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Comparable diameter resulted in larger leaf area and denser foliage in the park trees than in street trees: A study on Norway maples of Karlsruhe city, Germany

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ABSTRACT

The leaf area of trees is the main surface of energy and matter exchange between the plant canopy and the atmosphere. A better understanding of canopy structure variations in cities is a prerequisite to evaluating leaf area and ecosystem services. We selected 58 single-standing and healthy Norway maple trees (*Acer platanoides* L.), equally distributed between the park and street at the same tree size for canopy structure and leaf area measurements. The canopy structures of street trees and park trees were different. Street trees had significantly higher dieback ($p < 0.01$), crown damage ($p < 0.01$), and branch-free bole length ($p < 0.001$) than park trees. Even though we sampled trees with similar diameters, park tree crowns tended to be healthier and denser than street trees. The crown volume, crown projection area (CPA), light availability (Crown Light Exposure or CLE), and foliage density were lower in street trees than in park trees. The average foliage density of street trees is 20 % lower than park trees. All the above differences in crown volume and foliage density lead to a significantly lower leaf area in street trees. The total leaf area of a single street tree was only 83 m^2 on average, compared to 186 m^2 among park trees. We demonstrated that crown volume and growing habitats (i.e., park or street) are important explanatory variables for leaf area. We conclude that a precise and site-specific evaluation of leaf areas is a prerequisite for accuracy in quantifying ecosystem services from urban trees.

1. Introduction

Single-standing trees in parks or near streets are essential to urban green space, and their numbers are declining due to climate change impacts, diseases, and urbanization [1]. Trees in cities provide many ecosystem services for urban residents [2], including air purification [3,4], mitigation of gaseous nitrogen pollution [5], increasing human thermal comfort [6], and reducing runoff in cities [7]. Leaves are the main surface for exchanging energy and matter between the plant canopy and the atmosphere. Therefore, leaf area

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is a crucial variable in the biological processes of plants, such as gas exchange, photosynthesis, dry deposition of air pollutants, and water storage during rainfall [5,7,8]. Evaluating urban forest ecosystem services is vital to gaining public and political support for urban tree conservation and maintenance [9]. At the same time, precise leaf area quantification is essential to evaluating ecosystem services. Leaf area or leaf area index (LAI) is the predictor variable of many ecosystem services, such as urban temperature regulation, noise reduction, and air purification [10].

LAI is the total one-sided area of leaf tissue per unit of ground surface area, a key parameter in ecophysiology, especially for scaling up the gas exchange from leaf to canopy level [8,11]. As expected, a significantly strong positive correlation exists between the reductions in surface temperature and the leaf area density [12] and LAI [6]. Generally, higher LAI and higher stomatal conductivity mean more cooling effects, and a sparse and thin canopy will result in low cooling effects [13]. For example, trees with a leaf area density of 1.1 can lead to 20 °C greater cooling for a brick on the same wall in one day than trees with a leaf area density of 0.3 [14]. The canopy storage capacity of water was well correlated to plant surface area (m^2), plant area index (m^2/m^2), and plant area density (m^2/m^3) [7]. The air purification function of trees, which includes the deposition of various gas and particle pollutants and their influence on microclimate and air turbulence, is complex and highly depends on the provision of large leaf area and varies between tree species [15]. The dry deposition velocity is sensitive to LAI and relative humidity in a nearly linear way [16].

The evaluation of LAI faces more problems in cities than in the natural forest. Many studies used i-tree-eco software to evaluate leaf area; however, the model estimation may have errors when the growing habitat of a tree is not considered in the estimation [17]. Even the combination of hyperspectral and LiDAR data only reached a limited accuracy in LAI estimation [18]. Identifying foliage density variations in cities is essential to estimate LAI better. Tree canopy structure is often unevenly distributed, with leaf clustering leading to leaf area density variability within the canopy, as demonstrated in many previous studies [19]. However, whether or not foliage density would vary between same-sized street trees and park trees under similar light conditions has not been investigated. Street trees offer the particular potential for cooling urban microclimates, as well as providing other ecosystem services [20–22]. On the other hand, street trees expose much more to pollutants than park trees and would improve air quality [23]. Especially when street trees growing along hospitals, nursing homes, or childcare facilities play a significant role in reducing heat stress, air pollution and improving public health and well-being [24]. Urban parks are important leisure and recreation places for urban residents; park trees are valued highly by the public [25]. Both street trees and park trees are essential parts of public life, however, trees growing in parks and along streets face different growing environments and stressors.

There are different techniques for estimating LAI. Direct methods include destructive sampling and litter fall collection [26]. It is also possible to estimate LAI indirectly from the incident radiation transmitted through the canopy at a given zenith angle, which is known as the gap fraction method and is used by different instruments (LAI-2200, DEMON, Ceptometer, or hemispherical photography) [8,27]. In this study, we chose the LAI-2200C Plant Canopy Analyzer from LI-COR to analyze the leaf area of single-standing

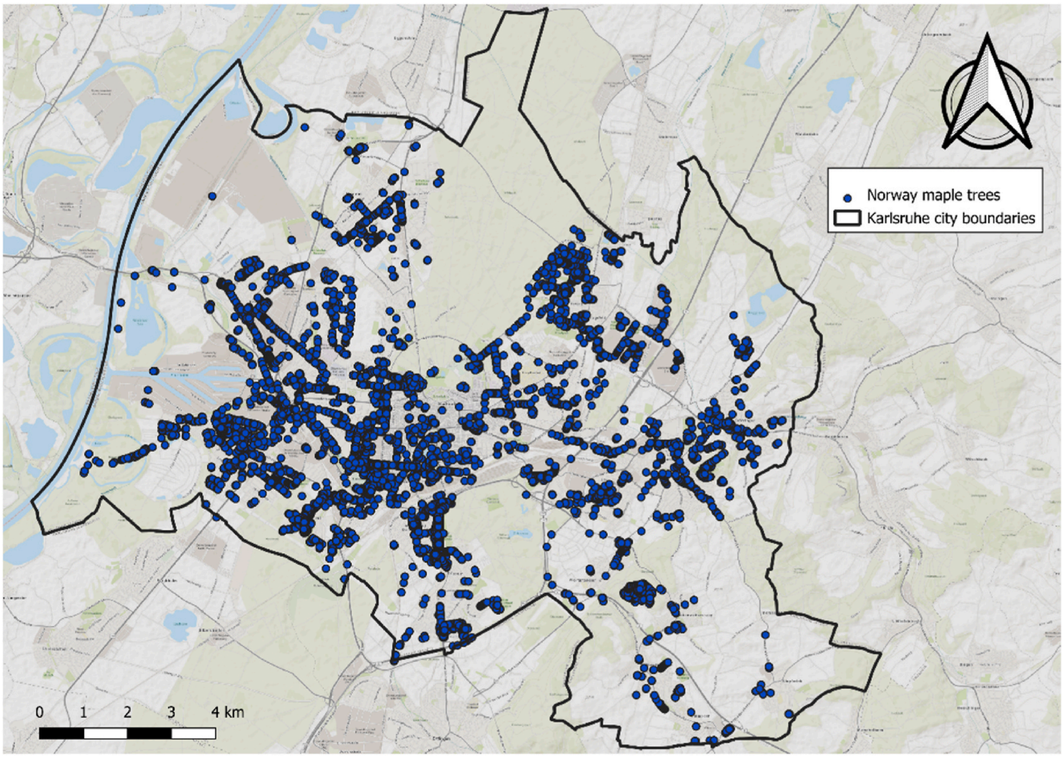

Fig. 1. Distribution of 12,592 Norway maple trees in Karlsruhe.

trees.

Norway maple (*Acer platanoides* L.) is a deciduous tree species native to eastern and central Europe. Norway maples can grow up to 20–30 m high and 1.5 m in diameter and have a broad, rounded crown. In the city of Karlsruhe, there are around 395,000 single-standing trees [28]. Of these, approximately 150,000 trees were owned and managed by the City Horticulture Department in 2022, and other trees belonged to private, other government, and religious agencies. There are 12,592 Norway maple trees in Karlsruhe, which are owned by the Horticulture Department of Karlsruhe city [29].

Our objectives were: 1) to compare foliage density and leaf area of single-standing Norway maple trees between street and park at the same tree size; 2) to test the influence of morphological variables and growing environment (i.e., park vs. street) on foliage density and leaf area.

2. Materials and methods

2.1. Study area

This study was conducted in the municipal area of Karlsruhe (see Fig. 1), which has an approximate area of 173 km^2. Karlsruhe is the second-largest city in Baden-Wurttemberg and has approximately 305,000 inhabitants [30]. According to the statistics of Karlsruhe city, about 42 % of the urban area of Karlsruhe is accounted for as built-up or traffic areas. Forests still cover 26 % of the city area, and agricultural land is still predominant (21 % of the municipal area).

2.2. Experimental design

In Karlsruhe city, there are in total of 12,592 Norway maple trees within built-up areas of the city, which are owned by the City Horticulture department (Fig. 1). Fig. 1 shows the distribution of Norway maple trees across the city.

29 street trees (a street tree was recognized as trees standing next to a road or if parts of its crown were located above the road) and 29 park trees (park trees were defined as trees inside parks) of the most commonly used tree species Norway maple (Fig. 2). We could cover 31 % of all Norway maple trees in five parks in our sampling. We could cover 6 % of all Norway maple trees in three streets (Table 1).

The single-standing trees (with a crown light exposure of 4 or 5 sides, which means the tree receives direct light from 4 or all 5

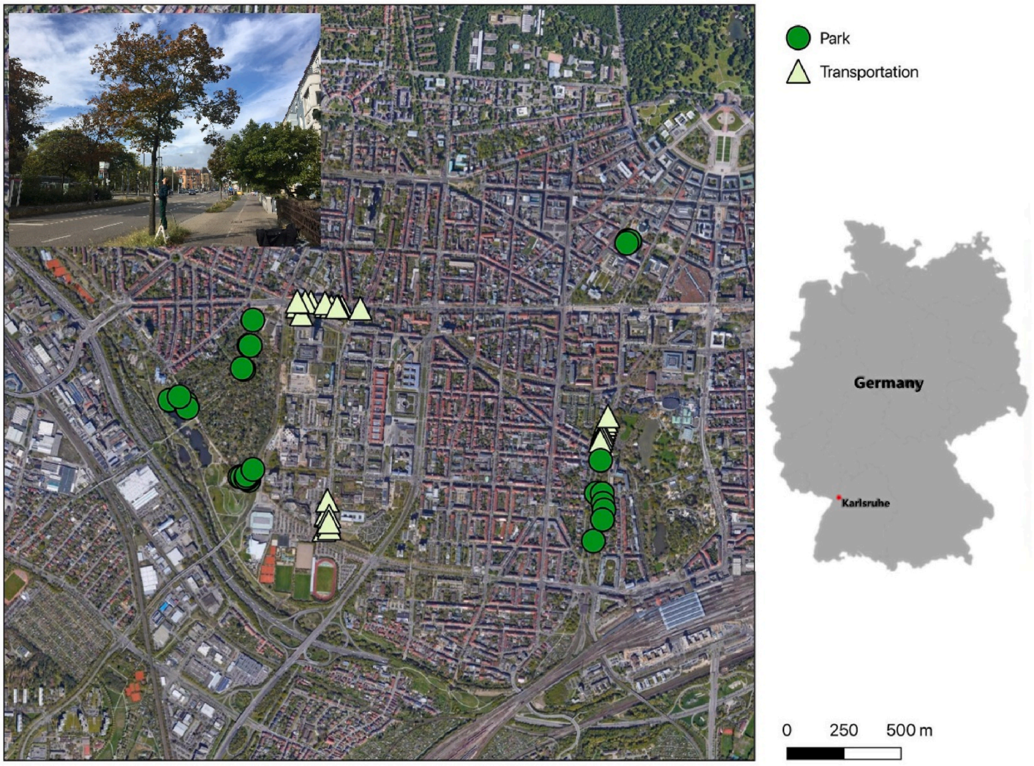

Fig. 2. The location of Karlsruhe City (right) and location of sample trees chosen for leaf area measurements using QGIS (QGIS Development Team 2019) with the exhibition of field measurement picture in the upper left.

Table 1
The number of park and street trees selected in the study is 58 Norway maple trees, of which 29 were located along streets and 29 in parks. The number of Norway maple trees available in the corresponding street or park is given in brackets.

Parks	N of trees	Streets	N of trees
Bahnhofparkanlage	7 (17)	Kriegstrasse	12 (112)
Badische Landesbibliothek	3 (5)	Beiertheimer Allee	9 (62)
Günther-Klotz-Anlage	14 (64)	Steinhäuserstrasse	8 (263)
Beiertheimer Feld	4 (5)		
Spielplatz Weinbrennerplatz	1 (1)		
Total	29 (92)		29 (437)
			58 (529)

sides) with tree size (DBH, diameter at 1.3 m height) ranging from 11 to 53 cm were selected to avoid the competition effect. The average DBH of both street and park trees was 23 cm, and the total height of street trees and park trees were 8.4 and 9 m, respectively. All trees belonged to "Artificial surfaces" land cover that denotes the city's built-up area. Only healthy individuals with a maximum value of 10 % crown dieback were chosen.

2.3. Field measurements of the tree structure and growing environment variables

Field data collection included the measurement of DBH, height, crown dieback, crown width, crown openness, canopy missing, and crown light exposure (CLE) (Table 2). The total tree height, crown width, and branch-free bole length were measured using a laser range finder (TruPulse 360B). DBH was measured using a diameter tape. Crown dieback, CLE, and canopy missing were measured by visualization and qualitative estimation based on the i-tree eco Field Guide [31]. Crown openness was visually measured based on Kosztra et al. [32]. For better measurement, we modified this method using a three-dimensional space not occupied by leaves to illustrate crown openness.

CPA (crown projection area) was calculated using a simplified vertical sighting method [33] with four directions of crown width and an ideal ellipsoid shape (Equation (1)). Crown volume was calculated assuming an ellipsoid shape for the tree crown and adjusted downward based on missing canopy (Equation (2)).

$$\text{CPA} = \pi ab \tag{1}$$

$$\text{crown volume} = \frac{4}{3}\pi r^2 h \times \textit{canopy missing} \tag{2}$$

where a is the radius of N–S direction crown width, b is the radius of W-E direction crown width, r is the radius of crown width, and h is half of the crown height.

2.4. Field data collection on foliage density and leaf area

The foliage density was measured using the LAI-2200C, an optical sensor that calculates canopy attributes from light measurements

Table 2
Tree variables were collected during fieldwork.

Variable	Unit	Measured (M) or visually estimated (V)	Description
Tree ID			Unique tree number
Street/Park tree	S/P		S if it is a street tree, P if it is a park tree
DBH	cm	M	Diameter at breast height (1,37 m)
Dieback	%	V	Percentage crown dieback
Total height	m	M	Height to top of the tree
Crown height	m	M	Height to crown top
Branch free bole length	m	M	Height from the bottom to the base of the crown
Crown width	m	M	Distance between the outermost points of the crown in two directions (north-south and east-west)
Impervious cover beneath the canopy	%	V	Percentage of the land area beneath the entire tree canopy's drip line that is impervious
Shrub cover beneath the canopy	%	V	Percentage of the land area beneath the entire tree canopy's drip line that is covered with shrubs
Crown Light Exposure (CLE)	0-5 sides	V	The number of sides the tree is receiving the sunlight from above. The top of the tree counted as one side
Canopy missing	%	V	Imagine an elliptic shape of the crown, estimate the percentage of the crown volume that is not occupied by branches and leaves
Crown openness	%	V	Estimation of the proportion of an m^3 of crown volume that is not occupied by leaves; this is the total amount of empty space within the projection of a crown

in five different directions [34]. Determining leaf area index (LAI) for an isolated plant involves difficulties because the amount of foliage over a given ground area depends on the ground position. The amount of foliage above a unit of ground area at the tree center is, for example, different from the amount of foliage near the tree edge. Therefore, a more useful measure is foliage density, which is m^2 leaf area per m^3 canopy volume.

Foliage density measurements require the transmittance values and the mean path lengths that each ring sees through the canopy and are reanalyzed through FV2200 software [34]. For the conversion of foliage density measurements to leaf area, the canopy volume is needed. Therefore, a photograph of the tree and the sensor position was taken at an angle of 90° to the measuring direction during the measurement process (see left top corner in Fig. 2).

The measurements of foliage density for single-standing trees were done using a 90° view cap to prevent the sensor from seeing the trunk. One measurement above and below the canopy is used to calculate canopy light interception at five zenith angles. One above reading (A reading) and three below readings (B readings) were taken in each cardinal direction. The LAI 2200C measurements were not adjusted downward in this study [26,35]. The measurements were taken on two days with continuous cloud cover to avoid errors from direct sunlight.

2.5. Statistical analysis

The bar plots were used to compare the differences between tree structures and the growing environments between the street and park trees. The bar plots were created in Origin 8.0 software. The significance level in bar plots was analyzed based on Welch ANOVA in SPSS (IBM SPSS Statistics 28.0.1.1) because of the non-Gaussian distribution of the data. The Shapiro-Wilk in SPSS was used to check the normality or Gaussian distribution.

The relationships of leaf area and foliage density to tree structure attributes and growing environment were analyzed with Automatic linear modeling (ALM) in SPSS. ALM can trim outliers, better deal with non-Gaussian data, and work with categorical, ordinal, binomial, and scale data in the same model [36]. The importance of a predictor is listed in Table 3, which indicates the relative importance of each predictor in estimating the model. It is the residual sum of squares with the predictor removed from the model, normalized so that the importance values sum to 1.

After checking collinearity using Spearman's rank correlation [37], DBH, crown height, crown width, crown projection area (CPA), and crown volume were highly correlated. Therefore, crown volume was used as a variable that combines height, width, and CPA. The variable impervious cover ("impervious cover beneath the canopy" of the i-tree-eco datasheet) was highly related to growing habitat (i.e., street or park). Therefore, only the street tree was used as a variable. The variable canopy missing correlated with crown dieback. Therefore, crown dieback was used as a variable. The final predictors in the ALM to find the influence on leaf area and foliage density were crown dieback, CLE, crown openness, crown volume, and growing habitat (i.e., street or park).

3. Results

3.1. Comparison of growing environment and tree structures between the street trees and park trees

The growing environment of park trees and street trees was significantly different. The impervious cover beneath the canopy ($p < 0.001$) and shrub cover beneath the canopy ($p < 0.05$) of street trees were significantly higher in street trees than in park trees (Fig. 3). Forty percent of the canopy cover beneath a street tree was impervious cover, while the impervious cover of a park tree only accounted for less than 10 %. The park trees received light from all five directions (east, west, north, south, and top; CLE = 5), whereas street trees received light primarily from 4 directions (CLE = 4). Even though we sampled relatively healthy trees with dieback of less than 10 %, street trees tended to have significantly higher crown dieback ($p < 0.01$) than park trees, and the average crown dieback of street trees and park trees was 4.1 % and 1.6 %, respectively.

Street trees tended to have a significantly higher branch-free bole length ($p < 0.001$), crown openness ($p < 0.01$), and canopy

Table 3

The results of Automatic Linear Modelling (ALM) with predictors' importance and influence of crown dieback, CLE, crown openness, crown volume, and tree location (street or park) on leaf area and foliage density.

	Source	Parameter estimate (β)	Standard Error of β	*t*-value	*p* value	Predictors' importance
Leaf area (Adjusted R square: 0.797)	Intercept	−74.969	95.191	−0.788	0.396	
	Crown volume	0.475	0.039	12.067	**0.000**	**0.848**
	Street tree (False)	73.566	16.828	4.372	**0.000**	**0.111**
	CLE	34.164	15.793	2.163	**0.035**	**0.027**
	Crown openness	−1.044	0.697	−1.499	0.140	0.013
	Crown dieback	0.423	2.508	0.168	0.867	0.000
Foliage density (Adjusted R square: 0.532)	Intercept	2.023	1.051	1.925	0.060	
	Crown volume	−0.003	0.000	−6.298	**0.000**	**0.687**
	Street tree (False)	0.522	0.186	2.811	**0.007**	**0.137**
	Crown openness	−0.021	0.008	−2.746	**0.008**	**0.131**
	CLE	0.227	0.174	1.303	0.198	0.029
	Crown dieback	0.027	0.028	0.974	0.335	0.016

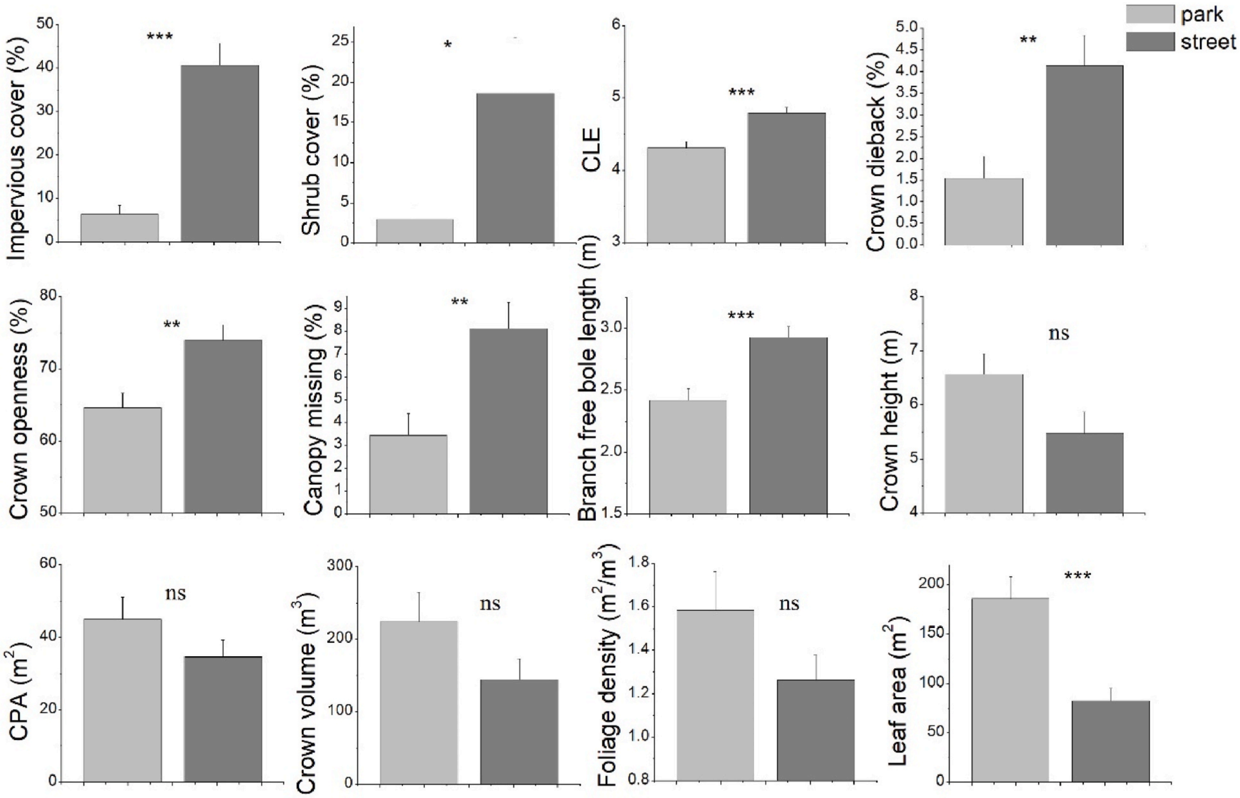

Fig. 3. Comparision of impervious cover (%, impervious cover beneath canopy), shrub cover (%, shrub cover beneath canopy), CLE (crown light exposure), crown dieback (%), canopy missing (%), crown openness (%), branch free bole length (m), crown height (m), CPA (m^2, crown projection area), crown volume (m^3), foliage density (m^2/m^3), and leaf area (m^2) between the street and park trees. The error bar is the standard error (SE). * is significance based on welch ANOVA. * <0.05, **<0.01, ***<0.001, ns > 0.05.

missing ($p < 0.01$) than park trees at the same tree size and same health conditions (Fig. 2). The average branch-free bole length of trees growing in the street was 0.5 m higher than trees in parks. The average canopy missing of street and park trees was 8 % and 3 %, respectively. Both street trees and park trees had high crown openness, while the crown openness in street trees was 14 % higher than in park trees.

The crown projection area (CPA), the crown volume of street trees, and park trees had no significant difference ($p > 0.05$); the average crown volume of park trees was 225 m^3, which was 55 % higher than that in street trees (Fig. 3). In addition, the average foliage density of street trees was 1.27 m^2/m^3, which was 20 % lower than park trees. As leaf area was the product of crown volume and foliage density, both crown volume and foliage density of street trees were lower than park trees, resulting in significant differences in leaf area ($p < 0.001$). The average leaf area per tree of street trees was only 83 m^2, which was 186 m^2 in park trees with comparable DBH.

3.2. Variables influencing leaf area and foliage density

The ALM modeling showed that the predictor variables can explain nearly 80 % of the variance in leaf area. Crown volume, park tree, and CLE were the three significant variables for predicting the size of leaf area among individual trees (Table 3). However, the predictor importance of crown volume (0.848) was far higher than that of the park trees (0.111) and CLE (0.027). Leaf area increased along with crown volume and CLE. Furthermore, the fact that a tree was a park tree increased the modeled leaf area compared to street trees. In contrast, crown openness and dieback showed no significance in predicting leaf area.

The ALM modeling showed that the predictor variables can explain 53 % of the variance in foliage density. The three significant variables for predicting foliage density were crown volume, growing habitat (park *vs.* street tree), and crown openness (Table 3). The predictor importance of crown volume (0.687) was much higher than that of park tree (0.137) and crown openness (0.131). Foliage density declined with an increase in crown volume, high crown openness, and the location of trees near streets. Street trees decreased the modeled foliage density in comparison to park trees. Trees with big crowns tend to have lower foliage density than trees with small crowns. Furthermore, CLE and crown dieback showed no significance in predicting foliage density.

4. Discussions

4.1. Crown volume, leaf area, and foliage density variations

Klingberg et al. measured the foliage density of street trees for six common urban tree species in Gothenburg, Sweden [38]. They found the highest mean foliage density was in Norway maple (1.8 $m^2\ m^{-3}$), and the lowest was in *Aesculus hippocastanum* (0.7 $m^2\ m^{-3}$) without mentioning the sampled size. Our results indicated that the mean foliage density of street trees in Norway maple with an average tree size of 23 cm (DBH ranges 11–53 cm) was 1.3 $m^2\ m^{-3}$ in Karlsruhe, while park trees had a foliage density of 1.6 $m^2\ m^{-3}$ (Fig. 2). Crown size (crown volume) was the dominant factor that influenced leaf area and foliage density (see Table 3). Leaf area was positively correlated with crown volume, meaning that big crown size was accompanied by large leaf area of the tree. At the same time, trees with big crown sizes have low foliage density. This can be interpreted by the fact that the branches and leaves of big trees are more sparse than small trees. Jack and Long [39] explored the organization of foliage within the crown and canopy of two conifer species and demonstrated that the development of large non-foliated areas inside tree crowns was associated with a large crown, which means that foliage density decreased with increasing crown volume. Research about the gray alder (*Alnus incana*) canopy estimation also illustrated that the heterogeneous distribution of foliage in crowns resulted in leaf area density decreasing rapidly with distance from the stem [40]. Trees may use this pattern of foliage density to make more efficient use of light. With the self-shading effects, light resources were unevenly distributed among leaves and gradually attenuated within the canopy [41]. Canopy structures have been shown to control light transmittance, light-use efficiency strongly, and the absorption of photosynthetically active radiation (PAR); forest canopy was far from homogeneous and was more likely asymmetry to increase light-use efficiency [42,43]. That is why leaf area postivly correlated with crown volume while foliage density negetively correlated with crown volume.

4.2. Why lower foliage density and smaller leaf area in street trees than in park trees?

Understanding tree canopy structure is critical to understand better tree growth and its response to disturbance [44,45]. In our research, foliage density and leaf area were influenced by crown size and whether a tree is a street tree or a park tree. Even though we sampled park and street trees at the same tree size and health conditions, the crowns of park trees still tend to be larger, more compact, and healthier than street trees. Crown dieback and crown openness of park trees were significantly smaller than street trees (Fig. 3). The crowns of street trees were also impacted by tree maintenance, such as regular pruning of branches to guarantee transport human and utility security [46]. Peper, McPherson [47] examined the leaf area of 12 common street tree species in the San Joaquin Valley city of Modesto, California, and concluded that pruning significantly impacted tree size and leaf area, potentially more than climate and soil characteristics. Pruning is an important arboricultural intervention involving multiple managers and could largely influence crown characteristics in street trees [44].

4.3. Poor health of street trees

As the global climate changes, trees in cities face severe heat and drought problems, and high tree mortality rates were reported [48,49]. Norway maple as street trees was observed to have an average "site age" of 48 years, far below its natural life span [50,51]. The plantation of trees, especially street trees, is always challenged by the high impervious coverage that can accelerate heat and drought and impact tree health and survival rate [52]. In this research, we found that the impervious coverage beneath the canopy of park trees and street trees was 6 % and 41 %, respectively, and the shrub cover beneath the canopy of street trees and park trees were both in low coverage (3 % under park tree canopies and 19 % under street tree canopies). The different impervious coverage site conditions may be the reason for canopy structure differences (higher dieback and crown openness in street trees and higher leaf area and foliage density in park trees), which warrants further ecophysiological and tree mortality research among street trees.

4.4. The implication of our results to ecosystem service estimation

Trees provide various ecosystem services and disservices which can be quantified using models based on field and environmental data [16]. Ecosystem service modeling can help decision-making regarding planting urban trees for climate change mitigation and air pollution reduction [53,54]. However, calculating leaf area from information on forest structure and compositions includes many assumptions and uncertainties. Better understanding of crown structure variations could mitigate this uncertainty and benefit model transparency, model development, effective communication of model output, and decision-making [55]. For example, park and street trees could be separated when modeling ecosystem services to promote accuracy. Street tree is an important part of urban green infrastructure and supply of ecosystem services. For example, street trees (so-called “road forest”) accounted for 26 % of all forest coverage in Harbin City, Northeast China, similar to park trees (so-called “landscape forest”) [56]. It was observed that every increasing unit of leaf area density of street trees decreases the asphalt surface temperature by more than 4.63 K on hot, cloudless summer days [12]. Trees with higher canopy density may be preferred over asphalt surfaces, such as streets, for higher cooling.

In contrast, trees with lower canopy density may be preferred over grass surfaces, such as park trees [57]. Thus, we should pay more attention to the low leaf area in street trees and find solutions to maintain high leaf area and foliage density as park trees to increase urban ecosystem services provided by street trees. In this context, a precise estimation of leaf area between street and park trees is crucial for quantifying ecosystem services’ benefits from city trees.

4.5. Limitations of this study and an outlook on future research

We sampled only 58 trees due to lack of time and COVID-19-related restrictions on movement and data collection. With a much bigger sample size, the differences in foliage density between street trees and park trees would reach the 0.05 significant level in Fig. 2. Also, we could not adequately consider the impact of regular pruning on leaf area and foliage density between street and park trees. We focused on the role of tree size, morphological variables, health conditions, and location on the changes in leaf area and foliage density, and our ALM analyses explained nearly 80 % and 53 % variance, respectively. However, future research studies should focus on establishing controlled and long-term experiments to understand the ecological, physiological, biological, and arboricultural processes that determine the considerable variations among leaf areas and foliage density of the same tree species of the same size but growing in a contrasting environment of streets, parks and natural condition such as forests.

5. Conclusions

Tree crowns of park trees tend to be healthier and more compact than street trees with similar diameters. Among the Norway maple trees growing in Karlsruhe, street trees had 20 % lower foliage density and 56 % smaller leaf area than park trees of the same diameter. We found that crown volume was an essential variable influencing leaf area and foliage density. Big crown size led to a large leaf area but low foliage density. The big tree crown tended to be sparse in branches and leaves to gain light efficiently. Whether a tree is a street or a park tree was also a significant variable that predicted leaf area and foliage density. We concluded that street and park trees had different canopy structures. Therefore, we recommend ecosystem services modeling researchers and practitioners separately evaluate leaf areas for street and park trees when modeling urban ecosystem services.

Data availability

Data will be made available on request.

CRediT authorship contribution statement

Hailiang Lv: Writing - review & editing, Writing - original draft, Formal analysis, Data curation, Conceptualization. **Anna Dermann:** Writing - review & editing, Methodology, Investigation, Data curation. **Florian Dermann:** Writing - review & editing, Methodology, Investigation. **Zoe Petridis:** Writing - review & editing, Visualization, Validation, Data curation. **Mario Köhler:** Writing - review & editing, Resources, Methodology, Investigation. **Somidh Saha:** Writing - review & editing, Writing - original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors had no conflicts of interest.

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