Estimating the leaf area index of urban trees using terrestrial LiDAR and the PATH method: sensitivity analysis and comparison with optical and direct methods

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Abstract

Urban trees play a vital role in mitigating urban heat islands through shading and transpiration, processes directly governed by the Leaf Area Index (LAI). Accurately estimating LAI in complex urban environments remains a challenge. This study evaluates the PATH (Path Length Distribution) method for estimating the Plant Area Index (PAI) of individual urban trees using Terrestrial Laser Scanning (TLS). Focusing on three tree species in Strasbourg (France), we conduct a comprehensive sensitivity analysis of the geometric parameters of the PATH model, specifically the crown envelope reconstruction and the number of facets. A key contribution of this work is the validation of TLS-derived estimates against a direct destructive method and indirect optical measurements. Results indicate that a concave hull with approximately 3,000 facets provides a stable and reliable PAI estimation. Comparison with direct measurements shows that while the PATH method effectively captures seasonal leaf phenophases, it tends to underestimate PAI in high-density foliage conditions. This research also underlines the importance of geometric modeling in leaf area density estimation.

1. Introduction

Urban heat islands (UHIs) pose significant challenges to public health and energy consumption in cities, exacerbating thermal discomfort during heatwaves. Urban trees mitigate heat islands through shading and transpiration; processes directly linked to Leaf Area Index (LAI). LAI, defined as the one-sided leaf area per unit ground area, is a critical biophysical parameter controlling urban microclimate processes such as radiation, rainfall, atmospheric deposition interception and tree transpiration. However, it is complex to measure the surface area of all the leaves, both outside and in the heart of the crown.

Estimating this index for individual urban trees is challenging because trees are complex objects, with geometric heterogeneity (depending on their species, their age, their health) and temporal dynamic (size, asymmetric crowns, pruned trees, tree's phenological stage). All these factors impact the LAI.
Direct methods (litter collection) measure leaf area with few intermediate variables, making them the only methods that strictly determine the “true” LAI but are time-consuming and destructive as the allometry is concerned.
Indirect methods are based on the measurement of intermediate variables such as radiation transmission or gap fraction leading to the estimation of LAI. They are fast, non-destructive, largely automatable, and enable dynamic monitoring of canopy structure (Breda, 2003; Hu et al., 2018a).

Optical instruments (e.g., LAI-2000) are fast and useful for dynamic monitoring. They capture direct or diffuse radiation and use models to calculate the probability of light interaction with foliage, accounting for leaf inclination and radiation angle. Initially conceived for agronomic canopies, hence expanded to forested areas, they rely on numerous assumptions, such as random leaf distribution, which is often unrealistic in heterogeneous and discontinuous forest canopies (Breda, 2003).

Laserscanning techniques are accurate and easy-to-use tools for several purposes: delineating the geometrical dimensions of the crown, producing 3D models of trees, detecting trees, delineating the crown, mapping height, and retrieving DBH for forest inventory applications (Kükenbrink et al., 2022). Terrestrial laserscanning (TLS) techniques do not provide directly a complete recording of all leaves in a tree, due to the occlusions of leaves. However, they offer two possibilities for extracting LAI values indirectly via gap-based methods (Hu et al., 2018a) or voxel-based methods (Béland et al., 2011). Therefore, it offers an interesting alternative to optical techniques. Recent studies try to achieve true LAI by TLS; however, it is not possible to completely segment individual leaves. Many studies show that most indirect methods underestimate up to 30% the LAI compared to direct methods in forest canopies. The aggregation effect, i.e. the phenomenon where leaves are not randomly distributed in space, is the most influential issue (Yan et al., 2019). Additionally, numerous studies using TLS have addressed LAI in forested areas, but only rarely in urban areas. Moreover, indirect methods rather measure the Plant Area Index (PAI), which includes both foliage and part of woody surfaces, rather than the LAI alone (Breda, 2003).

The PATH (Path length distribution method) is an indirect approach that can use 3D laser scanning to account for crown-induced clumping effect and estimates Foliage Area Volume Density (FAVD), from which Plant Area (PA) and Leaf Area (LA) parameters can be deduced (Hu et al., 2018b). It accounts for non-random foliage arrangements and woody structure contributions, unlike optical methods that assume homogeneous leaf distribution.

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Whereas PATH has been validated for forest stands, its efficiency on single urban trees, for which species and geometry are variable in space and time, has been poorly studied. Before analysing the PAI it produces, it is necessary to estimate its sensitivity to tree geometric reconstruction parameters (envelope shape, facet resolution, and leaf angle distribution), which are required to launch the algorithm. Results were compared to LAI-2000 measurements and finally to a “true” LAI obtained by collecting leaves on a neighbouring tree.

The paper is organized as follows: Section 2 describes the TLS acquisition campaigns and the characteristics of the urban tree species studied. Section 3 details the PATH methodology, focusing on crown envelope reconstruction and the filtering of laser pulses. Section 4 presents a sensitivity analysis of the geometric parameters, while Section 5 discusses the results in comparison with optical and direct reference methods. Finally, Section 6 concludes the study and outlines future research directions.

2. TLS campaigns and trees under study

The experiment is conducted in a residential neighbourhood of Strasbourg (France) featuring three streets planted with monospecific alley trees. Three urban species have been selected: plane trees, hackberry trees and lime trees. The trees are 10 to 13 m high and crown diameters between 5 and 8 m. Two trees of each variety were selected and have not been pruned for two years.

Three acquisition campaigns were conducted at different stages of tree foliation: during the leafless period (02/14 and 03/16/2023), leaf expansion (05/04/2023), and full foliation (07/13 and 07/19/2023). The data was collected using two high-resolution phase-difference laser scanners (Z+F Imager 5016 and FARO Focus 3D X330) with theoretical spatial resolutions of 0.2 mm at 50 m for the Z+F scanner and 0.8 mm at 50 m for the FARO scanner. In the second campaign, the FARO Focus 3D X330 was substituted with a FARO Focus Premium 150 scanner, which has the same spatial resolution. The scanner models used in this study are not specified since the data sets produced identical results regarding the estimated LAI in the first and second campaigns.

A tree has a complex geometry, making it necessary to set up multiple scanning stations to reconstruct the envelope of its crown. This minimizes occlusion, whether in its core (leaves, branches) or in its environment (neighbouring trees, street furniture, etc.). It is not necessary for the tree to be entirely visible at each scan, but enough stations must be set up to characterize it once the point clouds have been merged. This is the registration stage. It involves grouping the point clouds in the same coordinate system using homologous points. For this study, the system does not need to be attached to a known coordinate system. The consolidation step is crucial as it enables subsequent work on the merged cloud, such as envelope reconstruction, as well as on the point clouds exported by station and georeferenced at least locally. To achieve this registration, we placed targets (spheres) in the scene, making sure that there were at least three targets visible from both stations that needed to be merged.

Four stations were set up around each tree, positioned at distances ranging from 7 to 20 meters from the trunk. The acquisition parameters were selected to balance scan duration and data quantity. The point cloud should provide enough detail to accurately reconstruct the surveyed tree, without adding unnecessary burden to calculation times. The point spacing has been set at 6 mm at 10 m as suggested in Hu et al. (2018b).

3. Method

The PATH method involves modelling the FAVD based on point clouds from four registered stations. The product of the tree’s FAVD and the known volume of its envelope yields the LA. The core principle is to calculate the path length distribution of the laser beam as it traverses the tree crown (Figure 1). The process consists of three main steps: (i) reconstructing a crown envelope from the point cloud; (ii) filtering laser pulses by computing the statistical distribution of beam path lengths, and retaining only the relevant pulses (e.g., c, d, and e in Figure 1); (iii) calculating LAI using LAI = (PA – WA) / GA, where PA stands for Plant Area, WA for Woody Area (measured in the leafless period), and GA for Ground Area (Hu et al., 2018a).

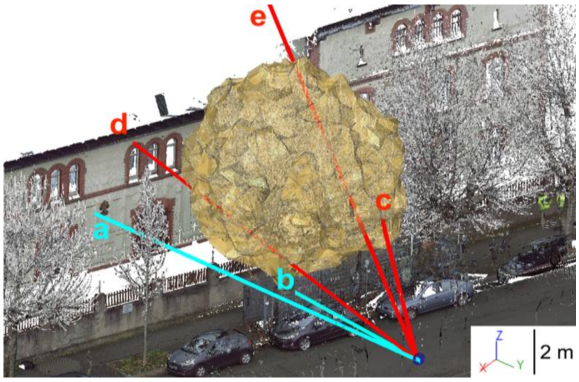

Figure 1. Classification of TLS pulses: (a) or (b) no intersection with envelope, (c) return inside crown, (d) return outside crown, (e) no return. Only c, d and e are kept for calculation.

3.1. Reconstruction of the crown envelope

After segmenting the tree crown from the merged point clouds, an algorithm is used to reconstruct its envelope. This algorithm, known as the “alpha shape” algorithm, generates both convex and concave envelopes. The convex envelope is the smallest surface that encompasses all the points, while the concave envelope reflects the tortuosity of the crown (Figure 2). The PATH method was initially applied on concave envelopes (Hu et al., 2018b).

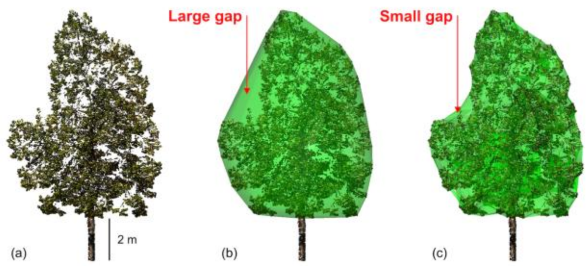

Figure 2. (a) 3D point cloud, (b) convex envelope, and (c) concave envelope of the lime tree under study during leaf expansion (05/04/2023).

3.2. Filtering of laser pulses

The envelope generated from the merged cloud is used as a mask for each scanning station. The objective is to exclude laser pulses that do not intersect the envelope (Figure 1(a), pulses a) and those that are stopped by objects in front of the tree (Figure 1(b), pulses b). This filtering enables to keep only the pulses that have passed through the crown envelope (Figure 1(b), pulses c, d and e) and are relevant for calculation.
The intersections between the emitted laser pulses and the crown envelope are calculated for each scanning station. It is then possible to determine the path length of a beam (Figure 1(a)), defined as the distance between the input and output intersection of the pulse through the envelope (Figure 1(b), pulses d and e. Pulses with a return inside the crown (Figure 1(b), pulses c) are also taken into account, even if they don't strictly cross the crown. These statistics allow for the calculation of the path length distribution for each station.
The crown mask can also be used to filter the individual laser beams and derive the gap probability for each station. This is calculated by comparing the number of pulses that pass through the crown with the total number of pulses that enter the crown. Pulses that pass through the mask, with or without the return of an object behind it, are considered gaps. Pulses blocked by objects in front of the mask are not included in the calculation.

The FAVD is calculated for each station based on the path length distributions (Equation 1) by Hu et al. (2018b).

$$P = \int_0^{l_{max}} e^{-G \cdot FAVD \cdot l} \cdot p_l(l)\, d(l) \quad (1)$$

where P = average gap probability
G = leaf projection coefficient
$FAVD$ = foliage area volume density
l = path length
$p_l(l)$ = path length distribution function

Instead of selecting one FAVD among all, a weighted average of the results per station is used to determine the global FAVD for the tree. This approach allows for the use of more samples and increases the level of confidence. Regarding the weighting factor, the principle is that more observations lead to greater reliability and therefore deserve greater weight. After testing the criteria of number of laser pulses and sum of path lengths as weighting factors, we concluded that weighting by the sum of path lengths is more reliable. Indeed, the sum of path lengths contains additional information on depth and is linked to volume proportion, whereas the number of laser pulses only relates to the number of samples in the scan direction.

3.3. Calculation of the leaf area index

As already mentioned, the product of the FAVD of the tree and the known volume of the envelope provides the LA.
In practice, this method calculates the Plant Area Density (PAD) during the leafy period and the Woody Area Density (WAD) during the leafless period, resulting in PA and WA, respectively. Therefore, LAI (m^2/m^2 or dimensionless) is calculated using Equation (2).

$$LAI = (PA - WA) / GA \quad (2)$$

where PA is Plant Area, WA is Woody Area (measured in the leafless period), and GA is the ground projection area.

4. Sensitivity results

Table 1 displays the calculated PA and PAI in this study. The surface areas increase as the trees grow.
The hackberry was the only one to experience a decrease in PA between the May and July campaigns. The precision, mentioned SD (standard deviation) in Table 1 is calculated based on the standard deviation of the values composing the sample. This outcome is consistent with the pruning of large branches that the tree underwent between the two campaigns (23th June 2023).

	May (05/04/2023)		July (07/13/2023)	
Tree species	PA ± SD (m^2)	PAI ± SD (m^2/m^2)	PA ± SD (m^2)	PAI ± SD (m^2/m^2)
Plane	430.9 ± 26.7	6.1 ± 0.4	599.5 ± 30.6	6.8 ± 0.3
Hack-berry	542.0 ± 30.2	10.5 ± 0.6	480.9 ± 13.9	7.6 ± 0.2
Lime	390.2 ± 33.0	11.7 ± 1.0	432.7 ± 39.0	12.8 ± 1.2

Table 1. PATH derived plant area (PA) and plant area index (PAI) for three species on two dates (SD: standard deviation).

Table 2 shows the LA and LAI assessed in leaf phenophases. As with PA, a decrease in hackberry's LA between the two campaigns can be observed.

	May (05/04/2023)		July (07/13/2023)	
Tree species	LA ± SD (m^2)	LAI ± SD (m^2/m^2)	LA ± SD (m^2)	LAI ± SD (m^2/m^2)
Plane	299.2 ± 36.1	4.2 ± 0.5	467.8 ± 38.7	5.3 ± 0.4
Hack-berry	384.1 ± 35.8	7.5 ± 0.7	323.0 ± 23.8	5.1 ± 0.4
Lime	297.9 ± 34.2	8.9 ± 1.0	340.3 ± 40.0	10.1 ± 1.2

Table 2. PATH derived leaf area (LA) and leaf area index (LAI) for three species on two dates (SD: standard deviation).

There is a scarcity of studies on urban trees that mention trees that are as large and dense as the ones we are examining, probably because it is difficult to collect a true LAI on very large trees. For instance, Sanusi et al. (2017) reported PAI ranging from 1 to 8 m^2/m^2 (based on canopy photographs) and focused on a few *Platanus x acerifolia* (PAI between 1 and 5 m^2/m^2). Other studies have focused on LAI, such as Wei et al. (2020), who presented LAI values ranging from 1 to 11 m^2/m^2 (based on realistic 3D models), or Rahman et al. (2018), who reported LAI values ranging from 1 to 7 m^2/m^2 for *Tilia cordata* (based on hemispherical photographs). Our results are relatively high in comparison. However, it is important to note that LAI values depend on various factors, including the species being studied, the growing and pruning conditions. Generalizing results from the literature as reference values for all deciduous is a delicate matter. To obtain reference values for our study, it is necessary to determine this index using a direct method (Moorthy et al., 2008).

To assess the sensitivity of PATH to geometric parameters while optimizing computation time, this paper specifically evaluates: a) the impact of envelope shape (concave vs. convex alpha-shapes) on PAI estimates; b) the impact of the number of facets of the envelope; c) the effect of leaf angle distribution assumptions (default vs. measured).

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4.1. Shape of the crown envelope

Hu (2018) considered the PATH method with two envelope shapes: a concave envelope and a convex envelope. He recommended working with a concave envelope limited to 5,000 facets instead of “unlimited” facets (exceeding 10,000 or even 25,000 facets) to reduce computation time. The results showed that the convex envelope underestimated the leaf area considerably when compared to the concave envelope. Since the trees under study are larger and of different species than those considered by Hu et al. (2018b) and Xing et al. (2024), this comparison was also carried out in our work. Also, a reduction of the concave envelope to 5,000 facets has been performed (Figure 3).

Firstly, visually, the concave envelope with unlimited facets and the concave envelope limited to 5,000 facets show no major difference (Figure 3), while the convex envelope naturally looks coarser.

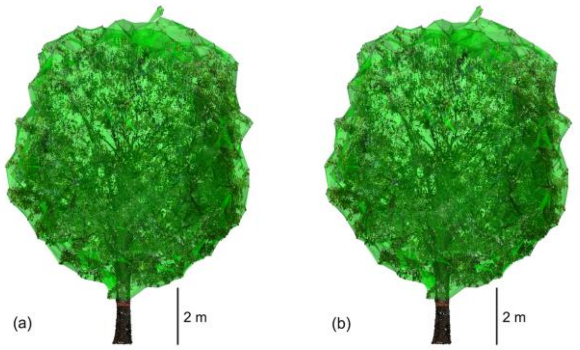

Figure 3. (a) concave envelope with unlimited facets, (b) concave envelope with 5,000 facets of the hackberry under study during leaf expansion (05/04/2023).

It was found that the PA from convex envelopes are lower than those from concave envelopes by approximately 100 m² (for the plane tree) to 200 m² (for the hackberry and the lime tree). Similarly, the PAI are underestimated by 2 m²/m² for plane trees and almost 6 m²/m² for lime trees. Additionally, the concave envelope with unlimited facets and the concave envelope limited to 5,000 facets produce similar results (on average, differences of approximately 5 m² in PA and 0.1 m²/m² in PAI).

4.2. Number of facets in the crown envelope mesh

As noticed previously, the concave envelope limited to 5,000 facets provides similar results to those of the concave envelope with unlimited facets. Therefore, it is interesting to test the limits of this facet reduction. We calculated the PAI of a tree of each species by further reducing the number of facets in the concave envelope from 5,000 to 500 facets, with a step of 500, and then determined it for concave envelopes limited to 100 and 25 facets.

As expected, the envelope becomes less detailed as the number of facets decreases. However, it still roughly describes the tortuosity of the crown. After a few hundred facets, concave envelopes exhibit an approximate appearance of a convex envelope.

The PAI decreases as the number of facets decreases. However, after a few hundred facets, no clear trend can be discerned (data not shown). Additionally, when comparing these values with the PAI determined using concave envelopes (6.1 m²/m² for the plane tree; 10.5 m²/m² for the hackberry; 11.7 m²/m² for the lime tree), the first significant differences appear from 2,500 facets onwards (differences of at least 0.5 m²/m²).

Reducing the number of facets is particularly interesting, because it also reduces the calculation time. Specifically, the calculation time for the PAD of the plane tree decreases from 14 minutes (for the concave envelope) to a range of 2 to 4 minutes (for concave envelopes limited in the number of facets).

In conclusion, there appears to be a correlation between the number of facets in the mesh and the PAI. As the number of facets decreases, the PAI also tends to decrease, up to a certain threshold of a few hundred facets. Beyond this threshold, the PAI value becomes random. Therefore, if the calculation duration is not a decisive criterion for the user, it is advisable to use the concave envelope to avoid any errors related to a limitation in the number of facets. However, if this is not the case, a limit of 3,000 or more facets would be appropriate. Significant deviations begin to appear below this threshold.

4.3. Leaf angle distribution

For this study, WA and PA were calculated using a default value for the leaf area projection coefficient ($G = 0.5$). This value provides relatively reasonable results when measured data are unavailable (Hu et al., 2018b). However, it is worth comparing the areas calculated using the default value with those obtained from the angular distributions measured on the trees surveyed during leaf expansion.

In order to ascertain the leaf angle distribution from a merged point cloud of a tree, it is necessary to first remove the trunk and branches. The inclinations of the leaves can then be measured using the tools available on CloudCompare (http://www.cloudcompare.org/). Finally, the results should be saved in a defined format, so that the algorithm for calculating the density of the plant surface can take these values into account.

After identifying the PA associated with each situation, the results are very similar. The surfaces calculated using the measured angle values deviated by only 7 % (31.8 m² for the plane tree), 1 % (7.3 m² for the hackberry), and 3 % (12.3 m² for the lime tree) from the results obtained using the default angular distribution value. Therefore, it can be considered that, in the absence of data on the leaf angle distribution of a tree, the default value does indeed provide positive outcomes.
However, the default angular distribution tends to underestimate the PA compared to the actual leaf angle distribution of the tree.

During the summer of 2023, an experiment was carried out on the three species under study to manually measure the inclination of the leaves. The process consists of positioning the operator so that the leaf to measure is oriented nearly parallel to the viewing direction. Using a protractor and a plumb line (indicating the vertical direction), the operator can read the angle of inclination of the leaf. Given the time-consuming nature of the process, we measured the inclinations of only a dozen leaves at the bottom of the canopy for each tree. Pisek et al. (2013) report that at least 75 angle measurements are needed to estimate the leaf angle distribution of a tree. The number of measurements in our experiment is therefore insufficient to guarantee a reliable result. Consequently, the experiment should be repeated with a larger sample in the future. However, the complexity of its implementation and the time-consuming nature, especially for such large trees, demonstrate the utility of a theoretical estimation using point clouds. The digital method is particularly interesting because it provides realistic outcomes.

In conclusion, first results show that envelope geometry significantly influences PAI estimates, up to 6 m²/m² and therefore concave shapes are recommended. Stable and accurate PAI values were achieved with at least 3,000 facets, while coarser meshes led to deviations greater than 0.5 m²/m². Leaf angle distribution (LAD) assumptions influenced PAI by less than 7 %, deviating only 1 to 3 % from measured distributions. These results validate the parameters to be set.

5. Discussion regarding species and comparison to the reference (LAI-2000 and true LAI)

By comparing leaf expansion (May) and at full foliation (July) periods, it can be noticed, as expected, that leaf area (LA) increases with foliage development, peaking in July (Table 2). Interesting differences between the three species can be highlighted. In May, plane trees exhibited the lowest LAI, which is consistent regarding their canopy in which large branches are dominant compared to the other species. In July, LAI estimates range from 5 m²/m² (plane and hackberry tree) to 10 m²/m² (lime tree), reflecting species-specific crown densities.

5.1. Plant areas using LAI-2000

During the leaf phenophase, LAI-2000 measurements are influenced by the contribution of woody surfaces. Therefore, we recommend using a PA instead of a LA.

For an individual tree, the calculation of the PAI from LAI-2000 (Li-Cor, Nebraska, US) data follows the same theoretical principle as the PATH method. The data from the canopy analyzer does not directly provide PA but PAD. The amount of vegetation on a given surface depends on the position of the sensor on the ground. For instance, a measurement taken at the center of a tree does not record the same amount of vegetation as a measurement taken at the edge of the same tree.

Measurements taken during leaf expansion were used to determine the PA and PAI for one tree of each species (Table 3). The standard deviations were established based on the accuracy of the PAD, determined by the FV2200 (Li-Cor, Nebraska, US) software, and a variance propagation formula.

However, the LAI-2000 instrument does not take into account the non-random distribution of leaves in the crown space. Therefore, some authors suggest correcting the measurements with complementary data (Kucharik et al., 1998; Stenberg et al., 1994; Eriksson et al., 2005), such as Chen et al. (1997) who used the dedicated TRAC instrument. As these resources were not available for this study, we chose to use coefficients available in the literature to limit the phenomenon of aggregation. For instance, Stenberg et al. (1994) proposed the use of a shading factor. It is defined by Equation 3.

$$PAI_e = \beta \cdot PAI_{corr} \tag{3}$$

where PAI_e = effective PAI determined by LAI-2000
β = shading factor ($\beta < 1$)
PAI_{corr} = “true” PAI (or at least a corrected PAI that theoretically approximates the true LAI)

Nowak (1996) provides shading factors for several species, including *Celtis australis* and *Platanus x acerifolia*. For the lime tree, the shading factor for *Tilia cordata* was used as no value was available for *Tilia x euchlora*. Table 3 displays the LAI-2000 corrected PAI based on these coefficients.

	May (05/04/2023)	May (05/04/2023)		May (05/04/2023)
Tree species	PA_e ± SD (m²)	PAI_e ± SD (m²/m²)	β	PAI_{cor} (m²/m²)
Plane	108.0 ± 8.0.1	4.2 ± 0.3	0.86	4.8
Hack-berry	88.9 ± 6.8	8.1 ± 0.6	0.92	8.8
Lime	63.8 ± 4.0	8.3 ± 0.5	0.88	9.4

Table 3. LAI-2000 derived effective plant area (PA_e), effective plant area index (PAI_e) and corrected plant area index (PAI_{cor}) using shading factor (β) determined by Nowak (1996), for three species during leaf expansion (SD: standard deviation).

Upon comparison of all the results, it is apparent that the uncorrected PAI of the LAI-2000 are at least 2 m²/m² lower than those provided by the PATH method. This can be explained by the fact that the canopy analyser does not consider the non-random distribution of leaves in space, unlike the PATH method. Indeed, it only measures an effective LAI and therefore tends to underestimate the results.

After correcting the measurements with the shading factors taken from the literature, there was an increase in PAI. However, the corrected results are still lower than the PAI calculated using the PATH method.

Furthermore, the LAI-2000 was designed for data collection under homogeneous overcasts. While some techniques may enhance the outcomes for individual trees, the instrument is not specifically tailored for this type of measurement. Moreover, for line trees in the studied urban area, a lot of interferences disrupt the results. Therefore, the comparison of results obtained from both methods is limited.

Only reference values will enable us to assess the absolute accuracy of our results and determine the influence of the aggregation phenomenon.

5.2. Importance of reference values

To assess the accuracy of the estimations provided by the PATH method, reference values should be acquired through a direct method, such as collecting litter. In the fall of 2023, we measured direct LA on an isolated hackberry tree (Figure 4) by collecting all leaves in a huge net over seven collecting dates. The tree was directly neighbouring to the one under study.

After drying and sorting leaves from wood and fruits, estimating specific leaf area (cm²/g) at each collecting date, the measured LA (521 m²) and true LAI (11.4 m²/m²) exceeded the July PATH estimates.

An initial explanation for the origin of these discrepancies may lie in the pruning of branches prior to the July scan and the polycyclic flushing waves during the summer, which increased the LA/LAI until September. However, a thorough analysis of the gap fraction classification (especially for phase-shift TLS), is necessary. For May, PATH-derived PAI aligns more closely with true LAI than LAI-2000 estimates, but further work is needed to establish the link between PAI and LAI.

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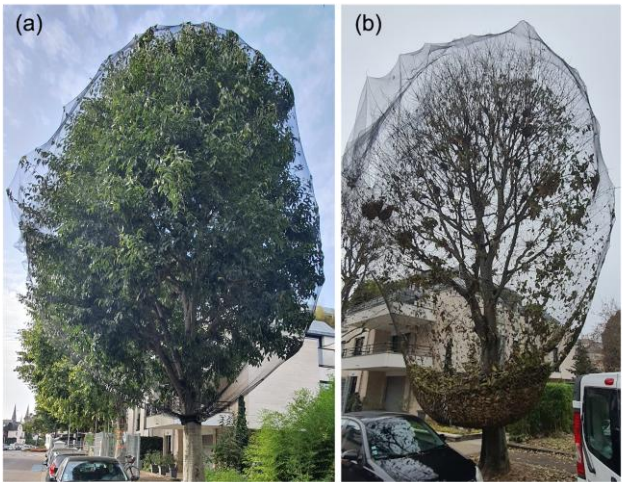

Figure 4. Wrapping the entire crown of a tree using a huge net (a) isolated hackberry tree before leaf fall (10/06/2023), (b) same tree during a harvest day (12/04/2023). Leaves have been collected about every 10 days during the fall by opening the net around tree trunk.

5.3. Consistency of equality $PA = WA + LA$

During the leaf period, indirect methods measure effective LAI. However, these methods are sensitive to the phenomenon of aggregation and the contribution of woody surfaces, resulting in the measurement of PA rather than LA. The PATH method attempts to limit aggregation but does not distinguish leaf surfaces from the rest of the vegetation. Hu et al. (2018b) and Xing et al. (2024) suggest evaluating PA as the sum of WA and LA. To collect LA, they then recommend subtracting WA from PA.

However, Dufrêne and Breda (1995) and Gower et al. (1999) argue that this equality is not always valid. They suggest that in canopies with non-random foliage and cortical surface distributions, the equality is unfounded as it fails to consider the coverage of branches by leaves and vice versa. This hypothesis would overestimate the contribution of WA to the value of PA, leading to an underestimation of LA. The authors Kucharik et al. (1998) demonstrated that for closed canopies, only 5-10% of branches affect the LA estimate. Therefore, they recommend disregarding this contribution and making a minor correction to account for the contribution of the trunks only.

Comparisons of the true LAI of a neighbouring hackberry with the results of the PATH method have demonstrated that the PAI determined by the PATH method is closer to the true LAI than the calculated LAI. Xing et al. (2024) also evaluated PA as the sum of WA and LA and subtracted WA to PA to estimate LA. However, their results indicate that their calculated LA was strongly correlated with the LA measured by allometry with Normalized Root Mean Square Error value of 0.13 (Xing et al., 2024). The divergence in findings between the two studies may have several reasons. Firstly, the reference method of Xing et al. (2024) is not litter collection but allometry, and allometry itself can present inherent uncertainties. Secondly, their trees are not as large and dense as ours. Consequently, their measurements may be less affected by branch occlusion by leaves. Conversely, for the trees with denser crowns in our study, leaves masked a large proportion of branches. Therefore, subtracting WA from PA to obtain LA would overestimate the contribution of WA in PA during the full foliated period, thereby leading to a significant underestimation of LA. These remarks require further analysis in the future.

6. Conclusion and outlooks

The PATH model based on TLS data provides accurate and robust estimates of PA for single urban trees but requires also adapting scanning protocols and parameters to the morphological characteristics of species, particularly for urban trees with large and dense crowns. While the method captures seasonal phenophases effectively, further investigation is needed to address the underestimation observed in high-density foliage conditions compared to direct measurements. Therefore, to further validate the versatility of the PATH method, further research should focus on its extension to a broader range of urban tree species with diverse architectures.
Future work will also leverage these species-specific PAI/LAI estimates to quantify the cooling potential of urban trees, specifically by linking canopy density to shading efficiency and transpiration rates in microclimate models.

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