

Evaluating Human Thermal Comfort Impact of Urban Tree Pruning through Solar Radiation Simulation using Quantitative Structure Model

SZU-YI LEE

National Cheng Kung University

CHI-KUEI WANG

chikuei@ncku.edu.tw

National Cheng Kung University

CHUNG-CHENG LEE

National Cheng Kung University

TZU-PING LIN

National Cheng Kung University

Article

Keywords: Tree pruning, Heat Island mitigation, Terrestrial LiDAR Scanning (TLS), QSM, Thermal comfort, Tree shade

Posted Date: October 27th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11276657/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Abstract

Urban trees mitigate thermal stress through shading, evapotranspiration, and airflow regulation, with cooling benefits strongly dependent on canopy structure, particularly Leaf Area Index (LAI). Pruning is the primary canopy management practice in urban environments for reducing windbreak risk, ensuring safety, and enhancing aesthetics, yet it inevitably alters canopy coverage and thus shading and thermal comfort beneath the canopy.

However, the effects of pruning on human thermal comfort remain insufficiently addressed, as existing simulations often assume uniform cooling beneath the canopy and fail to capture spatial variations after pruning. This study proposes an automated pruning workflow combining Terrestrial LiDAR Scanning (TLS), Quantitative Structure Model (QSM), and solar radiation simulation. A rain tree was scanned using TLS, and the point cloud was processed to generate a QSM. Multiple pruning models were then developed according to pruning principles to simulate solar radiation beneath the canopy. Physiological Equivalent Temperature (PET) was adopted as a thermal comfort proxy, and pruning effects were quantified by PET reduction. The workflow enables detailed assessment of the relationship between pruning and thermal comfort beneath urban tree canopies.

1. Introduction

As urbanization and climate change accelerate, urban trees have emerged as a critical component of green infrastructure, mitigating thermal stress through shading, evapotranspiration, and airflow regulation (de Abreu-Harbich et al., 2015; Oke et al., 1989; Meili et al., 2021; Jareemit & Srivanit, 2022). These cooling benefits are, however, highly dependent on canopy structural characteristics. High Leaf Area Index (LAI) enhances this solar radiation interception capacity, allowing around 8–15% of total radiation to reach the ground (Konarska et al., 2014; Shahidan et al., 2010). The findings underscore the importance of appropriate canopy management in enhancing human thermal comfort beneath tree canopies in urban environments.

Given that LAI is central to the cooling benefits of urban trees, tree management and pruning have become an increasingly critical concern in cities. Pruning is the primary tree caring practice in urban environments, carried out to reduce windbreak risk, ensure safety and enhance aesthetic value (Badrulhisham & Othman, 2016; Muscas et al., 2024). Improper pruning can have significant negative consequences, decreasing leaf area and shading quality, and reducing evapotranspiration (Speak & Salbitano, 2023; Comin et al., 2025; Franceschi et al., 2022), ultimately compromising tree health and increasing the likelihood of branch dieback. The studies indicate that pruning should not exceed 30% of the original wood volume and should be conducted as a low intensity pruning to facilitate the wellbeing of the tree while minimizing tree dieback (Ramirez et al., 2018; Fini et al., 2015). Nevertheless, any pruning intervention inevitably reduces canopy coverage, thereby diminishing the human thermal comfort experienced beneath the tree. Proper management of urban trees should therefore seek to

balance maintenance needs with canopy preservation, aiming to develop healthy and long-lived trees whose canopy maximizes cooling benefits and community wellbeing while minimizing windbreak risk.

While pruning is widely recognized for its benefits in enhancing safety and improving aesthetic value, how pruning practices may affect human thermal comfort beneath tree canopy remains insufficiently addressed in existing literature. While the simulation approaches have incorporated thermal comfort evaluation under tree shading, they predominantly rely on simplified models that treat the thermal comfort reduction beneath the canopy as a uniform estimate (Bruse & Fleer, 1998; Teshnehdel et al., 2020; Lin et al., 2021; Wei et al., 2025; Song et al., 2025). In recent years, Terrestrial LiDAR Scanning (TLS) offers a promising solution, whereby tree structure can be reconstructed from LiDAR point clouds in the form of Quantitative Structure Models (QSM), facilitating the extraction of tree characteristics, including canopy structure (Béland et al., 2014; Côté et al., 2012; Wei et al., 2020). TLS and QSM have further been applied to pruning volume estimation (Yazdi et al., 2024a; Yazdi et al., 2024b; Yazdi et al., 2023; Shu et al., 2024). However, to the authors' knowledge, the integration of these approaches with simulation to systematically evaluate the thermal comfort impacts of canopy changes after pruning remains unexplored.

To evaluate the thermal comfort impacts beneath a tree canopy after pruning, this study proposes an integrated workflow that combines TLS, QSM, and solar radiation simulation, with the simulated radiation subsequently converted into Physiological Equivalent Temperature (PET). A rain tree (*Samanea saman*) was scanned using TLS, and the resulting point cloud was processed to generate a QSM. Based on this model, a conservative pruning limit of 20%, below the 30% recommended by Ramirez et al., was adopted to avoid excessive pruning in the simulation. Multiple pruning models were then generated to simulate the solar radiation beneath the canopy under each condition. In this study, PET was adopted as a proxy for thermal comfort, which was quantified from solar radiation simulation based on field relation (Wu et al., 2026), enabling Δ PET to be further computed to quantify the reduction of thermal comfort after pruning. This automated pruning workflow allows a more accurate evaluation of how varying pruning intensities influence outdoor thermal comfort. The main contributions of this study are as follows:

1. To develop an automated 3D pruning workflow that integrates TLS and QSM by considering safety criterion.
2. To identify Δ PET of pruning induced canopy changes by simulating solar radiation beneath canopy.

2. Methodology

This study presents an integrated workflow for modeling tree structures under varying pruning scenarios and quantifying their thermal comfort impact. The workflow begins by acquiring terrestrial laser scanning (TLS) point clouds and separating them into leaf and wood points. The wood points are then reconstructed into a quantitative structure model (QSM), after which automated pruning is simulated according to three principles: conical crown angle, branch inclination angle, and uniform branch

distribution. Finally, solar radiation is simulated to calculate the resulting reduction in physiological equivalent temperature (PET).

2.1 Study tree and site

The study tree is a rain tree (*Samanea saman*), with point cloud data acquired from a rain tree located on the southern side of the Geomatics Building at the Cheng Kung Campus of National Cheng Kung University (NCKU), situated in the East District of Tainan City, Taiwan (Fig. 1).

According to climate records over the past decade, Tainan has a mean annual temperature of approximately 24.7°C, with the highest temperatures occurring in July (average 30.4°C) and the lowest in January (average 17.6°C) (Chen et al., 2018). The high levels of solar radiation, combined with relatively consistent summer weather, make this site especially suited for studying solar radiation and outdoor thermal comfort conditions.

Figure 1 Street view of rain tree.

2.2 LiDAR point cloud acquisition and classification

Terrestrial laser scanning was employed to acquire high density three dimensional point cloud data of the individual study tree, ensuring sufficient geometric detail for subsequent QSM reconstruction. In this study, an Emesent Hovermap ST-X mobile LiDAR system (Emesent Pty Ltd, Australia) was used (Fig. 2). The instrument integrates a 32-laser sensor with a nominal range of 0.5–300 m, a data-acquisition rate of up to 640,000 points s⁻¹ (single-return mode) or 1,920,000 points s⁻¹ (multi-return mode), a field of view of 360° × 290°, and a stated relative accuracy of ± 15 mm in outdoor environments and ± 10 mm in typical indoor settings. Point cloud density is highest along the sensor's primary scanning axis and decreases off-axis owing to the rotating scanning head. The scanner was carried around the study tree to capture the trunk, main branches, and crown from different viewpoints and reduce occlusion.

Figure 2 The view of the Emesent Hovermap ST-X mobile LiDAR scanner used for TLS data acquisition.

After acquisition, the point clouds were classified into wood and leaf points using a point-based classification approach. A Random Forest (RF) algorithm was used for this task, as it has been proven effective for wood-leaf classification (Sanam & Lakshmanan, 2023; Letard et al., 2024; Wang et al., 2025). To improve the classification, several geometric features were first computed from the point cloud over neighborhoods of different sizes, providing richer information that better represented the characteristics of each point. These features were then used as inputs to the RF algorithm for prediction. For training, small point cloud samples were manually selected from the tree structure, and the remaining points were used as the test set (Fig. 3).

Figure 3 Point cloud classification of the rain tree: (1) wood points (brown), representing woody structures including the trunk and branches; and (2) leaf points (green), representing the foliage.

2.3 QSM reconstruction

QSM reconstruction is to build up the rain tree trunk and branch detail. To efficiently reconstruct the tree structure, the branch point clouds were first processed using the open source TreeQSM algorithm from GitHub, which generated a three dimensional tree model (Raumonen et al., 2013; Raumonen, 2022).

After segmentation, each non-bifurcated segment was reconstructed as a sequence of cylinders fitted by total least squares, with cylinder radii constrained to a minimum of 0.0025 m. Parent-based corrections were applied so that a child cylinder's radius was almost always smaller than, or only slightly larger than, that of its parent, ensuring realistic branch geometry. The QSM was reconstructed up to branch order 0 to 9 and comprised 2,737 cylinders: 29 form the main trunk (branch order 0) and the remaining 2,708 represent the branch structure. The total reconstructed wood volume, computed as the sum of individual cylinder volumes, is 74.9018 m³, with a cumulative cylinder length of 1,829.32 m (Fig. 4).

Figure 4 TreeQSM reconstruction of the study rain tree, visualized in Rhinoceros.

2.4 Automated Pruning

To simulate tree pruning scenarios, an automated pruning procedure was developed to operate directly on QSM. Before executing, there are three principles for the rain tree to constrain the pruning process, each principle grounded in the article (Mattheck et al., 2015) and illustrated in Fig. 5, while considering the pruning level is under 20%:

(a) Conical Crown Angle: The target canopy structure was defined as a conical shape with a half-angle of 45°, with the main trunk aligned along the vertical axis. For each branch segment, it must ensure that all retained branches fall within this conical area and collectively form a radial canopy structure.

(b) Uniform Branch Distribution: To ensure uniform spatial distribution and prevent tree fall, the canopy was partitioned into four quadrants: NE, NW, SE, and SW in the horizontal plane. The cumulative branch volume within each quadrant was required to be as equal as possible across all four sectors, minimizing the variance among quadrant volumes and avoiding directional imbalance, promoting an even distribution of branch volume.

(c) Branch Inclination Angle: The angle between each lateral branch and the main trunk was required to be no greater than 45°. Branches exceeding this angle were removed because their excessive inclination increases the likelihood of branch falling, posing potential risks to pedestrians and surroundings.

Figure 5 Principles for rain tree pruning: (a) Conical Crown Angle; (b) Uniform Branch Distribution; (c) Branch Inclination Angle

Three principles were applied sequentially to keep each pruned crown biologically and structurally sound. The conical crown angle first produced two configurations, A and B. Applying the uniform branch distribution and the branch inclination angle to each then yielded four further configurations (A-1, A-2, B-1, and B-2) and six pruning scenarios in total for the solar radiation simulation.

For the conical crown angle, an imaginary cone is placed over the tree, opening upward and centered on the trunk, with its tip set at the height where the trunk first gives rise to a branch. This cone defines the target crown shape. Each branch is then evaluated against the cone: branches that extend beyond the cone are marked for removal, while those that remain within it are retained. Two safeguards refine these decisions. First, a branch is removed only if all its tips fall outside the cone. If any tip remains within the cone, the entire branch is retained because it still contributes to the canopy. Second, the trunk and the branches below 4 meters are always protected to maintain the tree's structural support. Whenever a branch is removed, all smaller branches growing from it are removed as well, leaving a clean and connected structure. The cone can be adjusted to different angles, and several conical shapes are tested to identify the crown form that best represents a healthy and balanced structure. Of the four angles, 50° and 55° produced the most suitable results while avoiding over thinning, and thus these two were retained as configurations A and B and the pruning results (Fig. 6). Four candidate cone angles are listed in Table 1.

Table 1 Pruning results for four candidate cone angles (45°, 50°, 55°, and 60°). "Cuts" is the number of independent branch removals; "Branches" is the total number of branch elements removed; "Volume (m³)" and "Volume (%)" report the absolute and relative wood volume removed.						
Scenario	θ(°)	Cuts	Branches	Volume (m³)	Volume (%)	Configuration
a	60	25	54	1.5214	2.0	
b	55	36	101	5.1345	6.9	A
c	50	40	153	8.6324	11.5	B
d	45	50	212	13.8325	18.5	

Figure 6 Pruning results in MATLAB under varying cone half-angles: (a) $\theta = 45^\circ$, (b) $\theta = 50^\circ$, (c) $\theta = 55^\circ$, and (d) $\theta = 60^\circ$. Blue cylinders are retained, and red cylinders are removed.

Table. 1 Pruning results for four candidate cone angles (45°, 50°, 55°, and 60°). "Cuts" is the number of independent branch removals; "Branches" is the total number of branch elements removed; "Volume (m³)" and "Volume (%)" report the absolute and relative wood volume removed.

After the branches lying outside the conical area have been removed, those that remain may still be unevenly distributed, with one side of the crown containing substantially more wood volume than another. The crown is then balanced by gradually thinning it until the volume is distributed more evenly around the tree. To do this, the crown is divided into four equal directional sectors around the trunk: NE, NW, SE, and SW, and every remaining branch is assigned to the sector it occupies. The share of wood volume within each sector is compared with the ideal of one quarter (25%) per sector, and the further these shares deviate from that equal distribution, the more uneven the crown is considered to be. Branches are then removed one at a time, each time selecting the cylinder whose removal contributes most to balancing the four sectors. The effect of removing that cylinder together with all descendant

branches is evaluated in advance, and the branch that brings the sectors closest to balance is selected for removal. The order in which cylinders are considered also reflects their risk of falling based on the inclination angle, so that the most hazardous branches are addressed first: priority is given, in turn to those inclined more than 45° from the vertical and standing at heights of at least 12 meters, then to similarly inclined at heights of at least 8 meters, and only when these are insufficient are any of the remaining considered. To avoid overthinning in simulation, the procedure always retains at least 80% of the tree's original wood volume, a threshold chosen to safeguard tree health based on previous studies (Ramirez et al., 2018; Fini et al., 2015). A branch is cut only if enough wood would remain above this limit afterwards, so the crown is reduced only modestly and its biomass is largely preserved. Removal continues until the four sectors are balanced to within a negligible tolerance, until any further cutting would drop the retained wood volume below the limit, or until no remaining branch can improve the balance, or until a maximum of 500 attempts has been reached, and the most balanced arrangement found along the way is kept. The final check then ensures that no branch is left dangling from a cut parent branch.

To compare different pruning outcomes, six pruning scenarios were simulated, built the information from the automated pruning in Table 2. The first part applies the conical crown angle alone, removing the branches that lie outside the cone, and yields two configurations, A and B, corresponding to cone half-angles of 55° and 50°, respectively. The second part takes each of these configurations and additionally applies the uniform branch distribution and branch inclination angle, removing interior branches to correct the remaining imbalance and producing four further configurations, A-1, A-2, B-1, and B-2. Among these, A-1 and B-1 retain 85% of the original woody volume, while A-2 and B-2 remain 80%.

Table 2
Results for the six pruning scenarios. A and B were generated using the conical crown angle with cone angles of 55° and 50°, respectively. A-1, A-2, B-1, and B-2 were further refined using the uniform branch distribution and branch inclination angle, with wood volume retention levels of 85% and 80%. NE, NW, SW, and SE (%) indicate after pruning quadrant volume sectors.

Configuration	θ (°)	Retained (%)	NE (%)	NW (%)	SW (%)	SE (%)
A	55	93.1	38.5	19.3	24.6	17.5
A-1	55	85	33.1	21.5	26.1	19.2
A-2	55	80	31.8	23.0	25.9	19.3
B	50	88.5	38.1	18.4	25.7	17.7
B-1	50	85	35.3	19.3	26.8	18.6
B-2	50	80	33.5	20.8	26.1	19.7

Table. 2 Results for the six pruning scenarios. A and B were generated using the conical crown angle with cone angles of 55° and 50°, respectively. A-1, A-2, B-1, and B-2 were further refined using the

uniform branch distribution and branch inclination angle, with wood volume retention levels of 85% and 80%. NE, NW, SW, and SE (%) indicate after pruning quadrant volume sectors.

After the automated pruning and before the solar radiation simulation, the foliage has to be reconstructed. The leaf point cloud was uniformly subsampled to a spatial resolution of 0.1 meter, and the resulting points were then processed in MATLAB and classified into nearest cylinders associated groups using QSM. Because the QSM represents the branch architecture as a hierarchical assembly of cylinders (each defined by a start point, axis direction, radius, and length), the midpoint of every cylinder axis was computed as a representative coordinate and allowed efficient nearest neighbor queries using KD tree method to group the leaf points. Each leaf point was then assigned to the cylinder whose midpoint was closest in three-dimensional space (Fig. 7).

Figure 7 Each leaf point is assigned to its nearest cylinder; colors are assigned randomly per group to visualize the spatial grouping.

Following the pruning procedure applied to the QSM, leaf points associated with cylinders retained in the pruning mask were preserved, whereas all others were removed. The filtered leaf point cloud was then imported into Rhinoceros for geometric reconstruction. Within each retained branch group, leaf points were converted into simplified volumetric elements represented as cubes with a uniform edge length of 0.1 m. These cubic units serve as standardized approximations of leaf volume, preserving the essential canopy structure while substantially improving computational efficiency in the subsequent radiation simulations. The resulting seven canopy configurations: an unpruned reference and six pruning scenarios are shown in Fig. 8.

Figure 8 Seven canopy configurations used for radiation simulation: (a) original (100% retention); (b) A (93.1% retention, $\theta = 55^\circ$); (c) A-1 (85%, $\theta = 55^\circ$); (d) A-2 (80%, $\theta = 55^\circ$); (e) B (88.5%, $\theta = 50^\circ$); (f) B-1 (85%, $\theta = 50^\circ$); (g) B-2 (80%, $\theta = 50^\circ$).

2.5 Solar radiation simulation

This study used Rhinoceros (Rhino) and its parametric design plugin, Grasshopper, for model development and solar radiation simulation. Grasshopper provides a visual programming environment for parametric modeling and supports a wide range of third-party plugins, including Ladybug, which was used for radiation analysis. Ladybug utilizes EnergyPlus Weather (EPW) data to perform climate analyses and can be directly integrated with Rhino models, providing an efficient platform for solar radiation simulation. Radiation analysis in Ladybug is based on a sky model generated from Typical Meteorological Year (TMY) data in EPW format. The sky is discretized using the Tregenza Sky subdivision (145 patches), with each patch containing direct and diffuse radiation components. Radiation received at each analysis point is calculated by projecting rays toward all sky patches and accumulating their contributions unless obstructed by surrounding geometry. It should be noted that Ladybug does not account for longwave radiation exchange, material heat storage, or surface reflectivity, and all modeled geometries are assumed to be opaque and non-thermally conductive.

The simulation environment is configured using an EPW weather file extracted from the TMYx dataset, compiled from observational records spanning 2011–2025 at Tainan Station (WMO 593580), Taiwan. The analysis period is defined as June 21, 12:00–13:00, corresponding to peak solar noon on the summer solstice, representing the most thermally critical hour of the year for solar exposure assessment. Radiation boundary conditions are established with a Global Horizontal Radiation (GHR) of 855 Wh/m², a Direct Normal Radiation (DNR) of 691 Wh/m², and a Diffuse Horizontal Radiation (DHR) of 188 Wh/m²; the resulting DNR/GHR ratio of approximately 0.81 indicates a predominance of direct beam radiation with moderate diffuse scattering, consistent with partly overcast sky conditions characteristic of the Tainan summer period. To comprehensively capture the thermal variation across all pruning scenarios, a circular analysis boundary of 50 meters in diameter is centered on the trunk, intentionally extending beyond the maximum canopy so that both shaded and unshaded areas are encompassed within the domain; consequently, the reported radiation values represent spatially averaged irradiance across the entire circular domain rather than exclusively shaded zones. The LB Real Time Incident Radiation component within the Ladybug Tools plugin, implemented in the Grasshopper environment, is employed to calculate cumulative incident radiation values (kWh/m²) at each grid point across the defined domain. The resulting radiation distribution is visualized through color mapped legend scaling and examined via the Perspective Viewer in Fig. 9, from which the spatially averaged incident radiation across the circular domain is extracted. This average value serves as the primary metric for evaluating solar thermal conditions and informing subsequent shading assessments.

Figure 9 Perspective view of the solar radiation simulation beneath the unpruned rain tree canopy. The color scale denotes cumulative incident radiation in kWh m⁻² (displayed in the legend as kWh/m²) accumulated over 12:00–13:00 on 21 June; the 50-m-diameter circular analysis domain is centered on the trunk.

3. Results

To express the simulated solar radiation in a thermally relevant comfort metric, the hourly accumulated radiation (kWh m⁻²) was first converted to instantaneous irradiance (W m⁻²). Because the analysis period spans a single one-hour interval, the cumulative radiation output is numerically equivalent to the mean irradiance over that period; accordingly, all values were multiplied by 1000 (1 kWh m⁻² = 1000 W m⁻² over one hour). The resulting irradiance was then converted to Physiologically Equivalent Temperature (PET) using a locally calibrated simplified PET–global radiation model (Wu et al., 2026), and the outcomes were compared across all pruning configurations to evaluate their relative impact in improving outdoor thermal comfort. The domain-averaged incident-radiation maps for all seven configurations are shown in Fig. 10.

Figure 10 Planview solar-radiation maps beneath the seven canopy configurations: (a) original (528.7 W m⁻²); (b) A (586.7 W m⁻²); (c) A-1 (636.9 W m⁻²); (d) A-2 (671.5 W m⁻²); (e) B (611.3 W m⁻²); (f) B-1 (636.9 W m⁻²); (g) B-2 (670.2 W m⁻²). Each map shows the 50-m-diameter circular analysis domain; the

colour scale denotes cumulative incident radiation in kWh m⁻² (displayed in the legend as kWh/m²) accumulated over 12:00–13:00 on 21 June.

3.1 Relationship between global radiation (GR) and PET

To translate simulated solar radiation into human thermal comfort impact, this study adopts a simplified PET–global radiation (GR) model calibrated on local meteorological observations collected on the summer solstice under hot humid subtropical conditions in western Taiwan (Wu et al., 2026):

$$PET = 0.0126GR + 1.2537T_a - 2.5537V - 1.6374 \quad (1)$$

where GR denotes global radiation (W m⁻²), T_a denotes air temperature (°C), and V denotes wind velocity (m s⁻¹). The model achieved a coefficient of determination of $R^2 = 0.95$ and has been validated at multiple sites in western Taiwan, confirming its reliability for assessing outdoor thermal comfort under the prevailing climatic conditions of the region.

If air temperature and wind speed remain spatially uniform between shaded and unshaded areas, and taking wind velocity $V \geq 1$ m s⁻¹, the change in thermal comfort attributable to tree-canopy shading can be expressed solely as a function of the reduction in incident global radiation:

$$\Delta PET = 0.0126 \times \Delta GR \quad (2)$$

Thermal comfort thresholds were defined following Lin and Matzarakis (2008), who established that a 4°C reduction in PET corresponds to an improvement of one thermal comfort level under the climatic conditions of Taiwan. Accordingly, canopy conditions where ΔPET falls below 4°C are considered to require microclimate improvement, while conditions where ΔPET does not reach at least 6°C indicate insufficient shading quality and warrant further canopy enhancement.

3.2 Effect of canopy configuration on global radiation and ΔPET

The solar radiation maps and corresponding domain averaged values in Table 3 reveal a consistent pattern: as canopy retention decreases, the global radiation beneath the tree increases, and thermal comfort deteriorates accordingly. Because the 50-m-diameter analysis domain extends beyond the maximum canopy spread of any configuration, the reported GR values represent spatially averaged irradiance across the entire circular domain rather than exclusively shaded zones, providing a conservative domain-scale comparison across configurations.

Table 3

Global radiation and Δ PET beneath the seven canopy configurations. Values are spatially averaged across the 50 meters diameter circular analysis domain centered on the trunk; Δ PET is referenced to the open sky condition ($GR = 855 \text{ W m}^{-2}$) via Eq. (2).

Configuration	θ (°)	Retention (%)	Global radiation (W m^{-2})	Δ PET (°C)
Original		100	528.7	-4.1
A	55	93.1	586.7	-3.4
A-1	55	85	636.9	-2.7
A-2	55	80	671.5	-2.3
B	50	88.5	611.3	-3.1
B-1	50	85	636.9	-2.7
B-2	50	80	670.2	-2.3

Table 3 Global radiation and Δ PET beneath the seven canopy configurations. Values are spatially averaged across the 50 meters diameter circular analysis domain centered on the trunk; Δ PET is referenced to the open sky condition ($GR = 855 \text{ W m}^{-2}$) via Eq. (2).

Under open sky conditions, the reference global radiation is 855 W m^{-2} ; beneath the unpruned rain tree canopy the domain averaged value is reduced to 528.7 W m^{-2} , corresponding to a Δ PET of -4.1°C relative to the unshaded baseline and demonstrating that the intact canopy provides a meaningful reduction in perceived thermal stress for pedestrians beneath the canopy. In the first stage, the conical crown angle alone was applied, removing branches outside the cone at half angles of 55° (Configuration A) and 50° (Configuration B); canopy retention declined to 93.1% and 88.5%, respectively. Domain averaged radiation increased to 586.7 W m^{-2} and 611.3 W m^{-2} , corresponding to Δ PET values of -3.4°C and -3.1°C . Although cooling benefit was reduced relative to the unpruned reference, both configurations continue to enhance substantial thermal comfort, suggesting that pruning at moderate intensity can be tolerated without critically compromising pedestrian thermal comfort. When further pruning was applied to configurations A and B using the uniform branch distribution and branch inclination angle, retention was further reduced to 85% or 80%, and the effects became more pronounced. Configurations A-1 and B-1 (85% retention) both yielded approximately $636\text{--}637 \text{ W m}^{-2}$, with Δ PET values of -2.7°C , while the most intensively pruned scenarios, A-2 and B-2 (80% retention), yielded 671.5 and 670.2 W m^{-2} , each associated with a Δ PET of -2.3°C . These results show that removing too much canopy can reduce the thermal comfort benefit, so even when pruning is carried out safely, the possibility of reducing thermal comfort too much should also be considered. Pruning is therefore best guided by a prioritized assessment that addresses structural safety and tree health first and then weighs the canopy to be removed against its effect on thermal comfort.

4. Discussion

This study demonstrates that preserving fine-scale branch and canopy geometry through QSM reconstruction enables a more detailed characterization of shading quality. However, several limitations should be acknowledged. First, the analysis was conducted on a single mature *Samanea saman*; the pruning principles, simulation parameters and thresholds adopted here reflect general umbrella tree assessment in the articles (Mattheck et al., 2015) applied to the broad crowned *Samanea saman*; species specific calibration will be required for trees with markedly different tree forms. Second, the solar radiation simulation covers a single critical hour (12:00–13:00 on the summer solstice), which represents a worst case thermal condition but does not characterize diurnal or seasonal variation; coupling the pruning workflow with a full radiation simulation would extend the assessment to seasonal thermal comfort dynamics. Third, the solar radiation simulation in Ladybug does not model longwave radiation exchange, material heat storage, or surface reflectivity, and the PET–GR model assumes spatially uniform air temperature and wind speed across shaded and unshaded surfaces. More physically complete microclimate solvers (e.g., ENVI-met) could be used in future work to validate the Δ PET estimates obtained here. Fourth, the foliage reconstruction approximates leaf volume using 0.1 m cubic units, which captures overall canopy opacity but not per leaf geometry or seasonal foliage dynamics. Despite these limitations, the workflow demonstrates the potential of integrating TLS and QSM reconstruction with solar radiation simulation to support urban tree pruning and thermal comfort assessment.

5. Conclusion

Pruning is a routine part of urban tree management, yet its effects on human thermal comfort have not been fully understood since the existing simulations cannot capture the tree spatial changes caused by pruning. To address this gap, this study developed an automated pruning workflow that combined TLS, QSM, and solar radiation simulation to quantify the thermal comfort impact of pruning. By coupling a detailed structural model, the approach captured the spatial variation of solar radiation beneath the canopy, supporting an objective evaluation of thermal comfort assessment. Applied to the study tree, the workflow showed that the original rain tree reduced PET by 4.1°C relative to open sky; this cooling fell to 3.1–3.4°C under form maintaining pruning (50° or 55°, 88.5–93.1% retention) and to 2.7°C and 2.3°C after rebalancing the crown to 85% and 80% retention, the latter nearly 1.8°C less than the original. Pruning intensity therefore exerted a measurable influence on outdoor thermal comfort, and pruning decisions should treat structural safety and tree health as the foremost priority before the branches to be removed and their thermal comfort are quantitatively assessed. Overall, the workflow provided a basis for integrating thermal comfort into urban tree management. By bridging tree pruning principle with cooling benefits beforehand, it supports more informed and balanced pruning decisions.

Declarations

Funding Declaration

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

Author Contribution

SZU-YI LEE contributed to the design and implementation of the research, to the analysis of the results and to the writing of the manuscript. SZU-YI LEE wrote the manuscript with support from CHI-KUEI WANG, CHUNG-CHENG LEE, and TZU-PING LIN. CHI-KUEI WANG and CHUNG-CHENG helped supervise the simulation. All authors reviewed the manuscript.

Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

References

1. Badrulhisham, N., & Othman, N. (2016). Knowledge in tree pruning for sustainable practices in urban setting: Improving our quality of life. *Procedia - Social and Behavioral Sciences*, 234, 210–217. <https://doi.org/10.1016/j.sbspro.2016.10.236>
2. Béland, M., Widlowski, J.-L., & Fournier, R. A. (2014). A model for deriving voxel-level tree leaf area density estimates from ground-based LiDAR. *Environmental Modelling & Software*, 51, 184–189. <https://doi.org/10.1016/j.envsoft.2013.09.034>
3. Bruse, M., & Fleer, H. (1998). Simulating surface–plant–air interactions inside urban environments with a three dimensional numerical model. *Environmental Modelling & Software*, 13(3–4), 373–384. [https://doi.org/10.1016/S1364-8152\(98\)00042-5](https://doi.org/10.1016/S1364-8152(98)00042-5)
4. Chen, Y.-C., Yao, C.-K., Honjo, T., & Lin, T.-P. (2018). The application of a high-density street-level air temperature observation network (HiSAN): Dynamic variation characteristics of urban heat island in Tainan, Taiwan. *Science of the Total Environment*, 626, 555–566. <https://doi.org/10.1016/j.scitotenv.2018.01.059>
5. Comin, S., Fini, A., Napoli, M., Frangi, P., Vigevani, I., Corsini, D., & Ferrini, F. (2025). Effects of severe pruning on the microclimate amelioration capacity and on the physiology of two urban tree species. *Urban Forestry & Urban Greening*, 103, 128583. <https://doi.org/10.1016/j.ufug.2024.128583>
6. Côté, J.-F., Fournier, R. A., Frazer, G. W., & Niemann, K. O. (2012). A fine-scale architectural model of trees to enhance LiDAR-derived measurements of forest canopy structure. *Agricultural and Forest Meteorology*, 166–167, 72–85. <https://doi.org/10.1016/j.agrformet.2012.06.007>
7. de Abreu-Harbich, L. V., Labaki, L. C., & Matzarakis, A. (2015). Effect of tree planting design and tree species on human thermal comfort in the tropics. *Landscape and Urban Planning*, 138, 99–109. <https://doi.org/10.1016/j.landurbplan.2015.02.008>

8. Fini, A., Frangi, P., Faoro, M., Piatti, R., Amoroso, G., & Ferrini, F. (2015). Effects of different pruning methods on an urban tree species: A four-year experiment scaling down from the whole tree to the chloroplasts. *Urban Forestry & Urban Greening*, 14(3), 664–674. <https://doi.org/10.1016/j.ufug.2015.06.011>
9. Franceschi, E., Moser-Reischl, A., Rahman, M. A., Pauleit, S., Pretzsch, H., & Rötzer, T. (2022). Crown shapes of urban trees—Their dependences on tree species, tree age and local environment, and effects on ecosystem services. *Forests*, 13(5), 748. <https://doi.org/10.3390/f13050748>
10. Jareemit, D., & Srivanit, M. (2022). A comparative study of cooling performance and thermal comfort under street market shades and tree canopies in tropical savanna climate. *Sustainability*, 14(8), 4653. <https://doi.org/10.3390/su14084653>
11. Konarska, J., Lindberg, F., Larsson, A., Thorsson, S., & Holmer, B. (2014). Transmissivity of solar radiation through crowns of single urban trees—Application for outdoor thermal comfort modelling. *Theoretical and Applied Climatology*, 117(1–2), 1–14. <https://doi.org/10.1007/s00704-013-1000-3>
12. Letard, M., Lague, D., Le Guennec, A., Lefèvre, S., Feldmann, B., Leroy, P., Girardeau-Montaut, D., & Corpetti, T. (2024). 3DMASC: Accessible, explainable 3D point clouds classification. Application to bi-spectral topo-bathymetric lidar data. *ISPRS Journal of Photogrammetry and Remote Sensing*, 207, 175–197. <https://doi.org/10.1016/j.isprsjprs.2023.11.022>
13. Lin, B.-S., Cho, Y.-H., & Hsieh, C.-I. (2021). Study of the thermal environment of sidewalks within varied urban road structures. *Urban Forestry & Urban Greening*, 62, 127137. <https://doi.org/10.1016/j.ufug.2021.127137>
14. Lin, T.-P., & Matzarakis, A. (2008). Tourism climate and thermal comfort in Sun Moon Lake, Taiwan. *International Journal of Biometeorology*, 52(4), 281–290. <https://doi.org/10.1007/s00484-007-0122-7>
15. Mattheck, C., Bethge, K., & Weber, K. (2015). The body language of trees: Encyclopedia of visual tree assessment. Karlsruhe Institute of Technology.
16. Meili, N., Manoli, G., Burlando, P., Carmeliet, J., Chow, W. T. L., Coutts, A. M., Roth, M., Velasco, E., Vivoni, E. R., & Fatichi, S. (2021). Tree effects on urban microclimate: Diurnal, seasonal, and climatic temperature differences explained by separating radiation, evapotranspiration, and roughness effects. *Urban Forestry & Urban Greening*, 58, 126970. <https://doi.org/10.1016/j.ufug.2020.126970>
17. Muscas, D., Orlandi, F., Petrucci, R., Proietti, C., Ruga, L., & Fornaciari, M. (2024). Effects of urban tree pruning on ecosystem services performance. *Trees, Forests and People*, 15, 100503. <https://doi.org/10.1016/j.tfp.2024.100503>
18. Oke, T. R., Crowther, J. M., McNaughton, K. G., Monteith, J. L., & Gardiner, B. (1989). The micrometeorology of the urban forest [and discussion]. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 324(1223), 335–349. <https://doi.org/10.1098/rstb.1989.0051>
19. Ramirez, J. A., Handa, I. T., Posada, J. M., Delagrangé, S., & Messier, C. (2018). Carbohydrate dynamics in roots, stems, and branches after maintenance pruning in two common urban tree

- species of North America. *Urban Forestry & Urban Greening*, 30, 24–31.
<https://doi.org/10.1016/j.ufug.2018.01.013>
20. Raumonen, P. (2022). TreeQSM: Quantitative structure models of single trees from laser scanner data [Computer software, Manual]. GitHub.
<https://github.com/InverseTampere/TreeQSM/tree/master/Manual>
21. Raumonen, P., Kaasalainen, M., Åkerblom, M., Kaasalainen, S., Kaartinen, H., Vastaranta, M., Holopainen, M., Disney, M., & Lewis, P. (2013). Fast automatic precision tree models from terrestrial laser scanner data. *Remote Sensing*, 5(2), 491–520. <https://doi.org/10.3390/rs5020491>
22. Sanam, H., & Lakshmanan, G. (2023). Leaf Wood Separation of TLS Point Cloud of Mangroves. IGARSS 2023–2023 IEEE International Geoscience and Remote Sensing Symposium, 3145–3148. <https://doi.org/10.1109/IGARSS52108.2023.10282683>
23. Shahidan, M. F., Shariff, M. K. M., Jones, P., Salleh, E., & Abdullah, A. M. (2010). A comparison of *Mesua ferrea* L. and *Hura crepitans* L. for shade creation and radiation modification in improving thermal comfort. *Landscape and Urban Planning*, 97(3), 168–181.
<https://doi.org/10.1016/j.landurbplan.2010.05.008>
24. Shu, Q., Yazdi, H., Rötzer, T., & Ludwig, F. (2024). Predicting resprouting of *Platanus × hispanica* following branch pruning by means of machine learning. *Frontiers in Plant Science*, 15, 1297390. <https://doi.org/10.3389/fpls.2024.1297390>
25. Song, L., Tang, Z., Zhang, X., Wang, Z., & Hong, B. (2025). Assessing effects of seasonal variations in 3D canopy structure characteristics on thermal comfort in urban parks. *Urban Forestry & Urban Greening*, 112, 128901. <https://doi.org/10.1016/j.ufug.2025.128901>
26. Speak, A. F., & Salbitano, F. (2023). The impact of pruning and mortality on urban tree canopy volume. *Urban Forestry & Urban Greening*, 79, 127810. <https://doi.org/10.1016/j.ufug.2022.127810>
27. Teshnehdel, S., Akbari, H., Di Giuseppe, E., & Brown, R. D. (2020). Effect of tree cover and tree species on microclimate and pedestrian comfort in a residential district in Iran. *Building and Environment*, 178, 106899. <https://doi.org/10.1016/j.buildenv.2020.106899>
28. Wang, W., Wu, Y., Jia, S., Xie, L., Guo, R., & Tang, S. (2025). Leaf–Wood Separation in Tree Point Clouds via Unlearning-Driven Supervoxel Random Forest. *IEEE Transactions on Geoscience and Remote Sensing*, 63, 1–19. <https://doi.org/10.1109/TGRS.2025.3601652>
29. Wei, S., Yin, T., Dissegna, M. A., Whittle, A. J., Ow, G. L. F., Yusof, M. L. M., Lauret, N., & Gastellu-Etchegorry, J.-P. (2020). An assessment study of three indirect methods for estimating leaf area density and leaf area index of individual trees. *Agricultural and Forest Meteorology*, 292–293, 108101. <https://doi.org/10.1016/j.agrformet.2020.108101>
30. Wei, Y.-Y., Cheng, C.-Y., & Lin, T.-P. (2025). The influence of trees shade level on human thermal comfort and the development of applied assessment tools. *Landscape and Urban Planning*, 263, 105436. <https://doi.org/10.1016/j.landurbplan.2025.105436>
31. Wu, Y.-C., Matzarakis, A., & Lin, T.-P. (2026). Simplified physiological equivalent temperature (PET) estimation formula for the climate of Taiwan. *Urban Climate*, 66, 102841.

<https://doi.org/10.1016/j.uclim.2026.102841>

32. Yazdi, H., Shu, Q., & Ludwig, F. (2023). A target-driven tree planting and maintenance approach for next generation urban green infrastructure (UGI). *Proceedings of the International Conference on Education and Research in Computer Aided Architectural Design in Europe (eCAADe)*, 178–185. <https://doi.org/10.14627/537740019>
33. Yazdi, H., Shu, Q., Chen, X., Rötzer, T., & Ludwig, F. (2024a). GroTree—A novel toolbox for simulating and managing urban tree canopy growth. *Proceedings of the International Conference on Education and Research in Computer Aided Architectural Design in Europe (eCAADe)*. <https://doi.org/10.14627/537752076>
34. Yazdi, H., Moser-Reischl, A., Rötzer, T., Petzold, F., & Ludwig, F. (2024b). Machine learning-based prediction of tree crown development in competitive urban environments. *Urban Forestry & Urban Greening*, 101, 128527. <https://doi.org/10.1016/j.ufug.2024.128527>

Figures



Figure 1

Street view of rain tree.

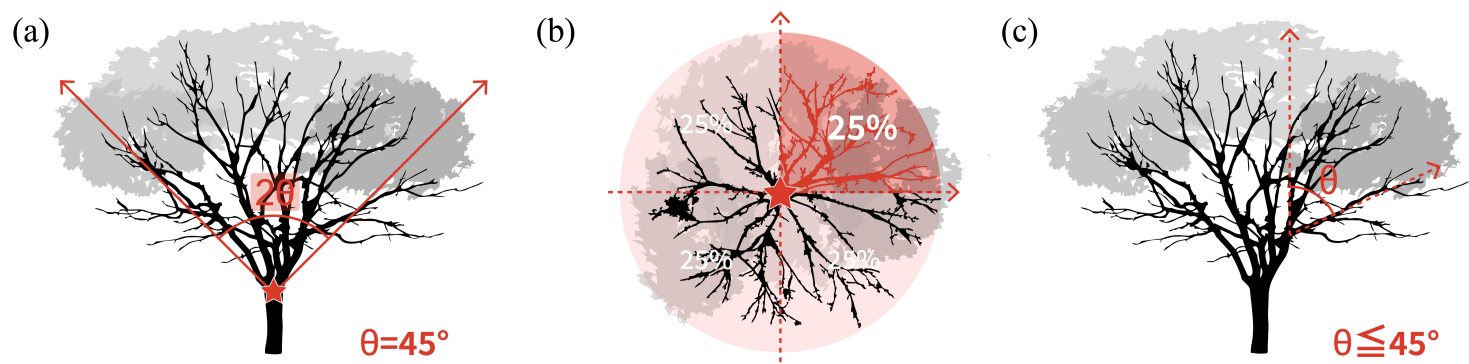


Figure 5

Principles for rain tree pruning: (a) Conical Crown Angle; (b) Uniform Branch Distribution; (c) Branch Inclination Angle

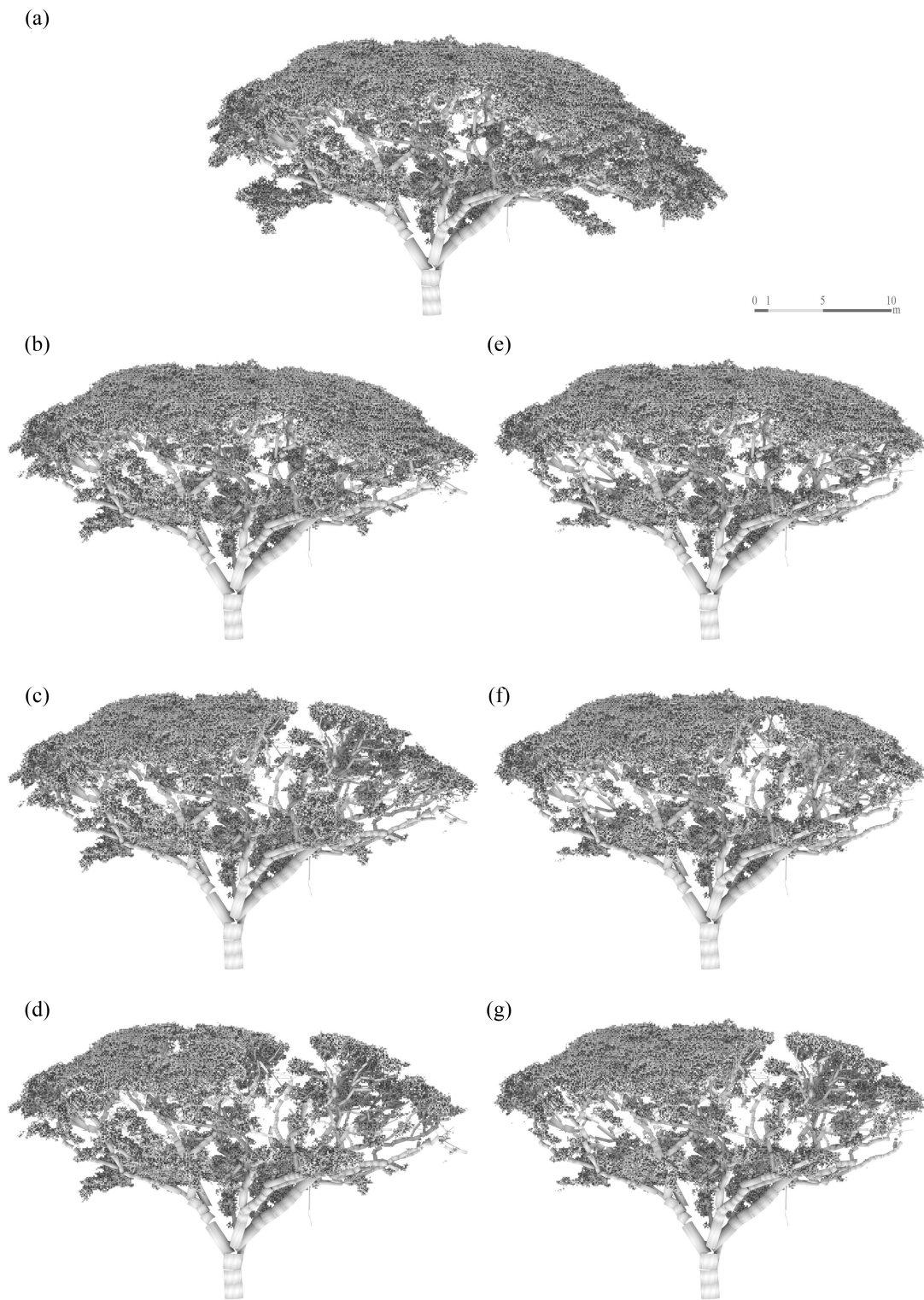


Figure 8

Seven canopy configurations used for radiation simulation: (a) original (100% retention); (b) A (93.1% retention, $\theta = 55^\circ$); (c) A-1 (85%, $\theta = 55^\circ$); (d) A-2 (80%, $\theta = 55^\circ$); (e) B (88.5%, $\theta = 50^\circ$); (f) B-1 (85%, $\theta = 50^\circ$); (g) B-2 (80%, $\theta = 50^\circ$).