity of urban soils, and provide transpiration of sequestered runoff for additional stormwater storage. Tree canopy effectiveness is highest during short, low-intensity storms and lower as rainfall volume and intensity increases. While soils are the best medium to store and filter stormwater, trees may be integrated with other runoff reduction strategies to bring more natural hydrologic processes to urban watersheds by taking advantage of multiple points of retention. Gaps remain in the body of research, but there is a basis for considering trees an integral part of the watershed-scale green infrastructure network that helps reduce the volume and intensity of urban stormwater runoff.

KEYWORDS

green infrastructure, hydrology, interception, stemflow, throughfall, transpiration, tree, urban forest

1 | INTRODUCTION

Trees play an important role in the water cycle. They return water to the atmosphere through interception and evaporation, regulate water flow to the ground in the form of throughfall and stemflow allowing more efficient infiltration of stormwater by soils, condition the soil both physically and chemically through root action allowing for greater infiltration and percolation of water through the soil profile, and transpire water out of the soil freeing up pore space and allowing for increased soil water-holding capacity. In forested areas, this system provides ecosystem services leading to clean water for streams that feed to rivers and lakes.

Urban development traditionally has eliminated these systems (and the accompanying processes) by removing tree canopy structure, compacting and covering the soil with impervious surfaces, and replacing vegetative groundcover and mulch with high-maintenance lawns. This has led to increased urban stormwater runoff, reduced water quality, and an overall shift away from natural hydrologic regimes. With population in our urban areas predicted to further increase in the coming decades (Colby & Ortman, 2015), forest systems will increasingly be removed from the urban landscape, and excessive stormwater runoff will gradually cause localized flooding and water quality degradation resulting in scarcity of clean water for consumption and recreation. Maintaining and/or restoring forest functionality in urban ecosystems may help reduce stormwater runoff and improve water quality (Boggs & Sun, 2011; Rose & Peters, 2001; Schoonover, Lockaby, & Helms, 2006).

Green infrastructure networks include the interactive combination of natural systems in built environments that, in addition to providing numerous other ecosystem services, act to manage stormwater runoff. It is understood that trees and/or forests may not be appropriate for all land uses in a city; however, the urban environment can be designed or retrofitted to be more accommodating to trees and natural systems. Given adequate growing conditions, trees and the urban forest system may be useful to stormwater managers and design engineers to help them manage and mitigate the effects of stormwater runoff. The purpose of this literature review is to (a) highlight research performed to quantify stormwater runoff mitigation benefits supplied by urban trees, (b) to provide areas of need for future study to better understand how trees contribute to more natural hydrology in urban watersheds, and (c) to influence policy by providing a basis for taking credits for trees in stormwater designs.

This review is focused solely on the benefits directly attributable to trees for urban stormwater management and thus does not include discussion of riparian system interactions with streams, or tree contributions to other green infrastructure practices such as bioretention or stormwater wetlands, both of which are critical and worthy of study in their own right. Many studies of tree influence on hydrology are performed at the site scale; thus, this is the primary focus of this review. Where possible, the effects of these local processes on watershed scale hydrology are presented, but literature in this area is largely lacking.

2 | TREE CANOPY AND RAINFALL RETENTION

At the site scale, the tree canopy (i.e., leaves and branches) is often the first point of contact for rainfall. It acts to intercept and facilitate evaporation of captured water and prevent it from reaching the ground and becoming runoff. Despite relatively limited study in urban areas, quantification of rainfall interception by tree canopy in natural forests has been performed extensively around the world (Sun & Lockaby, 2012). Typically, conifer forests intercept and evaporate 20–40% of annual rainfall while deciduous forests intercept 10–20% (Xiao, McPherson, Ustin, Grismer, & Simpson, 2000). Known as interception loss, this retained percentage of rainfall does not contribute to stormwater runoff. However, Xiao et al. (2000) explained that tree canopy architecture (i.e., leaf area, leaf angle distribution, leaf surface characteristics) and tree spacing in these natural forests differ from open-grown trees in urban settings and as such may not intercept as much rainfall under canopy as urban trees. Thus, investigation into research performed in a more similar environment is important.

Interception loss by tree canopy depends on many variables, including rainfall intensity and duration, climatic conditions (i.e., solar intensity, relative humidity, wind speed, and ambient temperature), and tree crown structure (Asadian & Weiler, 2009; Livesley, Baudinette, & Glover, 2014; Staelens, Schrijver, Verheyen, & Verhoest, 2008; Xiao et al., 2000). The amount of reported interception loss under open-grown tree canopy, a more similar environment to that of urban settings compared to forest-based evaluations, ranges from less than 10% under citrus trees in southeast Florida during the summer, where rainfall volume and intensity can be great, (Li, Alva, Calvert, & Zhang, 1997) to more than 80% for coniferous trees in Vancouver, British Columbia, where rainfall intensity is relatively light (Asadian, 2010).

2.1 | Leaf area

Leaf area is one factor that affects rainfall retention. Xiao et al. (2000) showed that open-grown, evergreen cork oak (*Quercus suber*) canopy retained 27% of the gross winter precipitation compared to 15% for a leafless Bradford pear (*Pyrus calleryana* "Bradford") canopy over two separate winter seasons in a Mediterranean climate region in California. Staelens et al. (2008) also found that a mature, deciduous beech (*Fagus grandifolia*) with leaves retained 31% of the cumulative precipitation in leaf-on periods compared to 10% in leaf-off periods in Ghent, Belgium. Cumulatively, the tree canopy was reported to retain 21% of the rainfall over the 2-year period. Comparing cumulative rainfall retention among three different tree species of varying sizes in Oakland, CA, Xiao and McPherson (2011) showed that a small, evergreen lemon tree (*Citrus limon*) retained relatively more rainfall (27.0%) than the medium-sized, deciduous sweetgum (*Liquidambar styrciflua*; 14.3%) and larger, deciduous ginkgo (*Ginkgo biloba*; 25.2%) during the October through May rainy season. They explained that the greater leaf surface area during the winter rainy season allowed the lemon tree to store a greater percentage of rainfall. Livesley et al. (2014) likewise found a positive relationship between leaf area and rainfall retention using two species of street trees common in Melbourne, Australia. They reported 44% annual rainfall retention for Eucalyptus nichollii (3.9 plant area index, PAI) compared with 29% retention for *Eucalyptus saligna* (3.0 PAI). They reason that planting trees with high leaf area over open, impervious surfaces could easily achieve 20% annual stormwater runoff reduction. In a semi-arid, urban setting in the mountains of central Mexico, Guevara-Escobar, Gonzalez-Soza, Veliz-Chavez, Ventura-Ramos, and Ramos-Salinas (2007) reported that a weeping fig (*Ficus benjamina*) retained almost 60% of the gross precipitation over a 3-month period during the summer rainy season. They acknowledged that their results were much greater than those of others but explained that evaporation due to low-relative humidity and high-ambient temperatures attributed to the high-retention rate. In Coastal British Columbia, evergreen species, Douglas-fir (*Pseudotsuga menziesii*) and Western red cedar (*Thuja plicata*), were also found to retain 49% and 61% cumulative gross precipitation, respectively (Asadian & Weiler, 2009). It was explained that this large percentage of retention was due to the long, low rainfall intensity events. Expanding rainfall retention rates to the urban forest canopy level, Inkilainen, McHale, Blank, James, and Nikinmaa (2013) calculated that the study area, having 67% tree canopy cover in a sub-tropical climate in Raleigh, NC, retained between 9.1% and 10.6% of the cumulative rainfall during the 4-month study period between late July and mid-November. By averaging the means of each storm, they reported retention to be 19.9 or 21.4% assuming stemflow to be either 0.5% or 2.0% of throughfall, respectively. They explain that comparing stand-level results, such as their study, with crown-level results, such as mentioned above, would be faulty because they captured throughfall at random locations throughout the study area and not necessarily directly under tree canopy cover. As a result, they reported much lower retention percentages compared to the above crown-based studies. In their study, percent canopy cover statistically explained interception more so than leaf area index (LAI). Table 1 provides percentages of interception loss from urban or open-grown trees from literature, where the influence of rainfall patterns is apparent and a critical explanatory variable for tree interception quantification.

2.2 | Leaf storage capacity

Fundamentally, leaves have an approximate depth of water retention that ranges by species from 0.03 mm (or kg H_2O m^{-2} of one-sided leaf area; Aston, 1979) to 2.24 mm (Xiao & McPherson, 2016) when subjected to simulated rainfall events in the laboratory. Aston (1979) reported interception storage depth for common deciduous field species in Australia ranging from 0.03 mm for *Eucalyptus viminalis* and *E. maculata* to 0.18 mm for *E. pauciflora*. The lone evergreen species studied, *Pinus radiata*, was reported to have a mean depth of water storage of 0.08 mm. These values were recorded 2 min after the simulated rainfall had stopped, thus allowing excess water to drip from the leaves surfaces. The depth of foliar retention during the rainfall event for this study was calculated to be two to four times greater than what was reported based on drip rates from Keim, Skaugset, and Weiler (2006). Using deciduous forest species common to the Pacific Northwest, *Acer macrophyllum* and *Alnus rubra*, Keim et al. (2006) showed that foliage stored between 0.09 and 0.42 mm of rainfall during a simulated rain event. The three evergreen species studied (*Thuja plicata*, *Pseudotsuga menziesii*, and *Tsuga heterophylla*) showed greater depth of water retention compared to the deciduous species storing between 0.17 and 1.08 mm depending on rainfall intensity. Foliar rainfall retention was also shown to increase with increasing rainfall intensity but quickly fell to some steady-state storage capacity after rainfall simulation stopped. This implies that a portion of rainfall is temporarily stored and not truly retained.

2.3 | Leaf characteristics

Leaf architecture, morphology, and hydrophobicity seem to play a role in rainfall retention. Using 10 commonly found broadleaf street tree species from Davis, California, Xiao and McPherson (2016) reported mean leaf surface retention depths of 0.97 mm ranging from a minimum of 0.29 mm for Raywood ash (*Fraxinus angustifolia* Vahl "Raywood") to a maximum of 2.24 mm for Chinese pistache (*Pistachio chinensis* Bunge). These values may overestimate the depth of water that is retained as they are means taken from 12 sequential rainfall intensities ranging from 3.6 to 139.7 mm/hr. As with Keim et al. (2006), these values show that rainfall is temporarily stored. They explain that rigid, rough-surfaced leaves tend to store greater volume of water than flexible, smooth surfaces. Raywood ash has flexible leaves with smooth surfaces that may contribute to its reduced water-holding ability, while Chinese pistache leaves are more rigid with rough surfaces. Holder (2013) also found in a rainfall simulation study using common Colorado tree species that leaf surface water storage was lower on leaves with higher leaf hydrophobicity, a measure of

TABLE 1 Relevant urban or open-grown tree canopy and rainfall interception research

Species	Reported rainfall retention (%)	Foliage present	Crown area index	Rainfall intensity (mm/hr)	Location	Reference
Citrus	6–9	Yes	–[a]	38–61[b]	Fort Pierce, FL	Li et al. (1997)
Citrus limon	27	Yes	3.0	11–14[b]	San Francisco, CA	Xiao and McPherson (2011)
Eucalyptus nicholii	44	Yes	3.9	14[f]	Melbourne, Australia	Livesley et al. (2014)
Eucalyptus saligna	29	Yes	3.0	14[f]	Melbourne, Australia	Livesley et al. (2014)
Fagus grandifolia	31	Yes	5.5	0.8,1.6[c]	Ghent, Belgium	Staelens et al. (2008)
Fagus grandifolia	10	No	–[a]	0.6,1.4[c]	Ghent, Belgium	Staelens et al. (2008)
Ficus benjamina	60	Yes	–[a]	1.2–20.3	Queretaro City, Mex.	Guevara-Escobar et al. (2007)
Gingko biloba	38	Seasonal	5.2	11–14[b]	San Francisco, CA	Xiao and McPherson (2011)
Liquidambar styraciflua	14	Seasonal	4.7	11–14[b]	San Francisco, CA	Xiao and McPherson (2011)
Pyrus calleryana	15	No	–[a]	1–28	Davis, CA	Xiao et al. (2000)
Pseudotsuga menziesii	49	Yes	–[a]	1.1,13.3[c]	Vancouver, BC	Asadian and Weiler (2009)
Quercus suber	27	Yes	3.4	1–28	Davis, CA	Xiao et al. (2000)
Thuja plicata	61	Yes	–[a]	1.1,13.3[c]	Vancouver, BC	Asadian and Weiler (2009)
Coniferous—summer[e] Coniferous—winter Deciduous—summer Deciduous—winter	81.7 71.4 67.1 45.8	Yes Yes Yes No	[a]	1.2	Vancouver, BC	Asadian (2010)
Variable (67% tree canopy cover)	21[d]20	Seasonal	1.9	32–38[b]	Raleigh, NC	Inkilainen et al. (2013)

[a]Crown area index not provided.

[b]Rainfall intensity not given; 90% confidence interval of rainfall intensity provided by NOAA Atlas 14 Point Precipitation Frequency Estimates for the 1-year, 60-min rainfall event (http://hdsc.nws.noaa.gov/hdsc/pfds).

[c]Average rainfall intensity over the period of study and maximum 60-min event intensity, respectively.

[d]Storm-based average assuming stemflow of 0.5% and 2.0%.

[e]Summer is defined as data collected between April and October, and winter is between November and March.

[f]Rainfall intensity not given; average recurrence interval of rainfall intensity for the 1-year, 60-min rainfall event provided by Australian Government, Bureau of Meteorology Rainfall IFD Data System (http://www.bom.gov.au/water/designRainfalls/ifd/).

how repellent a water droplet is on the surface of leaves. He reported ranges from 0.13 mm for *Catalpa speciosa* to 0.21 mm for *Ulmus pumilla* after adjusting his results from two-sided to one-sided mean leaf surface retention by doubling his reported values. Table 2 shows depth of water on leaves and branches by species from published reports.

2.4 | Contribution of branches and stems

Tree branches and stems have also been found to intercept and store a significant volume of rainfall. Open-grown trees, as typically found in urban settings, have been found to have differing interception coefficients compared to rural forest trees due to crown architecture among other factors (Asadian & Weiler, 2009; Xiao et al., 2000). Urban trees typically have greater branch and stem bark area compared to trees in forested stands. Therefore, open-grown trees tend to have greater crown volume or live crown ratio due to the lack of direct competition for sunlight (Smith, 1986). Xiao et al. (2000) reported that a 9-year-old, leafless Bradford pear (*Pyrus calleryana* "Bradford") retained 15% of the total winter rainfall. Open-grown European beech (*Fagus sylvatica*) was reported to cumulatively retain 10% of rainfall over two winter seasons in Belgium when the tree was leafless (Staelens et al., 2008). In a laboratory rainfall simulation study, Xiao and McPherson (2016) reported that leafless stem samples from 10 deciduous, urban street tree species temporarily stored on average 0.25 mm (volume of water per unit of surface area) of rainfall during the event ranging between 0.14 and 0.36 mm. This was approximately 25% of the rainfall stored by the foliage of these samples.

2.5 | Scaling hydrologic effects

Tree canopy with foliage typically retains the first 2–4 mm of rainfall (Livesley et al., 2014; Staelens et al., 2008; Xiao et al., 2000) depending on the amount of leaf area. Using this range of 2–4 mm for a large tree with an average crown diameter of 10 m yielding a projected canopy area of 314 m^2, we could expect to retain 0.63 to 1.26 m^3 of rainfall per event. That is equivalent to 166 to 332 gallons of water. Greater leaf area within the crown provides greater rainfall interception (Aston, 1979; Livesley et al., 2014). As a result, very little rainfall will reach the ground under the tree canopy in small rainfall events. Although this amount (2–4 mm) seems small, runoff can occur with very little rainfall on impervious surfaces, as studies such as Pandit and Heck (2009) showed nearly all rainfall becomes runoff on asphalt with a shallow slope.

3 | TREE CANOPY AND RAINFALL DETENTION

The characteristic temporal distribution of rainfall for a given region can influence canopy interception. Rainfall patterns vary substantially across the world, with greater intensity observed in locations such as the Southeastern United States. It has been argued that with these types of storm events, increasing tree canopy cover will not increase rainfall retention appreciably (Inkilainen et al., 2013). For smaller, less intense storm events, trees with greater aboveground surface area are able to retain a larger percentage of rainfall; however, with prolonged and/or more intense storm events, rainfall is temporarily stored in the canopy and released gradually as throughfall or stemflow. During intense rainfall events, tree canopy can temporarily detain rainfall and gradually release it, thus delaying peak runoff to stormwater infrastructure and potentially increasing soil infiltration capacity (Asadian & Weiler, 2009; Keim et al., 2006; Livesley et al., 2014; Xiao et al., 2000).

As the surfaces in a tree's canopy approach their maximum holding capacity, throughfall and stemflow become critical processes. Throughfall is that portion of the intercepted rainfall that drips from the canopy of trees, and stemflow is the runoff that travels from the canopy to the ground via the tree stem. Both throughfall and stemflow contribute to delaying stormwater runoff.

Directing rainfall to a single point at the base of a tree via stemflow rather than throughout the projected canopy area as throughfall can be a useful urban stormwater runoff mitigation strategy. Usually, the base of urban trees interact with some permeable surface cover such as soil or mulch allowing runoff to infiltrate into the surrounding soil or be stored in the mulch layer. Stemflow volume has been shown to be greatly affected by bark texture (smoothness), branch angle, rainfall intensity, and windspeed (Carlyle-Moses & Schooling, 2015; Herwitz, 1987; Livesley et al., 2014; Schooling & Carlyle-Moses, 2015; Staelens et al., 2008; Xiao et al., 2000). Xiao et al. (2000) observed that stemflow accounted for approximately 15% of total rainfall on an open-grown, evergreen oak species with rough bark texture compared to 8% for an open-grown, leafless pear species with smooth bark. Staelens et al. (2008) likewise reported 8% of the cumulative annual rainfall went toward stemflow on a smooth-barked beech species. Differences were found between the in-leaf and leafless periods ranging from 6.4% stemflow during the leaf-on season to 9.5% during the leaf-off season. Using a larger sample size (37 trees) and more tree species (27 species) in an urban park, Schooling and Carlyle-Moses (2015) showed great variability among species and rainfall depth classes. Over the 18-month study period, stemflow accounted for approximately 3% of total rainfall for rain events greater than 10 mm. Generally, there was a positive relationship between rain depth class and stemflow percent. As the volume of rainfall increased a greater percentage of intercepted rainfall reached the ground as stemflow. Species demonstrating the greatest stemflow throughout the study included English columnar oak (*Quercus robur columnar*), Armstrong Freeman maple (*Acer x freemanii* "Armstrong"), and Riversii European beech (*Fagus sylvatica* "Riversii") which averaged approximately 10% stemflow for rain events greater than 5 mm. This is most likely due to their acute branch angles for the oak and maple and smooth bark with multiple codominant stems for the beech.

Throughfall by far makes up the greatest portion of rainfall interception by a tree canopy ranging from 29% under open-grown, evergreen weeping fig trees in semiarid regions of Mexico with average rainfall intensity of 7.5 mm/hr to 93% under open-grown citrus trees in Florida during the summer where rainfall intensity averages 49 mm/hr[1] (Guevara-Escobar et al., 2007; Li et al., 1997). This portion of the interception process has been shown to reduce rainfall intensity

[1]No intensity data given in article; estimation based on NOAA Hydrometeorological Design Studies Center, Precipitation Frequency Data Server at http://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html?bkmrk=fl

TABLE 2 Reported depth of water storage on foliage and stem per unit area in simulated rainfall research

Species	Foliage or Branch	Mean depth of water storage (mm)	Origin of plant material	Reference
Acacia longifolia	Foliage	0.08[a]	Forest	Aston (1979)
Acer macrophyllum	Foliage	0.18[b]	Forest	Keim et al. (2006)
Acer saccharinum	Foliage	0.13[c]	Urban	Holder (2013)
Alnus rubra	Foliage	0.20[b]	Forest	Keim et al. (2006)
Catalpa speciosa	Foliage	0.13[c]	Urban	Holder (2013)
Celtis sinensis	Foliage	0.94	Urban	Xiao and McPherson (2016)
Celtis sinensis	Branch	0.17	Urban	Xiao and McPherson (2016)
Cinnamomum camphora	Both	0.79	Urban	Xiao and McPherson (2016)
Eucalyptus cinerea	Foliage	0.11[a]	Forest	Aston (1979)
Eucalyptus dives	Foliage	0.07[a]	Forest	Aston (1979)
Eucalyptus globulus	Both	0.70	Urban	Xiao and McPherson (2016)
Eucalyptus maculata	Foliage	0.03[a]	Forest	Aston (1979)
Eucalyptus mannifera	Foliage	0.09[a]	Forest	Aston (1979)
Eucalyptus pauciflora	Foliage	0.18[a]	Forest	Aston (1979)
Eucalyptus viminalis	Foliage	0.03[a]	Forest	Aston (1979)
Fraxinus angustifolia	Foliage	0.75	Urban	Xiao and McPherson (2016)
Fraxinus angustifolia	Branch	0.25	Urban	Xiao and McPherson (2016)
Fraxinus uhdei	Both	0.78	Urban	Xiao and McPherson (2016)
Gingko biloba	Foliage	0.73	Urban	Xiao and McPherson (2016)
Gingko biloba	Branch	0.18	Urban	Xiao and McPherson (2016)
Gleditsia triacanthos	Foliage	0.70	Urban	Xiao and McPherson (2016)
Gleditsia triacanthos	Branch	0.33	Urban	Xiao and McPherson (2016)
Gleditsia triacanthos	Foliage	0.18[c]	Urban	Holder (2013)
Lagerstroemia indica	Both	0.59	Urban	Xiao and McPherson (2016)
Liquidambar styraciflua	Foliage	1.16	Urban	Xiao and McPherson (2016)
Liquidambar styraciflua	Branch	0.37	Urban	Xiao and McPherson (2016)
Magnolia grandiflora	Both	0.81	Urban	Xiao and McPherson (2016)
Picea pungens	Both	1.81	Urban	Xiao and McPherson (2016)
Pinus canariensis	Both	0.99	Urban	Xiao and McPherson (2016)
Pinus pinea	Both	1.04	Urban	Xiao and McPherson (2016)
Pinus radiata	Foliage	0.08[a]	Forest	Aston (1979)
Pistacia chinensis	Foliage	1.51	Urban	Xiao and McPherson (2016)
Pistacia chinensis	Branch	0.21	Urban	Xiao and McPherson (2016)
Platanus x hispanica	Foliage	1.10	Urban	Xiao and McPherson (2016)
Platanus x hispanica	Branch	0.28	Urban	Xiao and McPherson (2016)
Populus deltoides	Foliage	0.19[c]	Urban	Holder (2013)
Populus tremuloides	Foliage	0.15[c]	Urban	Holder (2013)
Pseudotsuga menziesii	Foliage	0.26[b]	Forest	Keim et al. (2006)
Pyrus calleryana	Foliage	0.57	Urban	Xiao and McPherson (2016)
Pyrus calleryana	Branch	0.23	Urban	Xiao and McPherson (2016)
Quercus gambelii	Foliage	0.15[c]	Urban	Holder (2013)
Quercus lobata	Foliage	1.20	Urban	Xiao and McPherson (2016)
Quercus lobata	Branch	0.25	Urban	Xiao and McPherson (2016)
Quercus ilex	Both	0.82	Urban	Xiao and McPherson (2016)
Sequoia sempervirens	Both	1.16	Urban	Xiao and McPherson (2016)
Thuja plicata	Foliage	0.26[b]	Forest	Keim et al. (2006)
Tsuga heterophylla	Foliage	0.48[b]	Forest	Keim et al. (2006)
Ulmus pumila	Foliage	0.21[c]	Urban	Holder (2013)

(*Continues*)

TABLE 2 (Continued)

Species	Foliage or Branch	Mean depth of water storage (mm)	Origin of plant material	Reference
Zelkova serrata	Foliage	1.05	Urban	Xiao and McPherson (2016)
Zelkova serrata	Branch	0.18	Urban	Xiao and McPherson (2016)

[a]Depth was calculated by converting water storage in kg to m^3, dividing by leaf area (m^2), and then converting to mm.

[b]Depth was calculated by converting steady-state water storage at 20 mm/hr from g to m^3, dividing by leaf area (m^2), and then converting to mm.

[c]Depth was calculated by converting leaf surface storage in g/m^2 to m^3/m^2, multiplying by 2 to account for two-sided leaf storage capacity, and then converting to mm.

and regulate stormwater flow that can help permeable surfaces infiltrate runoff more efficiently.

Rainfall intensity has a positive correlation with peak stormwater flow, potentially allowing downstream stormwater practices to work more efficiently after receiving more metered inflows. Trimble and Weitzman (1954) showed that rainfall intensity was reduced under a deciduous forest canopy cover by up to 21% in the summer when leaves are present and 19% during the winter when they are not present. Average maximum 5- and 15-min intensities were reduced during the summer from 1.18 to 1.00 in./hr (5 min) and 0.72 to 0.57 in./hr (15-min), while during the winter, reductions were reported from 0.64 to 0.52 in./hr (5-min) and 0.37 to 0.31 in./hr (15-min). They explain that these reductions are dependent on season and rainfall intensity. It was observed that foliated tree canopy reduced intensity more during lower intensity rainfall, less than 0.5 in./hr, while leafless tree canopy was better able to reduce rainfall intensity for storms greater than 0.5 in./hr. They explained that the possible reason for this reduction in effectiveness of leaf-on canopy during higher intensity rain events could be due to the force of water on the leaves causing a change in leaf orientation directing water stored on the leaf surface downward rather than toward the branch to which the leaf is attached. This would lead to increases in throughfall rather than stemflow. Keim and Skaugset (2003) reported greater rainfall intensity reductions in predominantly coniferous forests in western Oregon and Washington. Peak intensities were reduced by up to 52% in a younger forest stand with homogeneous canopy cover during a late-summer rain event with peak rainfall intensity approximately 0.8 mm/min. Average intensity reduction was about 27%. Meanwhile, in an old-growth forest with multiple gaps in the canopy, Keim and Skaugset (2003) observed that rainfall intensity was reduced by up to 83% in an early-summer storm with peak rainfall intensity near 1.6 mm/min. Average intensity reduction for that event was approximately 36%. Responses were more consistent in the younger stand because of its closed canopy.

Tree canopy detention of rainfall has been shown to increase with rainfall intensity (Keim et al., 2006; Xiao & McPherson, 2016). Keim et al. (2006) showed that foliage can temporarily store greater volume of rainfall with increasing rainfall intensity after canopy saturation. They dismiss the common bucket model concept that essentially states that once tree canopy area capacity for precipitation is reached no more rainfall can be detained. Instead, they offer a conceptual mechanical model for tree canopy interception processes that includes “static canopy storage” and “dynamic storage.” Static canopy storage is that water remaining on crown surfaces after rainfall ceases due to a balance between gravitational and interfacial forces, while dynamic storage has to do with changes in momentum due to external forces such as wind and rainfall intensity. This model explains how greater temporary storage capacity of rainfall in tree crowns can be achieved.

To our knowledge, no research investigating rainfall intensity under urban tree canopy cover has been performed. Increased rainfall intensity reduction benefits may be observed in urban environments because open-grown trees typically have greater above-ground surface area from branches and leaves compared to forest-grown trees. Using forest-based models for rainfall intensity could be a good starting point to develop models better suited for representing urban tree canopy cover. Quantifying these benefits could help stormwater managers and planners strategically manage developed watersheds to increase stormwater runoff mitigation efforts.

It should also be noted that throughfall has been shown to continue for a considerable amount of time after a storm event, further demonstrating that rainfall rates under tree canopy are regulated over time (Asadian & Weiler, 2009; Keim et al., 2006; Xiao et al., 2000). This ability of tree canopy to detain rainfall and gradually release it over time provides a type of controlled stormwater flow mechanism. This may be beneficial for metering the volume of water and minimizing overland flow velocity to stormwater infrastructure, thus reducing their incidences of inundation. Because of this delay in throughfall initiation, it is suggested that peak stormwater discharge could also be delayed (Asadian & Weiler, 2009; Xiao et al., 2000). This increased lag time between initiation of rainfall and peak runoff may help stormwater control measures (SCMs) reach their full storage and infiltrative capability. As noted by the small number of studies, this is an area of need for research. In particular, how these local observations of throughfall scale to the flow patterns in the larger watershed is largely not understood.

4 | URBAN FORESTS AND PEAK DISCHARGE REDUCTION

If tree canopy retains/detains rainfall and gradually releases throughfall/stemflow over time, we should expect that total peak stormwater discharge would also be reduced in urban watersheds with high percentages of forested land cover. This is likely true for smaller, less intense storms where a higher percentage of rainfall is retained by the tree canopy. However, the benefits of tree canopy are reduced as rainfall volume increases. Although several publications imply that urban forest cover reduces peak stormwater discharge (Asadian & Weiler, 2009; Chair, 2000; Inkilainen et al., 2013; Xiao et al., 2000), no literature could be found that specifically studied this relationship. Peak flow mitigation is a critical element in reducing the number of channel forming events, or events with sufficient magnitude to influence stream channel geometry, in urban streams. Leopold (1968) noted that an increased number of channel forming events is a product of urbanization that is detrimental to stream quality. Thus, migration of the water cycle back to a more natural state by increasing urban tree canopy is a topic worthy of further research.

5 | TREES AND SOIL INFILTRATION

It is well established that soil provides greater stormwater storage than tree canopy cover (Anderson, Hoover, & Reinhart, 1976). Soils store large amounts of water, delay flow to receiving waters, and filter pollutants from stormwater runoff. Typical urban development compacts existing soil to provide the necessary structural stability on which to build structures, roads, and so on. Compacted soil loses its ability to store and conduct water as macropores are reduced (Scheyer & Hipple, 2005). Gregory, Dukes, Jones, and Miller (2006) found that compaction due to construction activity reduced infiltration rates on sandy soils in North Central Florida by 70% to 99%. Increasing soil permeability of urban soils not only reduces stormwater runoff volume but also stores water belowground for urban tree use.

Tree root penetration into surrounding soils has been shown to increase water infiltration (penetration of rainfall into soil) and percolation (filtration of stormwater through soil). In a predominantly spruce forest in Switzerland, Lange, Luescher, and Germann (2009) found that tree root density in stagnic soils (soils periodically saturated with ground water) with predominantly clayey subsoil increased soil water storage capacity and preferential infiltration significantly. In a more urban setting, Zadeh and Sepaskhah (2016) reported greater water infiltration under tree canopy compared to soil away from tree canopy by 69–354% on the Shiraz University campus in Iran. The greatest cumulative infiltration was observed in clay loam soils with 37% clay and 34% silt content. Infiltration rates were also reported to increase by 800% under tree canopy in clay loam soil and 283% in sandy loam soil. They speculate that this increase in infiltration is due to the increased presence of roots under tree canopy where channels are formed to allow water to penetrate the soil layer. In a greenhouse study, Bartens, Day, Harris, Dove, and Wynn (2008) showed that the roots of two deciduous tree species grown in compacted clay loam subsoil were able to penetrate the compacted soil and increase infiltration rates by an average of 153% compared to the unplanted controls. The study also showed that the roots of trees growing in structural soil penetrated the underlying compacted clay loam subsoil base and increased infiltration rates by 27-fold compared to unplanted controls (Bartens et al., 2008). This body of research suggests that tree roots condition soil and increase its ability to infiltrate, store, and percolate stormwater runoff. Inclusion of urban trees in greenspaces around municipalities could help store more runoff and reduce volume to receiving waters. To our knowledge, no research has been carried out to quantify stormwater runoff volume reduction in urban watersheds due to impacts of trees or urban forest systems on a soil's infiltrative capability or water-holding capacity.

6 | URBAN FORESTS AND TRANSPIRATION

Trees remove stored water from soil through their roots and return it to the atmosphere as water vapor primarily via their foliage. This process, transpiration, depends on many environmental (i.e., light, temperature, humidity, wind, and soil moisture) and structural (i.e., species, density, and leaf area) factors. By removing water from the soil, trees free soil pore space such that the total amount of stormwater held by the soil is increased, that is, permitting subsequent rainfall to be stored in the vacated soil pores.

Little research has been performed to quantify the amount of water trees transpire from the soil in urban areas. Modeling transpiration using mean monthly stomatal conductance values, Scharenbroch, Morgenroth, and Maule (2016) reported that trees in parking lot bioretention systems in Chicago, IL, Unites States, accounted for 46–75% of the total water outputs of those practices. They argue that urban trees contribute greatly to green infrastructure practices and are effective in reducing stormwater runoff. In Rotterdam, the Netherlands, using sapflow measurements on five trees and extrapolating data upwards, Jacobs et al. (2015) estimated that the urban forest transpires 26% of the total precipitation over the growing season excluding the leafless and initial leaf-expansion periods early in the growing season. They suggested that this percentage of transpiration city-wide was low, but concede that their selection of tree species in this study may have affected the overall estimates as transpiration rates by species can be highly variable.

Quantifying transpiration rates at the tree level could be beneficial for engineers when designing green stormwater treatment practices; however, few studies on urban trees have been performed. In a greenhouse study using red maple cultivars in lysimeters, Fair, Metzger, and Vent (2012) reported mean daily transpiration rates of 0.3 to 0.6 mm of water per unit leaf area over a 3-year period. They found that soil bulk density may be a key factor in transpiration processes. For the first 2 years of the study, they found that transpiration rates were reduced by 70–80% in trees grown in soil compacted to a bulk density of 1.77 g/cm compared to that having a bulk density of 1.64 g/cm. They theorized that these differences may have been caused by higher volumetric water content and greater water availability in the less compacted soil treatment. Using potted Callery pear (*Pyrus callyerana*) trees, Kjelgren and Montague (1998) reported daily water loss of 1.04 and 0.75 mm per unit leaf area for trees set in a parking lot and turf environment, respectively, in Carbondale, IL, United States. In a follow-up investigation in Logan, UT, United States, they found that daily water loss for potted green ash (*Fraxinus pennsylvanica*) transpired between 0.75–2.60 mm of water per unit leaf area in parking lots and 1.52–2.10 mm on irrigated turf, while Norway maple (*Acer platanoides*) had a range of 0.49–1.61 and 1.13–1.46 mm in a parking lot and turf environment, respectively. They explained that increased long-wave radiation from the leaves of trees over parking lot surfaces had a significant effect on transpiration by increasing water flux in temperate areas or by causing stomatal closure in more arid areas. Wang et al. (2012) were able to show that tree canopy transpiration for horse chestnut (*Aesculus chinensis*) averaged 1.5 mm of water per day per square meter of projected canopy cover area during the growing season (April–October) in Beijing, China. It was observed to be as high as 2.5 mm. They found that transpiration rates were positively related to LAI, and it was the most important factor affecting transpiration. Chen et al. (2011) found similar results, where four species of trees, grown in urban settings in Liaoning Province, China, transpired an average of 1.4 mm of water per day per unit area of projected canopy cover during late-summer to early-autumn. They reported that daily transpiration was not significantly correlated with soil moisture content as they found no reduction in transpiration during short periods of drought. This lack of reduction was attributed to deep or extensive lateral root systems allowing the trees to access stored water deeper in the soil profile. In a more Mediterranean climate (Los Angeles, CA, United States), Pataki, McCarthy, Litvak, and Pincetl (2011) found transpiration to be highly variable among species and densities. They reported urban tree transpiration rates on a per ground plot area basis ranging between <0.5 mm per day for non-native Canary Island pine (*Pinus canariensis*) and 2 mm per day for native London planetree (*Platanus hybrida*). For comparison to urban trees, in a forested environment in western North Carolina, Ford, Hubbard, and Vose (2010) reported that deciduous and coniferous species transpired approximately 1.1 and 2.5 mm per day, respectively, per square meter of projected canopy cover area during the growing season (May through September). These transpiration rates correlate well with those of trees in urban settings. Table 3 shows relevant tree canopy and transpiration rate research. Further, green infrastructure technologies such as bioretention areas are constructed such that they receive runoff and thus may act as islands of high soil moisture in the urban environment. How such areas may influence transpiration rates for nearby and/or associated trees is not well understood.

7 | URBAN FORESTS AND STORMWATER RUNOFF MODELING

Because of the many environmental, structural, and vegetative variables found in developed areas, it has been difficult to accurately model the impacts of the urban forest on stormwater runoff mitigation (Wang, Endreny, & Nowak, 2008). Thus, attempts to model the hydrologic influence of the urban forest have been few and have varied in complexity. In a simplified, uncalibrated approach based on the curve number method, Sanders (1986) showed that the tree canopy cover (22%) in Dayton, OH, lowered potential stormwater runoff by approximately 7% for a 6-hr, 1-year storm event. By increasing tree canopy cover over non-paved, permeable areas from 37% to 50%, Sanders (1986) claimed that potential stormwater runoff could be further reduced to 12%. Although promising, such approaches are not mechanistic, instead relying on changes in the curve number based on land use or land cover adjustments. As the curve number method lumps many hydrologic losses, the true impact of the tree canopy (relative to other loss pathways) is obscured. More complex modeling by Wang et al. (2008) involved the Urban Forest Effects–Hydrology (UFORE-Hydro) model, a semi-distributed, object-oriented, topographic model developed specifically to study the effects of urban vegetation (tree, shrub, and herbaceous) and impervious surface cover. UFORE-Hydro has specific routines for interception, allowing isolation of the urban forest as component of the urban hydrologic system. After calibrating a model to existing conditions, Wang et al. (2008) investigated the variability in urban forest hydrologic benefits showing that interception decreases as rainfall intensity increases, decreases as LAI decreases, and increases as evaporation rates increase. Ultimately, the analysis led to an assessment of the effect of increased tree canopy, reporting that increasing canopy cover from 12% to 40% over permeable surfaces decreased stormwater runoff by 2.6% in a Baltimore, MD, watershed. However, total runoff could be reduced by 3.4% if trees over impervious surface cover were increased from 5% to 40%. As this model contains a number of variables related to interception and throughfall, field studies which actually quantify these parameters for urban systems could improve model accuracy.

These few modeling studies further emphasize that increasing tree canopy cover over impervious surfaces may help reduce stormwater

TABLE 3 Relevant tree canopy and transpiration research

Species	Reported mean daily transpiration rate (mm)	Per unit of measure	Study type	Average annual rainfall (mm)	Location	Reference
Acer x freemanii "Armstrong" *Acer rubrum* "Brandywine"	0.3–0.6	Leaf area	Greenhouse	NA[a]	Columbus, OH	Fair et al. (2012)
Acer platanoides	0.49–1.61	Leaf area	Urban field	NA[a]	Logan, UT	Kjelgren and Montague (1998)
Aesculus chinensis	1.5	Projected canopy cover	Urban field	586	Beijing, China	Wang et al. (2012)
Fraxinus excelsior *Tilia x europaea*	0.83	Projected canopy cover	Urban field	861	Arnhem, Netherlands	Jacobs et al. (2015)
Fraxinus pennsylvanica	0.75–2.60	Leaf area	Urban field	NA[a]	Logan, UT	Kjelgren and Montague (1998)
Pyrus calleryana	0.74–1.04	Leaf area	Urban field	NA[a]	Carbondale, IL	Kjelgren and Montague (1998)
Cedrus deodara, Euonymus bungeanus *Metasequoia glyptostroboides* *Zelkova schneideriana*	1.5	Projected canopy cover	Urban field	550–800	Liaoning Province, China	Chen et al. (2011)
Various	<0.1–2.2	Plot ground area	Urban field	380	Los Angeles, CA	Pataki et al. (2011)
Deciduous forest, White pine forest	1.1, 2.5	Plot ground area	Rural field	2014	western North Carolina	Ford et al. (2010)

[a]Average annual rainfall is not applicable because containerized plants were used in study; watering of plants was not dependent on ambient rainfall.

runoff, but those effects are modest and vary based on a range of variables. To reduce stormwater runoff adequately, impervious surface cover must be reduced or, at minimum, be routed into SCMs. As such, the tree canopy can be thought of as part of the treatment train of green infrastructure in an urban watershed.

8 | GAPS IN THE RESEARCH

Numerous gaps remain in the body of research on the role of trees in stormwater management. Specific needs based on this review include the following:

1. Fundamental research related specifically to urban trees and their contribution to interception and runoff delays across a variety of species and under both leaf on and leaf off conditions. These analyses should be performed for various rainfall intensities in various climatic regions to account for regional differences.
2. Understanding how tree canopy cover affects runoff coefficients over impervious as well as permeable surfaces, allowing watershed managers to better account for trees in stormwater design projects.
3. Studies which scale the local effects of urban trees to the larger watershed allowing a more holistic understanding of the urban tree canopy effects on hydrology.
4. Evaluating the potential for using trees to transpire water from urban stormwater controls. Tree-specific stormwater controls could be designed which wick water from belowground storage structures (i.e., soil and gravel beds). Using this design, smaller, economical, natural systems could be developed that provide for more belowground storage capacity.
5. Policy analyses that allow for the urban tree canopy to be properly integrated into stormwater management decisions and credited by regulators. Currently, regulations are mostly directed toward parcel scale development, leaving little value placed on the larger watershed scale network of green infrastructure, and reducing the value placed on forest connectivity in urban watersheds.

9 | SUMMARY

Forest systems (trees, groundcover, and soil) are an important part of the water cycle. These systems efficiently return water to the atmosphere (via evapotranspiration) and filter pollutants from the runoff (via infiltration and percolation). Thus, returning forest structure to built environments can help mitigate stormwater runoff, improve water quality, and conserve stormwater as a natural resource. Identifying potential areas for tree planting is a first step to increasing canopy cover. Increased tree canopy cover along with larger trees with greater leaf area increases rainfall retention and detention that, in turn, regulates the flow of stormwater runoff.

A strategy to maximize leaf area would be to retain and plant trees that typically have greater leaf area and group smaller, understory trees beneath taller over-story trees. Rain dripping off leaves from the taller trees will be intercepted by leaves of the smaller trees below, thereby increasing rainfall retention. This configuration would also be beneficial for reducing rainfall intensity, thus helping to slow stormwater runoff velocity to SCMs and increase their treatment efficiency. The inclusion of vegetative groundcover and mulch could also help to retain stormwater, slow runoff velocity, and provide good soil structure for infiltration, percolation, and root growth. Good soil conditions encourage increased transpiration. By increasing transpiration, more pore space in the soil can be made available to store stormwater, thus decreasing the amount of overland flow stormwater runoff to receiving waters.

Because of the impervious surface cover necessary in urban areas for roads and buildings, the urban forest system alone cannot be expected to mitigate all stormwater runoff problems. It is understood that trees in built environments will not function effectively in all locations, but managing the urban forest to work efficiently with other stormwater management practices (i.e., Green Infrastructure SCMs) where possible could be an asset to stormwater design engineers to help mitigate stormwater runoff and conserve water resources.

REFERENCES

Anderson, H. W., Hoover, M. D., & Reinhart K. G. (1976). Forests and water: Effects of forest management on floods, sedimentation, and water supply. USDA Forest Service General Technical Report PSW-18/1976. 115 p.

Asadian, Y., & Weiler, M. (2009). A new approach in measuring rainfall intercepted by urban trees in coastal British Columbia. *Water Quality Research Journal of Canada*, *44*, 16–25.

Asadian Y. (2010). Rainfall interception in an urban environment, Master of Science Thesis, The University of British Columbia, Vancouver, BC.

Aston, A. R. (1979). Rainfall interception by eight small trees. *Journal of Hydrology*, *42*, 383–396.

Bartens, J., Day, S. D., Harris, J. R., Dove, J. E., & Wynn, T. M. (2008). Can urban tree roots improve infiltration through compacted subsoils for stormwater management? *Journal of Environmental Quality*, *37*, 2048–2057.

Boggs, J. L., & Sun, G. (2011). Urbanization alters watershed hydrology in the piedmont of North Carolina. *Ecohydrology*, *4*, 256–264.

Carlyle-Moses, D. E., & Schooling, J. T. (2015). Tree traits and meteorological factors influencing the initiation and rate of stemflow from isolated deciduous trees. *Hydrological Processes*, *29*, 4083–4099. doi:10.1002/hyp.10519

Chair, J. T. (2000). *The hydrological effects of urban forests, with reference to the maritime Pacific Northwest*. Technical Bulletin: University of British Columbia, Vancouver, BC.

Chen, L., Zhang, Z., Li, Z., Tang, J., Caldwell, P., & Zhang, W. (2011). Biophysical control of whole tree transpiration under an urban environment in Northern China. *Journal of Hydrology*, *402*, 388–400.

Colby, S. L., Ortman, J. M. (2015). Projections of the Size and Composition of the U.S. Population: 2014 to 2060. U.S. Department of Commerce, Economics and Statistics Administration, U.S. Census Bureau, on-line publication. Retrieved from http://www.census.gov/content/dam/Census/library/publications/2015/demo/p25-1143.pdf (Accessed January 7, 2016)

Fair, B. A., Metzger, J. D., & Vent, J. (2012). Characterization of physical, gaseous, and hydrologic properties of compacted subsoil and its effects on growth and transpiration of two maples grown under greenhouse conditions. *Arboriculture & Urban Forestry*, *38*(4), 151–159.

Ford, C. R., Hubbard, R. M., & Vose, J. M. (2010). Quantifying structural and physiological controls on variation in canopy transpiration among planted pine and hardwood species in the southern Appalachians. *Ecohydrology*. doi:10.1002/eco.136

Gregory, J. H., Dukes, M. D., Jones, P. H., & Miller, G. L. (2006). Effect of urban soil compaction on infiltration rate. *Journal of Soil and Water Conservation*, *61*(3), 117–124.

Guevara-Escobar, A., Gonzalez-Soza, E., Veliz-Chavez, C., Ventura-Ramos, E., & Ramos-Salinas, M. (2007). Rainfall interception and distribution patterns of gross precipitation around an isolated *Ficus benjamina* tree in an urban area. *Journal of Hydrology*, *333*, 532–541.

Herwitz, S. R. (1987). Raindrop impact and water flow on the vegetative surfaces of trees and the effects on stemflow and throughfall generation. *Earth Surface Processes and Landforms*, *12*, 425–432.

Holder, C. D. (2013). Effects of leaf hydrophobicity and water droplet retention on canopy storage capacity. *Ecohydrology*, *6*, 483–490. doi:10.1002/eco.1278

Inkilainen, E. N. M., McHale, M. R., Blank, G. B., James, A. L., & Nikinmaa, E. (2013). The role of the residential urban forest in regulating throughfall: A case study in Raleigh, North Carolina, USA. *Landscape and Urban Planning*, *119*, 91–103.

Jacobs, C., Elbers, J., Brolsma, R., Hartogensis, O., Moors, E., Rodriguez-Carretero Marquez, M. T., & van Hove, B. (2015). Assessment of evaporative water loss from Dutch cities. *Building and Environment*, *83*, 27–38. doi:10.1016/j.buildenv.2014.07.005

Keim, R. F., & Skaugset, A. E. (2003). Modelling effects of forest canopies on slope stability. *Hydrological Processes*, *17*, 1457–1467. doi:10.1002/hyp.5121

Keim, R. F., Skaugset, A. E., & Weiler, M. (2006). Storage of water on vegetation under simulated rainfall of varying intensity. *Advances in Water Resources*, *29*, 974–986. doi:10.1016/j.advwatres.2005.07.017

Kjelgren, R., & Montague, T. (1998). Urban tree transpiration over turf and asphalt surfaces. *Atmospheric Environment*, *32*(1), 35–41.

Lange, B., Luescher, P., & Germann, P. F. (2009). Significance of tree roots for preferential infiltration in stagnic soils. *Hydrology and Earth System Sciences*, *13*, 1809–1821.

Leopold, L. (1968). Hydrology for urban land planning – A guidebook on the hydrologic effects of urban land use. *Geological Survey Circular*, *554*, 1–18.

Li, Y. C., Alva, A. K., Calvert, D. V., & Zhang, M. (1997). Stem flow, throughfall, and canopy interception of rainfall by citrus tree canopies. *HortScience*, *32*(6), 1059–1060.

Livesley, S. J., Baudinette, B., & Glover, D. (2014). Rainfall interception and stem flow by eucalypt street trees – the impacts of canopy density and bark type. *Urban Forestry & Urban Greening*, *13*, 192–197.

Pandit, A., & Heck, H. H. (2009). Estimations of soil conservation service curve numbers for concrete and asphalt. *Journal of Hydrologic Engineering*, *14*, 335–345.

Pataki, D. E., McCarthy, H. R., Litvak, E., & Pincetl, S. (2011). Transpiration of urban forests in the Los Angeles metropolitan area. *Ecological Applications*, *21*(3), 661–677.

Rose, S., & Peters, N. E. (2001). Effects of urbanization on streamflow in the Atlanta area (Georgia, USA): A comparative hydrological approach. *Hydrological Processes*, *15*, 1441–1457.

Sanders, R. A. (1986). Urban vegetation impacts on the hydrology of Dayton, Ohio. *Urban Ecology*, *9*, 361–376.

Scharenbroch, B. C., Morgenroth, J., & Maule, B. (2016). Tree species suitability to bioswales and impact on the urban water budget. *Journal of Environmental Quality*, *45*, 199–206.

Scheyer, J. M., Hipple, K. W. (2005). Urban soil primer. United States Department of Agriculture, Natural Resources Conservation Service, National Soil Survey Center, Lincoln, Nebraska. Retrieved from http://soils.usda.gov/use) (Accessed August 11, 2016)

Schooling, J. T., & Carlyle-Moses, D. E. (2015). The influence of rainfall depth class and deciduous tree traits on stemflow production in an urban park. *Urban Ecosystems*, *18*, 1261–1284. doi:10.1007/s11252-015-0441-0

Schoonover, J. E., Lockaby, B. G., & Helms, B. S. (2006). Impacts of land cover on stream hydrology in the west Georgia piedmont, USA. *Journal of Environmental Quality*, *35*, 2123–2131.

Smith, D. M. (1986). *The Practice of Silviculture*. New York: John Wiley and Sons.

Staelens, J., Schrijver, A. D., Verheyen, K., & Verhoest, N. E. C. (2008). Rainfall partitioning into throughfall, stemflow, and interception within a single beech (*Fagus sylvatica* L.) canopy: Influence of foliation, rain event characteristics, and meteorology. *Hydrological Processes*, *22*, 33–45.

Sun, G., & Lockaby, B. G. (2012). Water quantity and quality at the urban–rural interface. In D. N. Laband, B. G. Lockaby, & W. Zipperer (Eds.), *Urban–rural interfaces: Linking people and nature*. (pp. 29–48). Madison, WI: American Society of Agronomy, Crop Science Society of America, Soil Science Society of America.

Trimble, G. R., & Weitzman, S. (1954). Effect of a hardwood forest canopy on rainfall intensities. *Transactions – American Geophysical Union*, *35*(2), 226–234.

Wang, J. W., Endreny, T. A., & Nowak, D. J. (2008). Mechanistic simulation of tree effects in an urban water balance model. *Journal of the American Water Resources Association*, *44*, 75–85.

Wang, H., Wang, X., Zhao, P., Zheng, H., Ren, Y., Gao, F., & Ouyang, Z. (2012). Transpiration rates of urban trees, *Aesculus chinensis*. *Journal of Environmental Sciences*, *24*(7), 1278–1287.

Xiao, Q., McPherson, G., Ustin, S. L., Grismer, M. E., & Simpson, J. R. (2000). Winter rainfall interception by two mature open-grown trees in Davis, California. *Hydrological Processes*, *14*, 763–784.

Xiao, Q., & McPherson, E. G. (2011). Rainfall interception of three trees in Oakland, California. *Urban Ecosyst*, *14*, 755–769. doi:10.1007s11252-011-0192-5

Xiao, Q., & McPherson, E. G. (2016). Surface water storage capacity of twenty tree species in Davis, California. *Journal of Environmental Quality*, *45*, 188–198.

Zadeh, M. K., & Sepaskhah, A. R. (2016). Effect of tree roots on water infiltration rate into the soil. *Iran Agricultural Research*, *35*(1), 13–20.

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