



The effects of tree characteristics on rainfall interception in urban areas

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Received: 2 January 2019 / Revised: 5 June 2019 / Accepted: 10 June 2019 / Published online: 27 June 2019
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Abstract

Trees in urban areas have significant effects on the urban ecosystem. They can be used to improve the water cycle in urban areas by increasing evaporation and reducing runoff through rainfall interception. Street trees placed in planters on impervious areas reduce runoff by intercepting rainfall and by temporarily storing raindrops on leaves. Therefore, understanding tree canopy geometry and the effect of rainfall interception is important in urban hydrology. In this study, we assessed the effect of tree canopy morphology on rainfall interception using four major street tree species, *Sophora japonica* L., *Ginkgo biloba* L., *Zelkova serrata* (Thunb.) Makino, and *Aesculus turbinata* Blume, in Seoul, South Korea. We measured throughfall for each tree and also derived three-dimensional data of tree canopy morphology with a terrestrial laser scanner. Tree height, canopy crown width, leaf area index (LAI), leaf area density, mean leaf area, and mean leaf angle were used to determine canopy morphology. The interception rate was mostly affected by the LAI; a higher LAI tended to result in a higher interception rate. Leaf area affected the rainfall interception rate when trees had similar LAIs. These findings on individual tree canopy rainfall interception can help us to understand the importance of rainfall interception in hydrology and for ecological restoration when planning urban green spaces.

Keywords Terrestrial laser scanner · Urban water cycle · Leaf area index · Runoff · Tree species

Introduction

In the urban environment, trees play critical roles by balancing the water cycle and modifying local climate conditions (Guevara-Escobar et al. 2007; Natuhara 2018). Trees are important in urban catchment hydrology because of the interception of rainfall by their canopies. Interception of rainfall by the canopy reduces beneath-canopy throughfall and ultimately reduces runoff in urban catchments. In an urban environment with a high percentage of impervious surfaces, increasing interception and evaporation of rainfall and reducing runoff are crucial to restoring the urban water

cycle to its natural condition (Livesley et al. 2014). As it is not always feasible to expand the amount of green space in dense urban areas with a high proportion of impervious surface area to increase surface water infiltration and reduce runoff, it is important to select tree species with high rainfall interception to help improve the urban water cycle.

Canopy interception is the amount of rain that is intercepted by a canopy and then evaporates (Xiao et al. 2000). It can be calculated by measuring the difference between gross rainfall and the amount of rain passing through a crown (Huang et al. 2017). As raindrops fall, some drops directly pass through foliage and gaps between branches to reach the ground, which is called “free throughfall.” The raindrops intercepted by leaves or branches are temporarily stored on their surfaces (Xiao and McPherson 2016) and eventually evaporate after the rainfall has stopped.

It is important to include trees in an urban environment because of the interception of rain by their canopies. The processes of retaining water temporarily or until it evaporates contribute to improving the urban water cycle. These processes are affected by three main factors: the characteristics of a rainfall event (magnitude, intensity, and duration);

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the characteristics of a canopy (the density and area of leaves, canopy structure); and the weather preceding a rainfall event (Crockford and Richardson 2000).

Previous studies of rainfall interception by tree canopies have mainly been made in forest environments (Carlyle-Moses and Gash 2011; Iida et al. 2018; Yousefi et al. 2018). However, little research has been conducted to find out which canopy variables control rainfall interception in an urban environment (Huang et al. 2017; Xiao and McPherson 2011; Zabret et al. 2018). We expect factors affecting canopy interception of rainfall to differ between trees in an urban area and those in a natural forest because of differences in the local environment and because most urban tree canopies are isolated from each other (Livesley et al. 2016). For example, the rainfall storage capacity of a tree canopy is affected by leaf density (Gash et al. 1995) and temperature, wind, shade, and limited space in an urban environment may affect the growth of leaves or stems in comparison to those of trees growing in a forest (Baptista et al. 2018).

Leaf area index (LAI), the projected leaf area per unit ground area (Hosoi and Omasa 2006; Schumacher and Christiansen 2015), is a well-established index used to describe the leaf coverage of a canopy. It is broadly used to quantify the leaf area of a canopy and is used to analyze vegetation dynamics related to rainfall interception (Holder and Gibbes 2017) and radiative transfer (Grau et al. 2017). LAI can be measured in situ or estimated from remote sensing data (Hosoi and Omasa 2006; Sasaki et al. 2008). Recent advances in remote sensing technology have helped the development of diverse methods for the accurate estimation of LAI. High-resolution remote sensing data can be used to estimate to a high level of accuracy both the average LAI and also the spatial distribution of foliage. These data help us to understand tree canopy growth patterns in urban environments that affect rainfall interception (Baptista et al. 2018).

The aim of this study was (1) to explore the factors that affect the amount of rainfall intercepted by four types (species) of urban street trees [*Sophora japonica* L., *Ginkgo biloba* L., *Zelkova serrata* (Thunb.) Makino, and *Aesculus turbinata* Blume] in Seoul; and (2) to assess the effects of the spatial pattern of LAI on rainfall interception.

Materials and methods

Study area

To collect rainfall interception data from different trees, an automatic weather system including an S-RGD-M002 rain gauge (Davis Instruments, Hayward, CA), S-WCF-M003 wind speed and direction smart sensor (Davis Instruments), and HOBO USB micro station data logger (Onset Computer, Bourne, MA) were installed under street trees

on Gwanak Campus, Seoul National University (Figs. 1, 2), located in the southern part of Seoul, South Korea. The mean annual precipitation of 30 years (1981–2010) in this region is 1450.5 mm and the mean annual temperature 12.5 °C (Korea Meteorological Administration). Sixty-one percent of the precipitation is concentrated in the summer season when temperatures are high. The impervious surface in Seoul increased from 40.0% in 1962 to 47.7% in 2010 (Kim et al. 2016); this proportion of impervious surface is detrimental to the urban water cycle.

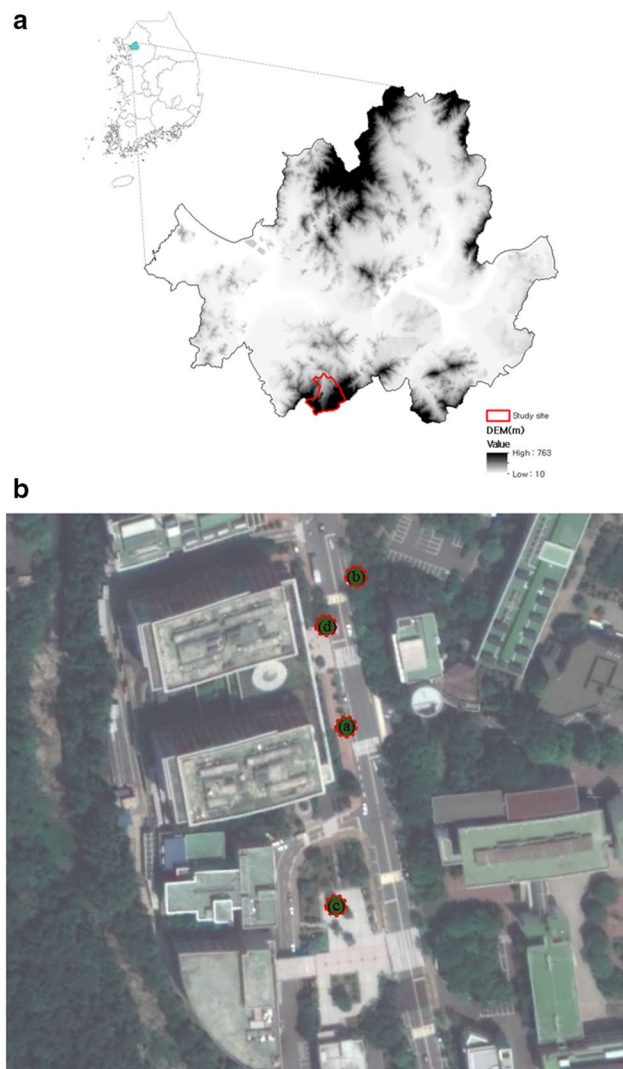


Fig. 1 Top Map of South Korea. Inset Topographic map of Seoul, South Korea; study site outlined in red. Bottom Location of studied trees [*Sophora japonica* (a), *Ginkgo biloba* (b), *Zelkova serrata* (c), and *Aesculus turbinata* (d)] on Gwanak Campus, Seoul National University (source: Google Earth)

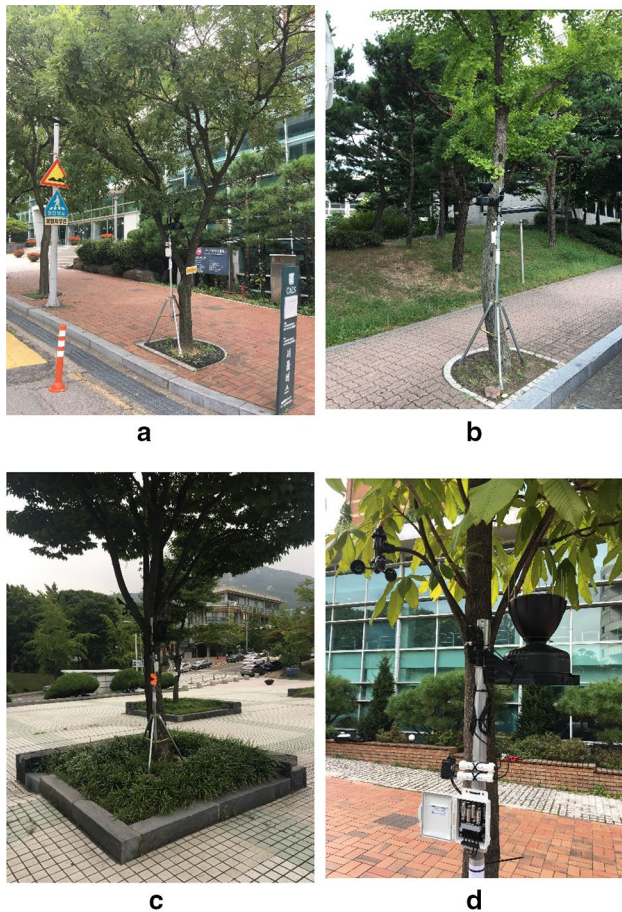


Fig. 2a–d Measurement of throughfall under street trees, Gwanak Campus, Seoul National University. **a** *S. japonica*, **b** *G. biloba*, **c** *Z. serrata*, and **d** *A. turbinata*

Data collection

Throughfall measurement

Throughfall was measured under the tree canopy of selected street trees on Gwanak Campus from 1 September to 31 November 2018. Eleven rain events were recorded during the measurement period. Minor rain events with precipitation under 5 mm or rain events with wind speed over 10 m s^{-1} were eliminated from the analysis leaving six rainfall events for analysis. The selected tree species for data collection were *Sophora japonica*, *Ginkgo biloba*, *Zelkova serrata*, and *Aesculus turbinata*. These species, which have different canopy characteristics, are the most popular street trees in South Korea. Gross precipitation was measured every 1 min at an open area to eliminate effects by buildings or trees on top of buildings near the street on which the studied trees were located. Wind speed was measured to ensure that only data when the wind speed was under 10 m s^{-1} were used, to reduce the wind effect.



Fig. 3 Scanning *Z. serrata* using a terrestrial laser scanner. White spheres were placed in multiple locations as reference points used to register scanned images

Measurement of canopy morphological variables

A terrestrial laser scanner (TLS) was used to measure characteristics for each tree species. TLS, also known as a ground-based light detection and ranging (LiDAR) system, measures an object using a point cloud to create a three-dimensional image. Pulses of laser light are directed at a surface and the time it takes for each pulse to bounce back is measured. TLS collects high-resolution data with positional accuracy at the millimeter level in a relatively short time. A Focus 3D-S350 (Faro Technologies, Lake Mary, FL) was used to scan each tree; point spacing of the scanning resolution was 6.1 mm at 10-m distance. Point clouds scanned from at least eight points were registered using CloudCompare [open source software (Baptista et al. 2018)] based on spheres placed in strategic locations prior to scanning (Fig. 3). The spheres are used to “tie” the image points taken from multiple locations to create one complete image of a single tree canopy. Tree data were cropped and noise data were removed using CloudCompare noise filter (Fig. 4).

We obtained foliage data from the point cloud data of the tree canopies to calculate LAI using MATLAB. Average

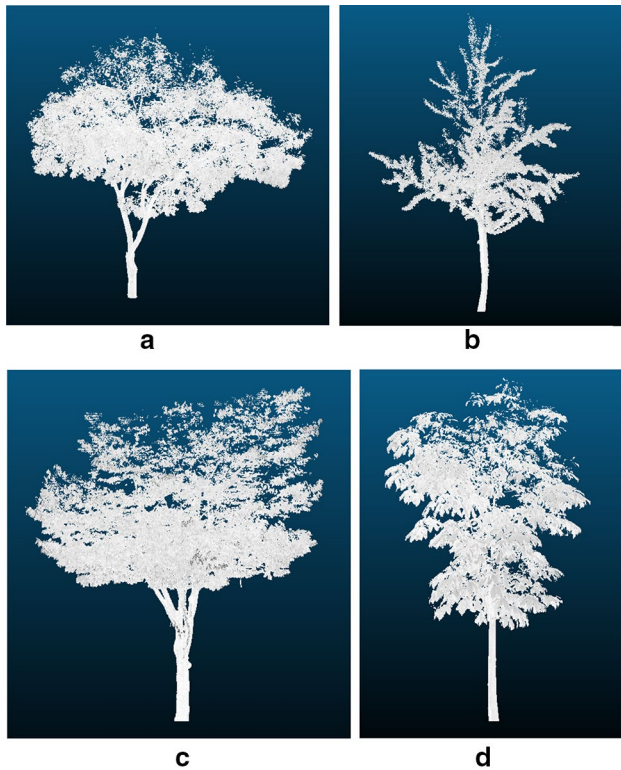


Fig. 4a–d Point cloud data of four trees. **a** *S. japonica*, **b** *G. biloba*, **c** *Z. serrata*, and **d** *A. turbinata*

LAI of total tree canopy was derived as well as the central section LAI of the canopy by using point clouds at 1-m radius from the trunk. Other canopy properties affect interception, such as mean leaf area and leaf area density (LAD), which affect the capacity of a tree to store rainfall (Baptista et al. 2018; Holder 2013; Holder and Gibbes 2017). Leaf angle, which affects water droplet retention (Holder 2012; Xiao et al. 2002), and tree height and width of canopy crown, which affect the total storage capacity of the tree canopy (Baptista et al. 2018; Xiao and McPherson 2011) were also derived using point cloud data. To calculate the mean leaf area and leaf angle, the tree canopy was divided into three sections vertically and horizontally. Ten leaves were

collected from each section, thus 90 leaves were used to calculate the mean leaf area and angle of each tree using MATLAB. Leaf angle was calculated by using the least squares method to find the plane that fit the leaf plane (Wei et al. 2016; Zhao et al. 2015). Each plane was calculated by using the normal vector of the base plane and fitted plane of the leaf (Hosoi and Omasa 2015; Li et al. 2018). The cloud point of each leaf was collected manually using CloudCompare and the calculation of leaf angle was coded in MATLAB. LAD was calculated by dividing leaf point cloud data into sections through voxelization (Li et al. 2018). Each 0.1-m voxel was the basic unit and the point cloud of leaves was used for LAD calculation. In addition, tree height and width of canopy crown were derived by using the maximum, minimum tree point cloud data in MATLAB. After retrieving canopy morphological variables, we used one-way ANOVA for LAI, LAD, leaf angle, tree height and width of canopy crown with rainfall interception rate.

Results

Throughfall

The gross precipitation ranged from 5.8 to 71.6 mm and rainfall intensity from 0.46 to 5.5 mm h⁻¹ (Table 1). Throughfall for each tree species varied depending on the gross precipitation and rainfall intensity.

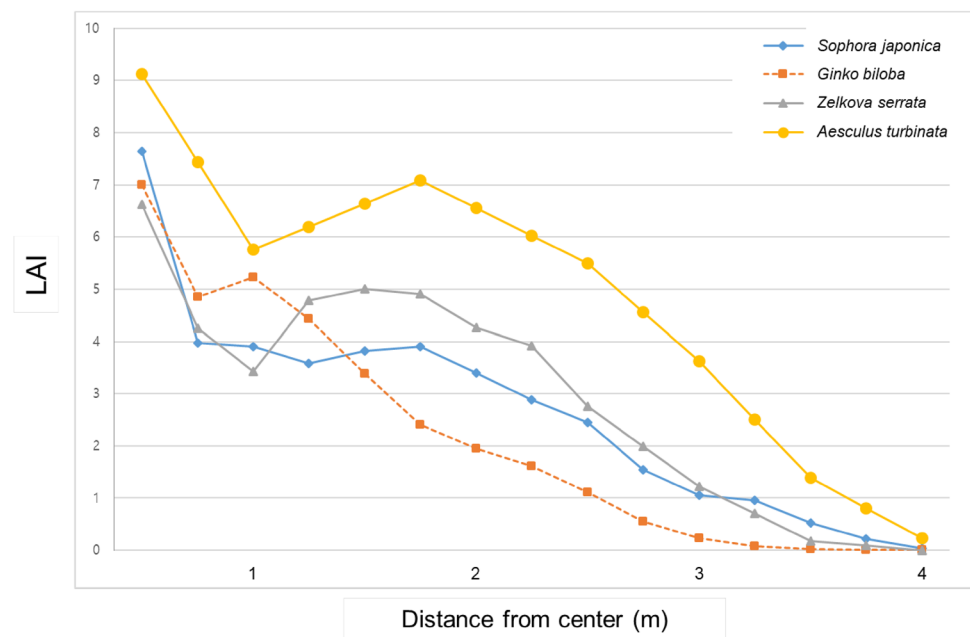
Canopy morphology

The radial LAI distribution showed a remarkable decrease from the center of the crown towards the edge of the crown. The highest LAI for all four tree species was typically in the range of 0.25–0.75 m from the center of the crown (Fig. 5). *A. turbinata* showed the highest LAI, 9, whereas the other species had an LAI of approximately 7. All trees showed the same overall decreasing trend of radial LAI. However, *G. biloba* showed a more gradual decrease in LAI with distance from the center of the tree crown up to 0.75 m compared to the other tree species.

Table 1 Throughfall for each tree and interception rate

Date	<i>Sophora japonica</i> Interception rate (%)	<i>Ginkgo biloba</i>	<i>Zelkova serrata</i>	<i>Aesculus turbinata</i>	Gross precipitation	Rainfall intensity (mm h ⁻¹)
3 September 2018	28.2 (20.34)	18.2 (48.59)	32.0 (9.60)	26.2 (25.99)	35.4	5.0
20 September 2018	3.0 (57.14)	2.6 (62.86)	5.2 (25.71)	4.6 (34.29)	7.0	0.4
21 September 2018	10.0 (48.98)	7.0 (64.29)	13.6 (30.61)	11.6 (40.82)	19.6	1.6
5 October 2018	17.6 (41.72)	15.6 (48.34)	25.2 (16.56)	20.0 (33.77)	30.2	5.0
6 October 2018	50.6 (29.33)	42.4 (40.78)	57.0 (20.39)	51.6 (27.93)	71.6	5.5
10 October 2018	4.8 (17.24)	1.0 (82.76)	4.6 (20.69)	4.6 (20.69)	5.8	2.9

Fig. 5 Radial distribution of leaf area index (LAI) for each tree species. *A. turbinata* had the highest LAI; the other trees had similar LAIs



The highest vertical LAIs were in the middle or middle-high section of *S. japonica*, *Z. serrata*, and *A. turbinata* crowns, and low section of the *G. biloba* crown (skewness of 0.503, 0.485, 0.024, and 0.949, respectively) (Fig. 6). *Z. serrata* had the highest LAI, 0.4–0.6 at a tree height of 2.5–3.5 m. *G. biloba* had the lowest LAI, which did not exceed 0.2 for all measured positions.

The ratio of tree height to width of canopy was used to indicate tree shape. *A. turbinata* had the highest ratio, 1.60, while *G. biloba*, *Z. serrata*, and *S. japonica* had ratios of 1.38, 1.03, and 0.84, respectively. The mean leaf area was highest for *A. turbinata* at approximately 1951 mm², while those of *Z. serrata*, *S. japonica*, and *G. biloba* were approximately 1365 mm², 933 mm², and 561 mm², respectively (Table 2). The mean leaf angle of *Z. serrata* was lowest at approximately 38°, while those of the other species were approximately 44° or more. The average LAD was similar between for the four trees, i.e., 0.13–0.16 m² m⁻³.

Influence of tree morphology on rainfall interception

Mean interception rate during six rainfall events varied between the tree species. *G. biloba* had the highest mean rainfall interception rate at 57.93%, while those of *S. japonica*, *A. turbinata*, and *Z. serrata* were 35.79, 30.58, and 20.59%, respectively. One-way ANOVA showed that tree canopy interception rate significantly differed between rainfall events and with tree canopy characteristics (Table 3). The data confirmed that LAI ($P = 7.61e^{-05}$), LAI of the central section of the canopy ($P = 0.002$), and mean leaf area ($P = 0.004$) significantly differed and that rainfall intensity

was marginally significantly different ($P = 0.071$) across all the analyses when explaining the variation in rainfall interception by the tree canopies. There was no significant correlation ($P > 0.01$) between rainfall interception rate and tree canopy morphological characteristics such as leaf angle, LAD, and tree height to width ratio.

Discussion

The LAI of the central section of the tree canopy is the most influential canopy characteristic for rainfall interception rate. *G. biloba* has the highest interception rate and LAI at the canopy center, and also the highest number of vertical layers with an LAI over 0.4 (Table 2). For trees with relatively similar LAIs such as the four species investigated, the difference in rainfall interception rate can be explained by the mean leaf area. *S. japonica* and *Z. serrata* had a similar LAI of approximately 5, whereas *G. biloba* and *A. turbinata* had a similar LAI of 7.0 and 6.3, respectively. The mean leaf areas of *S. japonica* and *Z. serrata* were 933 mm² and 1365 mm², and those of *G. biloba* and *A. turbinata* were 561 mm² and 1951 mm², respectively. These data indicate that smaller leaves are more effective in intercepting rainfall than larger leaves.

The relationship between LAI and rainfall interception in the present study is consistent with that of previous studies on urban street trees (Holder and Gibbes 2017; Huang et al. 2017). We also discovered that the mean leaf area significantly affects the rainfall interception rate. In addition, we showed that rainfall intensity is relevant to rainfall interception. The canopies intercepted more rain

Fig. 6a–d Vertical distribution of LAI. **a** *S. japonica*, **b** *G. biloba*, **c** *Z. serrata*, and **d** *A. turbinata*

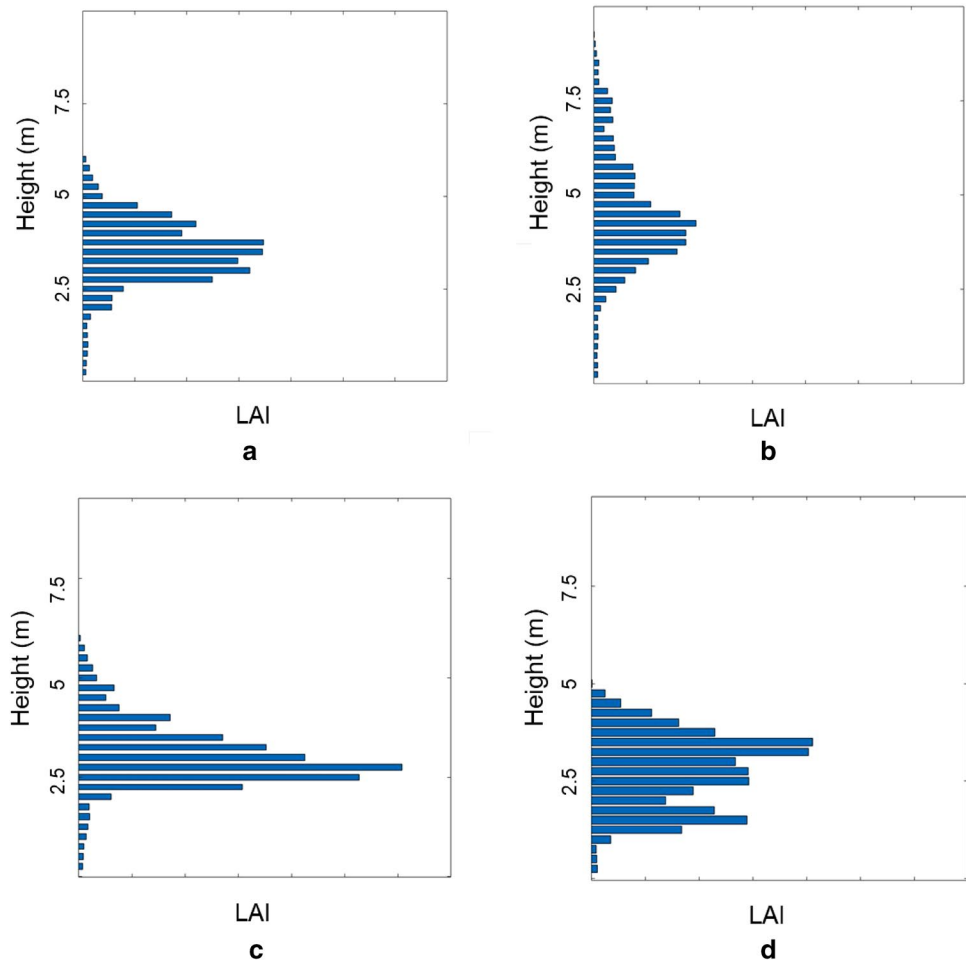


Table 2 Canopy rainfall interception rate and other canopy variables for each tree

	<i>S. japonica</i>	<i>G. biloba</i>	<i>Z. serrata</i>	<i>A. turbinata</i>
Mean interception rate and range (%)	35.79 (17.24–57.14)	57.93 (40.78–82.76)	20.59 (9.60–30.61)	30.58 (20.69–40.82)
Tree height/width of crown	0.84	1.38	1.03	1.60
Mean leaf area (mm ²)	933	561	1365	1951
Mean leaf angle (°)	46.21	47.68	38.95	44.06
LAD (m ² m ⁻³)	0.13	0.16	0.14	0.16
Leaf area index (LAI)	2.61	1.98	3.28	3.37
LAI of central section	5.11	7.02	5.02	6.37

during small storm events, which scatter rain rather than increase rainfall intensity (Barbier et al. 2009; Livesley et al. 2014). The differences in rainfall interception rates between the tree species were larger for rainfall of low intensity, since small rainfall events were not sufficient to totally saturate the tree canopies that had a large storage capacity (Huang et al. 2017). Thus, trees with a large rainfall storage capacity were not saturated while trees with a small storage capacity were. This indicates the importance of the spatial distribution of a tree canopy when estimating

its total rainfall interception. Traditionally, rainfall interception by a tree canopy is estimated by using the average LAI of the whole tree canopy (Fathizadeh et al. 2018; Liu et al. 2018), even though the saturation of certain leaves or a canopy section can affect spatial and total rainfall interception rates. By using the recently developed TLS and point cloud techniques (Hosoi and Omasa 2006), it is possible to estimate the spatial distribution of LAI in a tree canopy and the effect of this on urban ecology at a finer scale.

Table 3 One-way ANOVA of rainfall interception

	Source of variation	df	SS	MS	F	P
Rainfall intensity	Between group	1	1042	1042	3.57	0.071
	Within group	22	6412	291		
	Total	23	6921			
Mean leaf area	Between group	1	2372	2372	10.27	0.004
	Within group	22	5083	231		
	Total	23	7455			
LAI	Between group	1	3843	3843	23.41	7.61.E ⁻⁰⁵
	Within group	22	3612	164		
	Total	23	7455			
LAI central section	Between group	1	2664	2663	12.23	0.002
	Within group	22	4791	217		
	Total	23	7455			

It is difficult to quantify rainfall interception for every tree of interest, thus it is usually estimated indirectly by using LAI as a coefficient (Pereira et al. 2016; Su et al. 2016). However, the aim of this research was not to classify and generalize about each studied tree species by collecting a large amount of data (Holder and Gibbes 2017). Instead, in this study, tree species with different canopy characteristics were selected to assess which ones affect rainfall interception (Baptista et al. 2018; Holder 2013; Livesley et al. 2014; Xiao and McPherson 2011). Research designed to use data in the Gash model (Pereira et al. 2016; Su et al. 2016) needs to obtain a certain amount of measured data for generalizations. However, as the present study was not designed to examine the general characteristics of tree species but the characteristics of individual trees, we chose one tree of each of the four species assessed and measured their rainfall interception. To make generalizations and extrapolate the results to other trees, more numerous measurements of the species of interest are required.

Conclusion

We assessed tree canopy morphological variables that affect rainfall interception rate and demonstrated the importance of the spatial distribution of the canopy LAI. Tree species with a higher LAI had a higher rainfall interception rate. Where tree species had similar LAI, the rainfall interception rate was affected by average leaf area. Rainfall intensity and total intercepted precipitation varied for our study trees, which are the major street tree species in Seoul. The trees studied had average rainfall interception rates of approximately 20–60%, with higher rates occurring during less intense rainfall. It should be noted that, since throughfall data were measured in the central section of the crown, interception rate may have been overestimated. To overcome this limitation, the LAI was derived separately and compared with the average LAI of the whole tree.

Acknowledgements This subject is supported by the Korea Ministry of Environment (MOE, Project No. 2016000210004) as “Public Technology Program based on Environmental Policy” and by the BK 21 Plus Project in 2018 (Seoul National University Interdisciplinary Program in Landscape Architecture, Global Leadership Program Toward Innovative Green Infrastructure).

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