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Review Article

Towards optimized runoff reduction by urban tree cover: A review of key physical tree traits, site conditions, and management strategies

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HIGHLIGHTS

- Systematic review of the urban forestry and forest hydrology literature.
- Identification of physical tree traits that help optimize stormwater interception.
- Identification of physical tree traits that help optimize stormwater infiltration.
- Guidance for real-world applications in urban tree selection, care, and management.

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ABSTRACT

In this study, we conducted a systematic literature review to determine the physical tree traits, site conditions, and urban forest management strategies that provide optimal stormwater runoff mitigation through the interception of precipitation or enhanced infiltration of water routed toward the ground by urban tree cover. Our review found that foliar characteristics such as high leaf area index, low hydrophobicity, low inclination angles, and high surface roughness promote rainfall retention by the canopy, as do high bark water storage capacity and a denser crown. In addition, when soil conditions are suitable, infiltration can be enhanced by urban tree cover and promoted through efficient funneling of stemflow through the tree canopy, with this process facilitated by erectophile branching structure, bark of low microrelief and morphology conducive to water transport, and multi-leader canopies. Consideration of these traits should be made when selecting trees to enhance stormwater mitigation by urban tree cover. Applications related to the establishment, maintenance, and management of urban tree cover to maximize stormwater management benefits are also explored. Strategic selection and management of urban trees may significantly increase their collective capacity to reduce runoff volumes at a landscape scale.

1. Introduction

Expansive urbanization occurs at the expense of natural ecosystems. As urban populations grow, the land development required to accommodate them often results in the spatial reduction and fragmentation of forested land (Nowak & Greenfield, 2012), destruction of floral and faunal habitat (Stagoll et al., 2010), degradation of surface water quality (Van Metre et al., 2019), intensification of flood risk (Booth et al., 2002, Smith et al., 2005, Carlyle-Moses et al., 2020), localized elevation of air temperatures (i.e., creation of urban heat islands; Oke, 1982; Heisler & Brazel 2010), and reduction of air quality (Han et al., 2014). Collectively, the adverse impacts of urbanization compromise environmental quality and threaten the quality of life for residents of metropolitan areas. In recent years, urban planners and natural resource managers have worked to incorporate nature-based solutions to help mitigate these environmental issues in cities (Li et al., 2005, Capotorti et al., 2019, Escobedo et al., 2019). Urban forests are often included in these nature-based solutions as urban trees provide an array of regulating,

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provisioning, and social ecosystem services (Berland et al., 2017; Fan et al., 2019; Gonzalez-Sosa et al., 2017, Kuehler et al., 2017; Nowak, 2006; Smets et al., 2019, Nowak et al., 2018, Pataki et al., 2020; Rajoo et al., 2020; Roy et al., 2012; Synk et al., 2017).

Stormwater mitigation is a critical service provided by urban trees. Urban trees help reduce stormwater volumes by intercepting precipitation in their canopies, promoting infiltration in their root zones, and taking up soil water via transpiration (Livesely et al., 2016). This reduction in total runoff reduces the volume of water that is channeled to local grey stormwater infrastructure and surface water bodies, reducing stormwater treatment costs, and the risk of erosion and pollutant transport to rivers, streams, and lakes (Livesely et al., 2016).

Studies that use empirical data analysis, remote sensing, and modeling techniques have been helpful in estimating stormwater mitigation by urban trees and the related economic impacts (Xiao et al., 2000, McPherson et al., 2005, Coville et al., 2020, Song et al., 2020, Tan et al., 2021, Yang et al., 2019). In Dalian, Liaoning Province, China, i-Tree analysis estimated that urban trees intercept approximately 217,000 m^3 of precipitation annually, saving $460,000 USD in municipal water treatment costs (Wang et al., 2018). Similarly, in Lisbon, Portugal, stormwater mitigation by urban trees facilitated 186,773 m^3 in avoided runoff each year, reducing annual stormwater treatment and management costs by approximately $1.97 million USD (Soares et al., 2011). i-Tree model runs for New York City estimated that approximately 3.37 million m^3 of runoff were avoided annually due to municipal tree cover, saving the city nearly $33.6 million USD in stormwater treatment and management costs (Peper et al., 2007). These estimates underscore the vital contribution urban trees make in reducing runoff at the municipal scale. Given the high ecological and economic value of stormwater mitigation by urban trees, guidelines for selecting trees for urban plantings should consider species that are likely to maximize provision of this ecosystem service.

Urban tree selection is typically guided by a myriad of stakeholders, including landscape architects, nongovernmental organizations, local nurseries, municipal foresters, university extension, and the public (Conway & Vander Vecht, 2015; Yao et al., 2019). Among these stakeholder groups, there are often divergent factors that drive urban tree selection; however, there are also common shared considerations that ultimately influence what and where trees are planted. Urban tree selection is often based on the relative resiliency to pests, diseases, and harsh urban environments (Mácová et al., 2022, McPherson & Kotow, 2013; Wen et al., 2004; Xu et al., 2015; Zhang et al., 2015), and on goals to achieve biodiversity within the urban forest (Conway & Vander Vecht, 2015; Endress, 1990; Galvin, 1999; Ning et al., 2008; Thomsen et al., 2016). There are also social factors that influence urban tree selection, including shared goals to create desired landscape aesthetics (Vogt et al., 2017) or those promoted by government-led initiatives (Shackleton & Gwedla, 2021). Urban tree selection and planting decisions are also influenced by site factors that affect tree survival or limit maturation capacity, including adjacent ground cover (e.g., impervious cover), soil quality, and the presence of above- or below-ground utilities and other infrastructure (Jim, 1999; Vico et al., 2014).

In addition to the factors mentioned above, several authors suggest more strategic approaches to urban tree selection, care, and management, to ensure that planted trees maximize the yield of ecosystem services over their lifespan (Barwise & Kumar, 2020, McPherson et al., 2006, Jim, 1999). Guidance on how to best apply these strategic approaches, however, is not well documented in the literature. For example, while the work of Hughes et al. (2015) provides guidance on urban tree selection when prioritizing habitat for animals and insects, there remains a need for more detailed guidance on how to select urban trees to optimize provision of additional ecosystem services, including stormwater mitigation. Such recommendations should include insights on how best to select trees in accordance with knowledge of the physical tree traits that provide maximal capacity for runoff reduction by the canopy cover.

In this study we systematically review relevant literature to identify physical characteristics of trees that affect optimal stormwater mitigation by urban tree cover (UTC). Previous reviews have summarized the relationship between UTC and stormwater mitigation (Berland et al., 2017, Kuehler et al., 2017). Beidokhti and Moore (2021) conducted a meta-analysis to investigate the relative impacts of precipitation, tree phenology, leaf area index, and bark characteristics on throughfall in urban forests. Our review builds upon these previous works by synthesizing a broader array of physical tree traits, urban forest management approaches, and site conditions that increase stormwater mitigation efficacy by urban trees. We utilize a summary of these characteristics, as outlined in the literature, to provide insight on how to strategically select and manage urban trees to maximize runoff reduction via UTC. Our summation of findings from this work are intended to serve as a prescriptive guide for urban planners, foresters, natural resource managers, and related stakeholders who intend to utilize UTC to manage stormwater at local, municipal, and regional scales.

2. Materials and methods

To conduct this systematic review, we used the Web of Science database to search the urban forestry and forest hydrology literature. Our search was based on the query strings outlined in Table 1. We limited our search to peer-reviewed original research and review papers published in English before 31 May 2022. Any duplicates generated from the search queries were excluded in the total count of collected literature and subsequent review process. For each article, we initially reviewed abstracts to determine the suitability of each publication for our objectives, and subsequently excluded those articles for which the predominant focus was on (i) shrubs or herbaceous vegetation, or (ii) the linkage between urban forest structure and wildlife ecology, as for the latter, there was minimal to no strong connections to urban forest hydrology in the reported studies. Much of the existing literature on the relationship between forest structure, rainfall partitioning by the canopy, and infiltration has been based in rural and plantation forests. A smaller proportion of this work has taken place in urban forests. For this reason, we added one search query without the term "urban", so as to allow for the inclusion of foundational studies in forest hydrology that have served as the basis for much of the current related research in urban forestry. This review thus included studies conducted in both natural and urban ecosystems. Utilizing these selection criteria, we retained and reviewed 99 of the 708 articles generated by our initial search (Fig. 1).

Table 1
Search terms and literature review results. All searches were conducted using Web of Science, and results indicate all literature accessible via this database through 31 May 2022. Letters denote specific articles that were in the results of more than one search query.

Search query	Articles obtained from initial search	Unique articles retained and reviewed after applying selection criteria
Urban + Forest + Rainfall + Interception	104	40[a,b,d,e,f,g,h,i,j,k]
Urban + Forest + Stemflow	78	7[a,b,c,d,e,f,g,h]
Urban + Tree + Recommendation + Species	314	12
Urban + Forest + Rainfall + Partitioning	31	1[c,e]
Urban + Forest + Rainfall + Infiltration	87	6[d]
Urban + Forest + Stormwater + Mitigation	50	8
Forest canopy + Structure + Rainfall + Partitioning	34	25[e,i,j,k]
Total (duplicates removed)	690	99

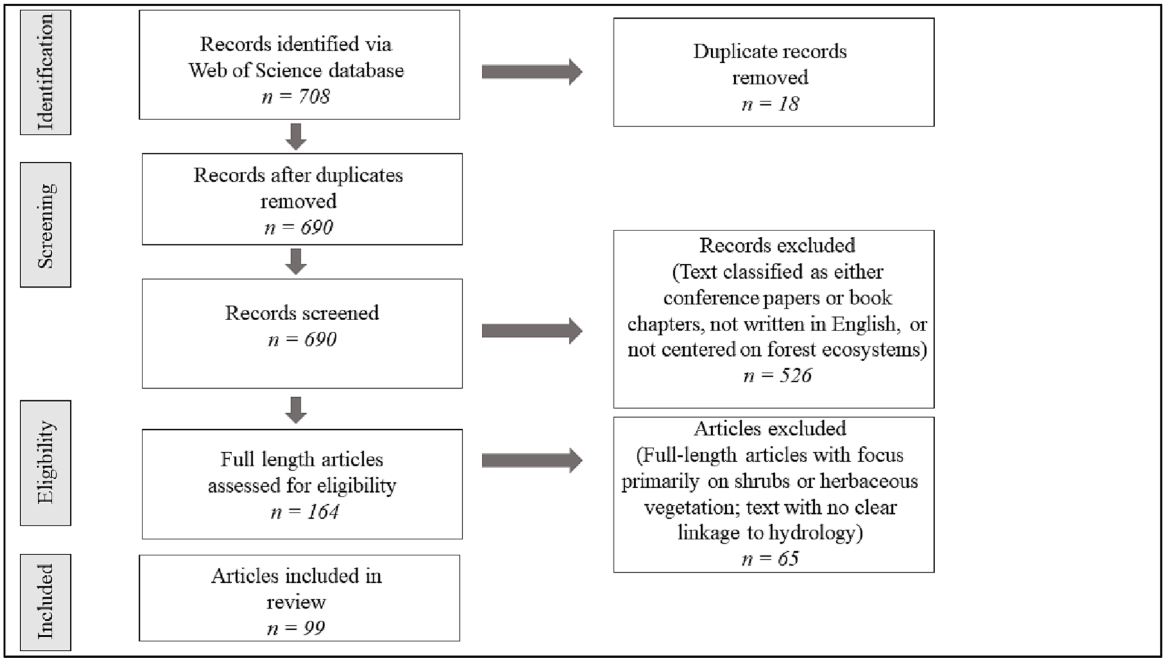

Fig. 1. PRISMA diagram outlining selection and screening criteria for systematic literature review process.

We conducted content analysis for each of the papers that were retained. Through this analysis, we identified the physical characteristics of urban trees that most closely aligned with rainfall interception and, accordingly, with throughfall and stemflow. We further analyzed the literature to determine the ecological attributes of urban forests that facilitate or hinder the infiltration of runoff by the urban canopy. We then synthesized these findings, in addition to insights from the urban tree selection literature, to provide guidance on the tree traits and management practices that should be prioritized when UTC is expected to contribute significantly to stormwater mitigation efforts.

3. Quantifying hydrologic fluxes and stormwater mitigation by urban forest canopies

Proper assessment of stormwater reduction by urban trees requires that rainfall partitioning and water uptake by trees is accurately characterized and quantified. When precipitation falls on trees, it may be partitioned into either throughfall, stemflow, or interception, with some throughfall, stemflow or other non-intercepted water absorbed by roots and subsequently transpired back to the atmosphere. In this study, we are ultimately focused on factors that impact runoff (i.e., throughfall + stemflow – interception) and therefore our focus is primarily on the physical tree traits that impact interception, throughfall, and stemflow. Bartens et al., 2009, Gotsch et al., 2018, Pataki et al., 2011, Tirpak et al., 2018, and Thom et al., 2020 provide insights on spatial, temporal, and interspecific variability in transpiration by urban trees.

Mass balance equations are typically used to quantify the degree to which gross, or total precipitation (*P*) is partitioned into throughfall, stemflow, and interception by urban trees. Interception (*I*) is precipitation that is captured on foliar or woody canopy surfaces, from which it is subsequently evaporated. Throughfall (*TF*) is that precipitation that passes through the canopy *en route* to the soil, either falling through canopy gaps or splashing or dripping from foliar or woody surfaces. Stemflow (*SF*) is precipitation that is transported to forest soils via the main stems of trees. Throughfall and stemflow collectively comprise net precipitation, or *Rn*. Mathematically, this partitioning of *P* is represented using the following equations:

$$P = I + Rn, \quad (1)$$

which can be expanded to

$$P = I + (TF + SF) \quad (2)$$

P, *TF*, and *SF* are most frequently measured directly in the field, while *I* is often calculated using the rearrangement of Eq. (2) into

$$I = P - (TF + SF) \quad (3)$$

While less frequently done, interception can also be calculated directly using accelerometers and strain gauges (Huang et al., 2005; Selker et al., 2020; Van Emmerik et al., 2017).

Various techniques are used to collect *in situ* measurements of throughfall and stemflow (e.g., André et al., 2011; Fathizadeh et al., 2017; Siegert et al., 2019). For throughfall, samples may be collected using individual collectors for which funnels are attached to a capture container, with the assembled collectors distributed below isolated trees, or dispersed below the canopy in a woodlot (Guevara-Escobar et al., 2007, Xiao & McPherson, 2011). Throughfall samples can be measured manually or through automated methods (Bean et al., 2021, Bolaños-Sánchez et al., 2021). Trough collectors have also been used to collect throughfall (Asadian & Weiler, 2009). Kostelnik et al. (1989) and Levia and Frost (2006) review ideal use of gauges and troughs based on the intended research objectives.

Stemflow measurements are made using collars attached to tree trunks in a helix fashion, with some form of sealant used to prevent seepage of stemflow between the bark and the collars. The collars channel precipitation that drains to the forest floor via the main stem into stationary collection bins, from which manual or automated sampling of stemflow yield may occur (Likens & Eaton 1970, Dowtin et al., 2021, Jochheim et al., 2022). Levia and Germer (2015) provide a thorough review of stemflow collection methodologies.

To quantify the proportion of *P* portioned into *TF* and *SF*, *in situ* volume measurements are converted to depth measurements based on the surface area of the collection devices, or projected crown areas in the case of stemflow (Table 2). Depth equivalents for both metrics can be used to determine interception, by which avoided runoff can be calculated. Volumetric stemflow measurements can be used to quantify additional important metrics, including the funneling ratio, *F*. *F* measures the degree to which outlying parts of the canopy amplify water

Table 2
Commonly used equations for quantifying throughfall (TF) and stemflow (SF) inputs.

Metric	Formula	Variables Defined	Purpose	Reference (where applicable)
Throughfall volume depth equivalent (TF_D)	$TF_D = \frac{V_T}{A}$	V_T = throughfall volume A = collector orifice area	Convert TF volume to depth when measured with non-automated collectors	
Stemflow rate (S_R)	$S_R = S_Y/P$	S_Y = stemflow volume P = gross precipitation depth	Quantify stemflow volume per unit precipitation depth	Levia & Germer, 2015
Stemflow depth (S_D)	$S_D = S_Y/B$	S_Y = stemflow volume B = basal area	Quantify stemflow depth per unit basal area	Levia & Germer, 2015
Stemflow as % of P, calculated per unit projected crown area (S_{PCA})	$S_{PCA} = \frac{S_{CA}}{P}*100$	S_{CA} = stemflow depth per unit crown area P = gross precipitation depth	Determine proportion of P partitioned into *SF*	
Funneling ratio (F)	$F = \frac{S_Y}{(P*B)}$	S_Y = stemflow volume P_g = gross precipitation depth B = tree basal area	Identify degree to which outlying portions of tree crown have contributed to stemflow	Herwitz, 1986

inputs to the soil (Herwitz, 1986) (Table 2) and can be calculated at the stand scale or for individual trees (Carlyle-Moses et al., 2018). F values > 1.0 indicate that water inputs channeled to the soil (per unit basal area) are higher than what would have occurred if a tree were not present, while F values < 1.0 indicate that water inputs to the soil are lower due to the presence of the tree. F values are attributed, in significant part, to those physical tree traits that either promote draining or storage of precipitation by the tree.

When it is not possible or practical to conduct *in situ* sampling of rainfall partitioning by the urban forest, modeling applications such as i-Tree are often used to quantify the hydrologic impact of urban canopy cover on runoff reduction (Wang et al., 2008, i-Tree Eco User's Manual, 2020). These models utilize the above principles of rainfall partitioning by the canopy, in conjunction with regional data on urban forest structure, percent canopy cover, land use land cover, and climate to develop estimates of stormwater mitigation by urban trees. i-Tree and similar models are sometimes limited in that they are based on limited input data (e.g., less than fully representative information on species performance for a broad range of tree species), which may introduce mis-estimation of stormwater mitigation effects of the urban canopy. Nevertheless, these models remain important tools in developing baseline estimates of runoff reduction by urban trees. The studies included in our literature review utilized both the above-mentioned *in situ* sampling methods and techniques for quantifying rainfall partitioning by the canopy, in addition to the above-mentioned precipitation partitioning metrics and models such as i-Tree, to quantify the contribution urban trees make to local stormwater mitigation.

4. Linkages between canopy structural characteristics and stormwater mitigation by urban trees

4.1. Urban trees and stormwater mitigation via interception

Urban trees facilitate stormwater mitigation through three key processes: canopy interception, infiltration, and transpiration. In the following two sections, we explore the structural characteristics that promote maximum canopy interception, which is well documented in the literature, and those that aid in promoting stemflow and subsequent infiltration of precipitation (for which there is notably less documentation in the literature, Table 1).

4.1.1. Canopy storage

Canopy interception of precipitation is partly governed by canopy water storage capacity, denoted by S, which is the maximum amount of precipitation that can be stored by the canopy's foliar and woody surfaces before saturation is reached (Xiao et al., 2000). S is impacted by both abiotic and biotic factors. Abiotic factors that may influence S include precipitation characteristics (e.g., intensity, duration, and magnitude), wind speed and direction, antecedent dry period, air temperature, and relative humidity (Crockford & Richardson, 2000, Frêne et al., 2022, Levia & Frost, 2006, Nytch et al., 2019, Xiao et al., 2000, Zabret et al., 2018). Given the high temporal variability of these abiotic factors, they can be challenging to incorporate into strategic planning for the selection of urban trees that will provide optimal stormwater mitigation. Numerous biotic factors, or physical tree traits, impact S, including characteristics of foliar and woody surfaces, total surface area and density of leaves and branches, and tree crown architecture (Fig. 2). While these physical tree traits vary over the lifespan of a tree, they display less temporal variability than their abiotic counterparts, making it more practical to use knowledge of their impacts on rainfall capture and redistribution to guide strategic selection of urban trees for maximum runoff reduction by the canopy.

4.1.2. Impacts of foliage on interception

Leaf area, which is often quantified using the leaf area index (LAI; the aboveground leaf area per unit ground area (m^2 m^{-2}), is a key determinant of canopy interception. There is a direct relationship between leaf area and interception, as higher leaf area and LAI result in a greater proportion of surface area over which precipitation may be captured (Acharya et al., 2020; Alves et al., 2018; Baptista et al., 2018; Dong et al., 2021; Ma et al., 2022, Wei et al., 2020; Xiao & McPherson, 2002; Yang et al., 2019). LAI of trees can vary spatially and temporally in accordance with species composition, tree phenology, tree health, and management practices (Pérez-Suárez et al., 2014; Xiao et al., 1998; Xiao & McPherson, 2011).

LAI varies across UTC due to differences in length of foliation period and canopy structure among trees comprising the urban forest, introducing spatial and temporal variability in S and interception among urban trees (Table 3). For evergreen species, LAI and thus interception of precipitation, is consistently higher throughout the year than for deciduous species that lose foliage for a significant portion of the year (Clapp et al., 2014). This temporal variability in foliation for deciduous trees decreases their canopy interception storage relative to evergreen trees over the course of a year and introduces a seasonality to their maximum interception capacity (Xiao & McPherson, 2011, Wu et al., 2019, Yue et al., 2021, Zong et al., 2021).

LAI can vary significantly among evergreen species, with noted differences between coniferous and broadleaved species. Evergreen conifers are able to retain needles over the course of multiple growing seasons. Additionally, conifer needles often have a more complex foliar geometry and shoot architecture than do broadleaves (i.e., needles may be flattened or more cylindrical, and their arrangement along shoots varies widely), providing them a higher capacity to effectively capture and store precipitation (Xiao & McPherson, 2016). The higher LAI and

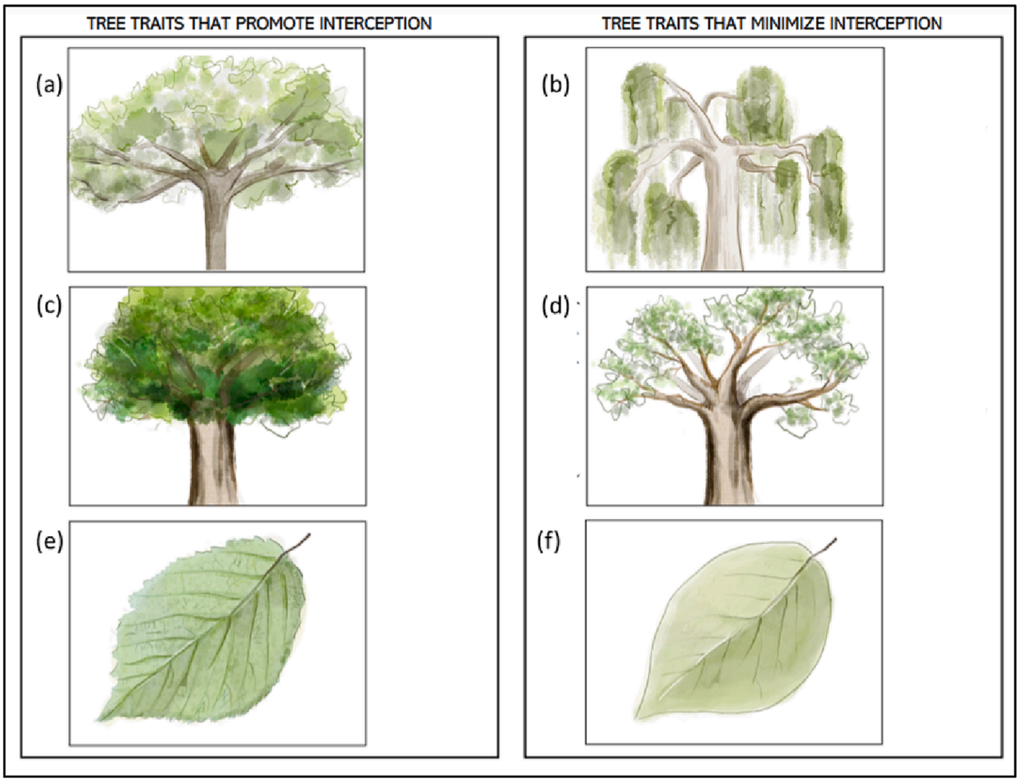

Fig. 2. Physical characteristics of urban trees that impact precipitation retention and drainage by the canopy. (a) High crown projection area, (b) downward sloping branches, (c) high canopy density, (d) low canopy density, (e) high foliar surface roughness, (f) low foliar surface roughness. (Technical illustration by Janice E. Hudson.)

Table 3
Mean proportion of rainfall intercepted by urban trees as reported in previous studies. For tree classification, *BD* denotes broadleaved deciduous, *BE* broadleaved evergreen, and *CE* coniferous evergreen.

Species	Interception %	Classification	Reference
Liquidambar styraciflua	14.3	BD	Xiao & McPherson 2011
Pyrus calleryana 'Bradford'	15.0	BD	Xiao et al. 2000
Zelkova serrata	20.6	BD	Yang et al. 2019
Fagus grandifolia	21.5	BD	Van Stan et al. 2015
Albizia procera (Roxb) Benth	22.8	BD	Nytch et al. 2019
Betula pendula (Roth)	23.7	BD	Zabret & Šraj 2019a
Ginkgo biloba	25.2	BD	Xiao & McPherson 2011
Liriodendron tulipifera	27.8	BD	Van Stan et al. 2015
Aesculus turbinata	30.6	BD	Yang et al. 2019
Sophora japonica	35.8	BD	Yang et al. 2019
Ginkgo biloba	57.9	BD	Yang et al. 2019
Calophyllum antillanum Britt	16.4	BE	Nytch et al. 2019
Citrus limon	27.0	BE	Xiao & McPherson 2011
Quercus suber	27.0	BE	Xiao et al. 2000
Ficus benjamina	68.9	BE	Guevara-Escobar et al. 2007
Pinus nigra Arnold	46.9	CE	Zabret & Šraj 2019a
Pseudotsuga menziesii	64.1	CE	Asadian & Weiler 2009
Thuja plicata	71.1	CE	Asadian & Weiler 2009

capture capacity of conifers produces higher *S* and interception capacity relative to broadleaved species. For isolated trees in Ljubljana, Slovenia, interception by *Pinus nigra* (Austrian pine) was nearly two times greater than for *Betula pendula* (silver birch), with *P. nigra* intercepting 45% of event rainfall, and *B. pendula* intercepting 23% of event rainfall (Zabret & Šraj, 2019a). Similarly, for commonly planted landscape trees in Shanghai, China, rainfall interception capacity for coniferous evergreen species was approximately two times larger than for broadleaf evergreen species, and exceeded that of broadleaf deciduous species by a factor of three (Guo et al., 2017).

LAI also varies notably among broadleaved deciduous species, causing interspecific variability in *S* and rainfall interception (Table 3). For *Albizia procera* (tall albizia) in San Juan, Puerto Rico, interception was 22.8%, compared to 16.4% for *Calophyllum antillanum* (Santa Maria), with differences attributed to variability in LAI between the two species (Nytch et al., 2019). For storms producing 5–10 mm of rainfall, *Tilia cordata* (littleleaf linden) in Etterbeek, Belgium intercepted approximately 38% more precipitation than *Acer platanoides* (Norway maple), with the higher interception for *T. cordata* attributed to its higher LAI relative to *A. platanoides* (Smetts et al., 2019). These differences in LAI, *S*, and their related influence on canopy interception loss can consequently affect species-level contributions to stormwater mitigation by UTC (Guo et al., 2017).

In addition to leaf area, physical traits of foliage can affect the quantity, spatial, and temporal variability of *S*. Leaf angle, hydrophobicity, morphogenesis, geometry, and roughness can all affect the degree to which rainfall is intercepted, producing marked variance in rainfall interception across UTC (Huang et al., 2017).

Leaf angle is inversely related to *S*, as more steeply inclined leaves are likely to release precipitation from foliar surfaces (Crockford & Richardson, 2000, Xiao et al., 2000). In Melbourne, Australia, *S* was lower for *Corymbia maculata* (spotted gum) than for *Ulmus procera* (English elm) and *Platanus* × *acerifolia* (London plane tree) (Baptista et al., 2018). Baptista et al. (2018) noted that these differences may be due, in part, to *C. maculata* having a higher leaf inclination angle, which promotes drainage rather than retention of precipitation. Huang et al. (2017) also suggest that variability in *S* and interception loss among

Quercus alba (white oak), *Acer platanoides* (Norway maple), *Fraxinus pennsylvanica* (green ash), and *Prunus* (cherry) spp. in Vancouver, British Columbia, Canada can partially be attributed to varying leaf inclination angles between the species.

Leaf hydrophobicity, which describes the degree to which water interacting with a leaf is likely to be repelled from its surface (Holder, 2013), also impacts canopy storage capacity. Foliar surfaces characterized by high hydrophobicity are less likely to retain intercepted precipitation, while those characterized by low hydrophobicity are more prone to retain water on their surfaces. Foliar hydrophobicity can vary significantly between the various species of woody vegetation that comprise the urban forest, producing interspecific and spatial variability in *S* and interception by UTC (Holder, 2013, Holder & Gibbes, 2017, Huang et al., 2017).

Foliar hydrophobicity is partly determined by physical leaf traits on both the adaxial and abaxial surfaces. These include, but are not limited to, trichome density and waxy surfaces, with higher trichome density linked to lower hydrophobicity and thus relatively high *S* and interception (Holder, 2012). In contrast, foliar surfaces that are smooth or waxy can be highly hydrophobic, significantly reducing *S*, whereas those with more rigid surfaces more effectively retain water and display higher *S* (Baptista et al., 2018; Calvo-Alvarado et al., 2022, Xiao & McPherson, 2016; Fig. 2). Foliar hydrophobicity can scale up to tree-level differences in interception loss and stormwater mitigation benefits. For *P. acerifolia* in Melbourne, Australia, *S* was notably higher than for *C. maculata*, due in part to the waxy surface of *C. maculata* leaves that impede water retention (Baptista et al., 2018). Similarly, *S* for *Pistachia chinensis* (Chinese pistache) was 2.5 times higher than for *Pyrus calleryana* (callery pear), as the relatively rough surface of *P. chinensis* allowed for greater *S* than did the relatively smooth leaves of *P. calleryana* (Xiao & McPherson, 2016).

Leaf morphology also impacts canopy water storage. Both *S* and interception can be higher for trees with compound rather than simple leaves, and for trees in which there is dense clustering of leaves around branches (Xiao & McPherson, 2016). For simulated rainfall events in Krakow, Poland, *S* was 3.5% higher for *Pinus sylvestris* (Scots pine) than for *Abies alba* (silver fir), and *S* for *Picea abies* (Norway spruce) was 10% higher than for *A. alba* (Klamerus-Iwan et al., 2018). The observed variation in *S* between these species was attributed to differences in needle distribution around tree branches, with *S* higher for trees in which needles were more densely clustered, increasing *S* and interception (Klamerus-Iwan et al., 2018).

4.1.3. Bark-water interactions and interception

Inasmuch as foliar characteristics impact *S* and interception, so too do the physical traits of tree bark, with bark water storage capacity variable among tree species (Levia & Herwitz, 2005, Van Stan et al., 2015). Different bark characteristics will determine its water storage capacity.

Bark morphology (i.e., the presence, shape, and orientation of plates, scales, and furrows on bark surfaces; Sadjak, 1967; Whitmore, 1962) is a significant determinant of bark water storage capacity (Oka et al., 2021). Collectively, the features that determine bark morphology affect the degree to which precipitation will drain or be retained by woody surfaces in the urban canopy. For example, smooth bark and bark with shallow, linearly aligned furrows, is often associated with more efficient drainage of net precipitation to the tree base as these characteristics reduce hindrances to the downward vertical flow of precipitation along the trunk. Contrarily, bark characterized by relatively high microrelief; deep, intricately stitched furrows; or overlapping plates is often affiliated with higher water storage capacity as these properties create crevices into which precipitation that interacts with the bark may be captured and stored (Levia & Herwitz, 2005; Livesley et al., 2014; Schooling & Carlyle-Moses, 2015) (Fig. 3).

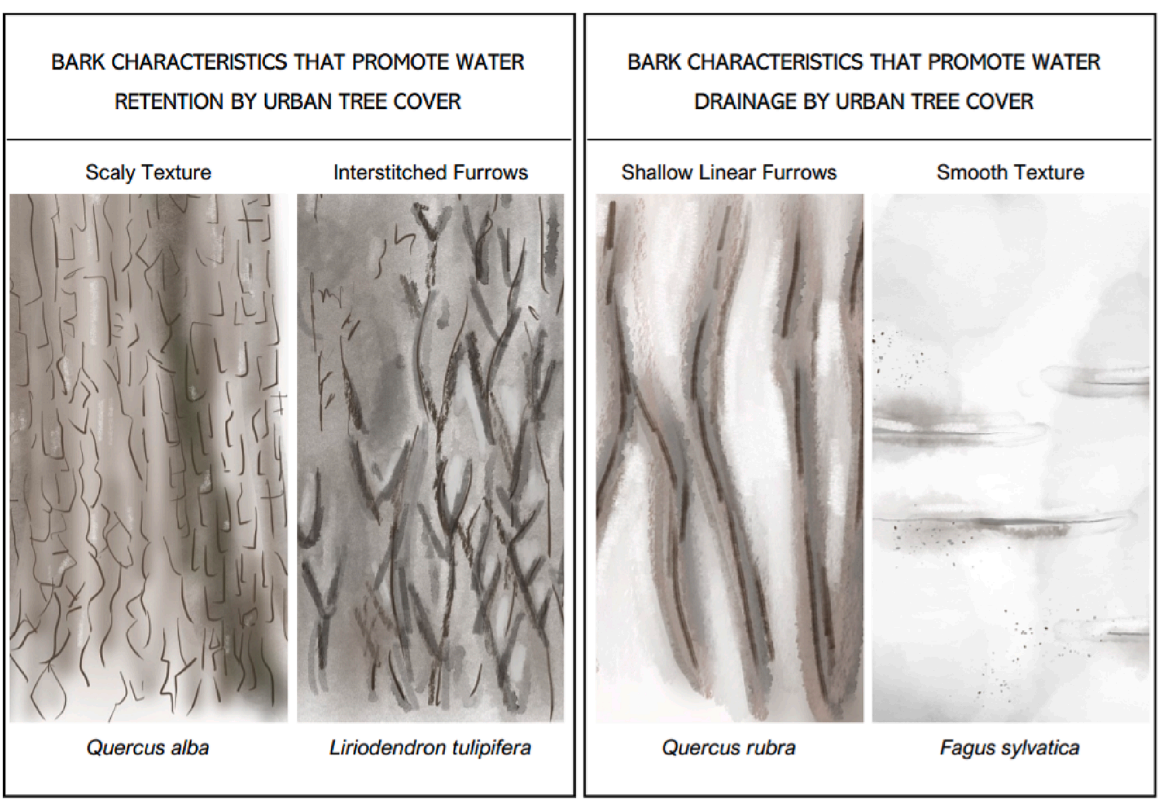

Fig. 3. Bark characteristics that correspond with efficient water retention and drainage by urban tree cover. Examples of species for which these traits are observed in mature trees are provided. (Note that physical bark traits will vary over the lifespan and in accordance with the life history of a tree.) (Technical illustration by Janice E. Hudson.)

Interspecific variability in bark morphology can create substantial differences in bark water storage capacity and tree scale interception. Levia and Herwitz (2005) found bark water storage for *Quercus rubra* (northern red oak) to be three times higher than for *Betula lenta* (sweet birch) and attributed this to the more complex morphology of *Q. rubra* bark, which facilitated higher water capture and storage. Variability in bark morphology influenced water storage capacity for *Ginkgo biloba* (ginkgo) and *Liquidambar styraciflua* (sweetgum) in Oakland, California, USA, contributing to approximately 11% more interception by ginkgo than by sweetgum (Xiao & McPherson, 2011). Interception for *Eucalyptus nicholli* (narrow leaved eucalyptus) exceeded that for *Eucalyptus saligna* (Sydney blue gum) in Melbourne, Australia, as *E. nicholli* had deeply fissured bark with higher water storage capacity relative to the smoother bark of *E. saligna* (Livesley et al., 2014).

4.1.4. Canopy structure, architecture, and interception

In addition to foliar and stem surface traits, canopy structure and crown architecture can affect S and interception by the canopy, both across the forest and for individual trees (Attarod et al., 2021; Gardon et al., 2020; Honda & Durigan, 2016; Sun et al., 2018). Increased canopy density, sometimes proxied by plant area index (PAI; measure of aboveground area occupied by woody and foliar surfaces relative to open area at the surface), often corresponds with higher water storage capacity and interception loss by the canopy (Jeong et al., 2019; Peng et al., 2014, Pflug et al., 2021). Among street trees common in Melbourne, Australia, S and interception were consistently higher for those trees in which canopy density was higher (Livesley et al., 2014, Baptista et al., 2018).

4.1.5. Impacts of anthropogenic activity on canopy water storage capacity

While species heterogeneity can impact canopy density, anthropogenic activity can also influence the structure of managed wooded ecosystems (Hakimi et al., 2018; Xu et al., 2020), including urban forests. Pruning can affect canopy density and related stormwater mitigation benefits of urban trees (Xiao & McPherson, 2002) as pruning reduces canopy density, thereby decreasing the potential for rainfall interception. For *Liquidambar styraciflua* (sweetgum) and *Cinnamomum camphora* (camphor) trees in Santa Monica, California, USA, interception was 46% and 65% lower, respectively, than for trees of the same species and age class in Modesto, California, USA (Xiao & McPherson, 2002). The lower interception of trees in Santa Monica was attributed to comparatively higher pruning activity in that municipality, related reductions in canopy density, and the consequential loss of surface area upon which precipitation could be captured (Xiao & McPherson, 2002).

Crown architecture also affects rainfall interception by urban forests (Fig. 2). Canopy interception is linked to crown projection area, crown width, and their related impacts on S (Guo et al., 2017, Kermavnar & Vilhar, 2017; Xiao & McPherson, 2002; Xiao et al., 2000). Trees characterized by greater crown projection area typically possess a greater total surface area over which precipitation may be captured, thereby increasing interception capacity (Xiao et al., 1998). Once intercepted by the canopy, branching architecture can notably impact how effectively precipitation is retained or drained by urban trees. Trees with erectophile branching structure are more effective at draining rather than retaining precipitation. These trees have branches that are oriented at angles that are more vertically than horizontally aligned, and are often characterized by smaller crown projection areas. The more steeply inclined orientation of the branches in erectophile trees promotes drainage to the main stem, where depending on bark and ground surface characteristics, it may be subsequently transported as stemflow and generate runoff (Levia et al., 2015, Carlyle-Moses & Schooling, 2015). Some trees with erectophile branching structure often have relatively high LAI, especially higher in the crown (Martin-Ducup et al., 2018), leading to increased interception capacity. Thus, drainage by these trees may display seasonal variability, such as increased efficiency for deciduous trees during the dormant season. Trees with plagiophile branching structure more effectively promote retention of precipitation by the canopy, rather than drainage. These trees have branches that are more horizontally, rather than vertically oriented and are often characterized by larger crown projection areas. Precipitation is not well drained to the main stem in these trees, but is more effectively retained within the canopy where it could be partitioned into throughfall.

4.1.6. Applications for urban tree selection and management

Fig. 2 and Table 4 summarize the physical and structural tree traits, in addition to the maintenance practices, that facilitate optimal interception by urban tree cover. Urban foresters, planners, and natural resource managers who aim to optimize rainfall interception by urban trees should be aware of the direct relationships that exist between rainfall interception by urban trees and leaf area, canopy density, foliar and woody surface roughness, and length of foliation period. Conversely, they should know that there are inverse relationships that exist between interception by urban trees, foliar hydrophobicity, and branch inclination angle. When stormwater management by urban tree cover, especially via interception, is a prioritized goal of a municipality

Table 4
Summary of physical tree traits, site conditions, and management actions that help promote interception, infiltration, and related stormwater mitigation benefits by urban tree cover (UTC).

UTC Characteristics		Promote interception via enhanced canopy water storage capacity	Promote infiltration and enhanced subsurface drainage via the double funneling effect[1]
Physical tree traits	High LAI	✓	
	High canopy density	✓	
	Low foliar hydrophobicity	✓	
	Low leaf inclination angle (relative to the horizontal)	✓	
	High bark water storage capacity	✓	
	High bark microrelief	✓	
	Interlacing/interstiched furrows in bark	✓	
	Platy, overlapping bark	✓	
	High crown projection area	✓	
	Low bark microrelief		✓
	Shallow linear furrows		✓
	Presence of multiple leaders		✓
	High branch inclination angle		✓
Site conditions	Complex vegetative structure (i.e., mix of herbaceous vegetation, shrubs, and trees; most applicable for urban green spaces rather than isolated trees)		✓
	Permeable soils		✓
Management actions	Regulated pruning activity that maintains moderate-to-high canopy density	✓	

[1] Where soil and site conditions are favorable.

or metropolitan region, selection of tree species should be guided by knowledge of these relationships. Optimizing interception by urban tree cover is most ideal for those areas in which impervious cover is high. Application of this understanding of physical tree traits and their impact on canopy interception should also be used in conjunction with an understanding of the ecoregion-appropriate trees that collectively display these traits and resilience to the urban stressors (e.g., heat islands, elevated road salt exposure, soil moisture extremes) present in the cities in which they are intended to be planted.

4.2. Urban trees and stormwater mitigation via infiltration

4.2.1. Overview of the double-funneling effect

Inasmuch as urban trees facilitate stormwater mitigation via interception, they can also promote the infiltration of potential stormwater where soil conditions are favorable, thereby helping to reduce runoff volumes in this manner as well. There are two key consecutive-order processes by which this infiltration is promoted. The first of these is the funneling of precipitation from outlying parts of a tree canopy to its main stem, and subsequently its base, via stemflow. The second of these processes is the funneling of precipitation from the tree base to increasingly deep subsurface layers of the soil via channelization along roots (Johnson & Lehmann, 2006) and the percolation through soil macropores of varying size and depth (Rahman et al., 2019), thereby mitigating the volume of standing water on ground surfaces. Collectively, these tree-induced precipitation drainage processes are known as the double-funneling effect (Johnson & Lehmann, 2006).

While it may seem contradictory to the guidance we provide in section 4.1 to select trees that promote the drainage, rather than the interception of precipitation, this approach may be beneficial in water-limited sites or regions where increasing soil water recharge may be an additional goal of local natural resource managers (e.g., Eshtawi et al., 2016, Tellman et al., 2018). This tree selection strategy may also be beneficial when municipal resource availability may limit capacity for irrigation. In such cases, selecting trees that display potential for effective drainage by the canopy may help to mitigate stormwater while simultaneously contributing to broader water resource management goals.

4.2.2. Precipitation funneling by the canopy and linkages to physical traits of urban trees

There are several physical tree traits that promote drainage of precipitation by urban trees, many of which are opposite of those that promote interception. To funnel precipitation to the base of the tree (where infiltration can occur), both the crown architecture and bark characteristics of the main stem must promote the downward vertical transport of precipitation. In terms of crown architecture, branch inclination angle can help determine the degree to which precipitation is funneled by outlying parts of the canopy to the main stem, with higher stemflow yields generally associated with trees for which branches are oriented above the horizontal at relatively high angles (Ford & Deans, 1978, Jiang et al., 2021, Rodrigues et al., 2022). Stemflow yield was higher for *Fagus sylvatica* (European beech) saplings with branches oriented approximately 39° above the horizontal than for those for which the orientation angle was nearly 10° lower (Levia et al., 2015). Gotsch et al. (2018) made similar observations for mature urban street trees in Lancaster, Pennsylvania, USA, with a higher proportion of precipitation funneled to the main stems of trees for which branch inclination angles were relatively high, relative to those trees for which these angles were comparatively low.

While relatively high branch inclination angles are generally ideal when it is a goal to promote the funneling of precipitation by UTC, there can be threshold angles above which stemflow production diminishes, and loss of water via canopy drip increases (Levia & Frost, 2003, Levia et al., 2015). This interaction between precipitation and the canopy can be attributed to the fact that high branch inclination angles can be counterbalanced by reduced crown projection area (i.e., effective capture area). Thus, water flows facilitated by these steeply inclined branches may result in branch saturation and subsequent release of water from the canopy (i.e., canopy drip; Levia & Frost, 2003).

An additional component of crown architecture that can impact drainage of precipitation is the number of terminal leaders. Schooling and Carlyle-Moses (2015) identified a direct relationship between the number of leaders and stemflow yield, noting that stemflow funneling ratios were higher for multi-leader, rather than single leader isolated urban trees.

To facilitate infiltration by UTC, precipitation that is effectively funneled to the main stem must then be effectively funneled by the main stem to the base of the tree, specifically via stemflow. Stemflow yield is significantly impacted by physical bark characteristics, with bark microrelief and morphology being key factors. Lower microrelief (i.e., relatively smooth bark) is often correlated with higher stemflow yield (Levia & Germer, 2015). Bark characterized by low microrelief possesses lower water storage capacity, and fewer impediments to the vertical transport of precipitation down the main stem, resulting in higher stemflow totals (Fig. 3). Interspecific variability in bark characteristics can produce marked differences in stemflow yield within the urban canopy, as smooth-barked trees have been found to produce 2–5 times more stemflow than their rough-barked counterparts in urban and peri-urban forests (Livesley et al., 2014; Van Stan et al., 2015; Xiao & McPherson, 2011).

Similar to bark microrelief, bark morphology can also affect stemflow yield. High stemflow yield is often correlated with morphological features such as the presence of shallow linear furrows, which aid in the downward conveyance of precipitation funneled to the main stem. Contrarily, lower stemflow yields have been affiliated with morphological features such as inter-stitched furrows and scaly or peeling bark, which help to capture and impede the vertical flow of precipitation funneled to the main stem (Fig. 3) (Levia & Frost, 2003). High stemflow yield for isolated *Acer platanoides* (Norway maple) and *Quercus palustris* (pin oak) trees in Kamloops, British Columbia, Canada were attributed to the linear furrows present on their respective main stems (Carlyle-Moses & Schooling, 2015). Despite the moderate microrelief of the bark on these trees, stemflow yields remained notably high due to the high capacity for stemflow conveyance that the linear furrows of these trees provided (Carlyle-Moses & Schooling, 2015).

It is important to note that depths of individual bark furrows, regardless of their orientation (e.g., interstitched or linear) will be variable on any given tree, partly being influenced by tree age and life history. Accordingly, any individual tree will have a range of bark furrow depths. A preponderance of linear bark furrows, especially shallower linear furrows, is conducive to water drainage.

4.2.3. Quantifying precipitation funneling by urban trees

Funneling ratio is an important metric for quantifying the degree to which precipitation is effectively drained from outlying parts of a tree to its base. While many studies regard stemflow as being only a minute component (i.e., 1–10%) of net precipitation (Hakimi et al., 2018, Loustau et al., 1992; Oyarzún et al., 2011), the funneling ratio aids in more accurately accounting for the amplified local inputs of water to the base of a tree that occur due to stemflow (Pérez-Suárez et al., 2014), and in indicating potential for subsurface funneling of precipitation via infiltration and subsequent preferential flow along roots. When aiming to promote infiltration by urban trees, care should be given to select species that tend to have higher funneling ratios when soil properties and conditions favor infiltration.

Several studies have noted interspecific variability in funneling ratios by urban trees in differing site types. Dowtin et al. (2021) found that in urban woodlots in Wilmington, Delaware, USA, funneling ratios for *Quercus alba* (white oak) and *Quercus rubra* (northern red oak) differed significantly, with median funneling ratios for the two species being 0.49 and 8.45, respectively. Dowtin et al. (2021) attributed this observed interspecific variability to differences in bark morphology, with the linear furrows of red oak facilitating precipitation drainage via stemflow, and the scaly bark of white oak promoting capture and retention of precipitation along the main stem. For isolated trees in a small city in British Columbia, Canada, Schooling and Carlyle-Moses (2015) observed mean funneling ratios ranging from 8.5 to 28 for several species. These studies indicate that many trees common to urban landscapes can significantly promote the funneling of precipitation to the tree base, where it can be infiltrated, should soil conditions allow.

4.2.4. *Quantifiable infiltration impacts by UTC*

High funneling ratios indicate there is a greater concentration of precipitation at the base of trees relative to areas in which trees are absent. These localized hydrologic hot spots at the surface can correspond with localized zones of increased infiltration. Carlyle-Moses et al. (2018) observed that in a juvenile *Pinus banksiana* (jack pine) stand, precipitation that reached the base of a tree infiltrated to depths 15 times greater than in areas in which there were no trees. This effect was attributed to the local amplified water inputs via stemflow, as indicated by the relatively high funneling ratios at the study site (Carlyle-Moses et al., 2018). While these observations were made in an area of low population and development density, they can help to elucidate the potential contribution UTC makes to increasing infiltration in urban landscapes, thereby facilitating runoff reduction.

Additional work has quantified the degree to which urban trees may facilitate infiltration of stormwater. In a greenhouse-based study, infiltration rates increased by 63% in containers with trees, relative to those containers in which only soil was present (Bartens et al., 2008). For urban tree pits, runoff reductions of 62% were largely attributed to tree-induced infiltration rather than to interception alone (Armson et al., 2013). Similarly, in Baltimore, Maryland, USA, approximately 68% of precipitation was effectively infiltrated in urban forest patches across the city (Phillips et al., 2019). This infiltration was notably higher than in areas in which impervious cover was dominant, thereby highlighting the vital role these remnant natural areas serve in contributing to local stormwater management (Phillips et al., 2019). When considered at scale, these observations indicate the important role UTC serves in reducing runoff via infiltration across the urban landscape.

4.2.5. *Applications for urban tree selection and management*

To promote optimal infiltration by urban trees, it is best to select trees with traits that promote the funneling of precipitation to and then down the main stem (Table 4). Branches oriented above the horizontal at relatively high angles help to stimulate drainage to the main stem, so trees with this branching structure are ideal. Species that have vase, columnar, and oval crown shapes should thus be considered. Additionally, trees characterized by relatively smooth bark with linear furrows are most effective in funneling precipitation from the main stem to the tree base, where infiltration can occur.

Following the effective drainage of precipitation to the tree base, urban trees optimize infiltration when trees are in soils that are conducive to infiltration. These include soils with relatively low compaction and high hydraulic conductivity (Yang & Zhang, 2011; Sjöman & Gill, 2014; Peng et al., 2015; Weiliang et al., 2021), as opposed to soils that are highly compacted and can become waterlogged, subsequently reducing stormwater mitigation potential and threatening tree health (Grey et al., 2018). Kuhlemann et al. (2021) and Ossola et al. (2015) observed direct linkages between vegetative structure and infiltration in areas in which urban trees have been planted and established. These studies noted that hydraulic conductivity, and thus infiltration capacity, were higher in areas in which vegetative structure was more complex (i.e., canopy trees present in conjunction with diverse understory vegetation), rather than those with less complex vegetation structure, including areas characterized by isolated trees with limited to no understory vegetation or treed landscapes in which lawn mowing occurs frequently.

Urban foresters and natural resource managers who intend to strategically optimize infiltration by urban trees should ensure that selected trees have the requisite physical traits for effective drainage of precipitation to soils. Further, they should also make certain that these trees are planted and maintained in areas where there is minimal landscaping activity, and thus mitigated risk for reduction of structural complexity and future soil compaction, both of which could reduce infiltration capacity.

5. Broader considerations

It is important to acknowledge that while strategic tree selection is an important management strategy for stormwater mitigation, expectations of UTC to provide this ecosystem service must be managed accordingly. There are limitations to the ability of trees to reduce runoff. Precipitation thresholds exist beyond which canopy surfaces and soils become saturated, and trees become increasingly ineffective in intercepting or helping to aid infiltration (Zabret & Šraj, 2019b, Li et al., 2021). Additionally, the physical traits of trees vary over the course of their respective lifespans, with morphological characteristics varying over time with age, size, and health conditions (Baker et al., 2021, MacFarlane & Luo, 2009). The degree to which urban trees are able to effectively capture or drain precipitation will vary temporally during their lives. Also, variability in tree life expectancy varies due to site conditions and maintenance (Hilbert et al., 2019; Roman et al., 2016), which can also impact the length of time over which individual urban trees are able to significantly aid in reducing stormwater.

In addition to temporal patterns in UTC capacity to mitigate runoff, spatial patterns may also be present as UTC and related stormwater benefits can vary at the neighborhood scale. In some cities in the United States of America, spatial variability and related disparities in UTC have been driven by factors such as ownership status of residential developments and differing socio-economic variables (e.g., race, household income) (Landry & Chakraborty, 2009, Inkiläinen et al., 2013, Nyelele et al., 2019). These inequities in UTC distribution and ecosystem service provision can leave some communities more vulnerable to elevated stormwater volumes and related health and safety risks. Care should thus be taken to ensure that there is equal priority given to the strategic selection of trees to optimize stormwater mitigation, and to the equitable distribution and long-term care of these trees.

6. Conclusions

The current literature strongly supports the notion that urban trees can notably aid in reducing runoff in densely developed areas through promoting the interception and, under favorable soil conditions, infiltration of precipitation. There are varying physical tree traits that impact the degree to which urban trees facilitate rainfall capture and redistribution. Care should be taken to identify the intended goals for UTC relative to stormwater management, as this can help guide tree selection for optimal runoff reduction. When maximizing interception by UTC is the goal, such as in areas with high impervious cover, tree selection should be guided by knowledge of those tree traits that facilitate the effective capture and storage of precipitation. When urban trees are intended to reduce runoff through promoting infiltration while simultaneously recharging soil water, such as in water limited areas, planting priority should be given to trees with traits that promote the drainage of precipitation from tree crowns to their bases, where infiltration can occur and be promoted by favorable soil conditions. Inasmuch as stormwater mitigation by urban tree cover relies on proper tree selection, it is equally important to conduct tree care and site management strategies that facilitate equitable, maximal provision of this service by UTC. Future studies will benefit from more in-depth analysis of interspecific and temporal variability in physical traits of urban trees, the related impacts on stormwater mitigation capacity over the lifespan of UTC, and the degree to which placement of urban trees within a specific site type (e.g., urban natural area, residential lot, industrial lot) may impact their potential stormwater mitigation capacity.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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