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Article

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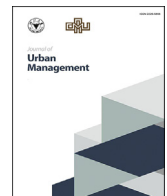
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Research Article

Tree crown geometry and its performances on human thermal comfort adjustment

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ABSTRACT

Trees play an important part in landscaping as well as thermal environment adjustment. This study selected a satellite city of Sichuan Province in China, Xindu, for field measurement about tree's crown characteristics on their cooling performances on five sunny summer days during August 2019. There were several parameters showing tree characteristics used, including tree canopied size (tree crown radius, TCR), tree geometry (the ratio of TCR to trunk height, R/TH), site openness (sky view factor, SVF), and leaf density (leaf area index, LAI). It was found that R/TH had the most significant thermal adjusting effects than others. The increase of R/TH by 1 can reduce physiological equivalent temperature by approximately 2.5 °C ($R^2 = 0.8932$) and 2.65 °C ($R^2 = 0.8424$) in the morning and afternoon respectively. SVF and LAI had less significant cooling effect due to the fact of dense-leaf season. This result provided good direction for future landscape design towards microclimate adjustment.

1. Introduction

Trees play an important part in landscaping as well as thermal environment adjustment, which is caused by their cooling effect, especially warm weathers (Zheng et al., 2016). This effect is important, since more than 50% of population is inhabiting in urban areas and suffering from poor urban microclimate globally (United Nations, 2014). Poor climate causes poor thermal environment, resulting in series of problems, including high energy consumption (Ihara et al., 2008), fire risk (Xu et al., 2021), and thermal discomforts (Yilmaz et al., 2007). Hence, it is urgent to explore cooling strategies to mitigate the poor climate. Vegetation was widely confirmed to be significantly cooling effective and frequently studied.

Among various vegetation types, trees were specifically frequently investigated for their relatively significant cooling effect (Guo et al., 2020; Zhang, Gou, & Lu, 2019; Zhang & Gou, 2020). Trees' cooling effects result from several aspects. Shade was confirmed to be a significant cooling factor through field measurement due to its temperature reduction performance (Lindberg & Grimmond, 2011). Similar results were also found through simulation (Zhao et al., 2018) and modelling (Jarolimek & Vierling, 2019). In standards, trees'

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cooling effects were indicated by its reduction effect on several thermal indicators, including MRT (mean radiant temperature (Herrmann & Matzarakis, 2012)), UTCI (Universal Thermal Climate Index (Cheung & Jim, 2018a)), and PET (physiological equivalent temperature (He et al., 2015)). Tree cooling effects were found resulting from canopying (Kong et al., 2016) and biological effects (Konarska et al., 2016). Trees' physical characteristics (i.e. crown colours) were confirmed cooling relevant (Rahman et al., 2020). Some advanced factors were developed to evaluate tree canopying or covering conditions in professional studies, such as SVF (sky view factor) (Zhang, Gou, Lu, & et al, 2019), which is significantly correlated to environmental temperature. For more detailed studies, tree species were engaged, which confirms that Ficus had better cooling effect than Mangifera, Bauhinia, and Michelia (Zheng et al., 2018). These studies have confirmed trees' significant cooling effect in different degrees.

The reviewed literatures have found cooling effect of tree to some extent, which is available to mitigate thermal stress. However, their limitations cannot be neglected. They just generally confirmed tree's cooling facts, rather than exploring tree's cooling characteristics in details. These limitations could be compensated by this study. In fact, microclimatic effects of trees come from one component of them, which is crown. This component was infrequently studied specially in the reviewed studies. Crown means the tree's top part, which bear the leaves for evaporation and transpiration (Russell, 2020). Crown is a key factor to differ different species of trees. Therefore, its characteristics would have significant effect on cooling performance, which is the key to explore in this study.

2. Methodologies

2.1. Tree crown parameters

Crowns are the top parts of trees, which are the key, for they bear the leaves. Leaves are the main part of a tree. They support a tree's biological (i.e. transpiration) and canopying effects. Crown is the important part for leaves. Larger size crowns generate higher quantity leaves, which is more biological and shadier effective. Therefore, crown characteristics are closely linked with trees' cooling performances. Crown characteristics can be evaluated by many parameters, including geometries and leaf densities.

2.1.1. Tree canopying size and geometry form

Tree canopying size could be evaluated by crown dimension. Due to general crown forms (round), its dimension could be evaluated by radius. Tree crown radius (TCR, Fig. 1a) means the distance between tree centre and its crown margin. Higher TCR usually refer to larger size crowns, resulting in more leaves and larger canopied areas, which is more climatic effective. Hence, TCR is an importance parameter for a tree's thermal effect evaluation. Nevertheless, tree crowns are rarely round in standards. For data accuracy, this study measured the mean value of max and min TCR of each sample tree for analysis.

TCR is not the only dimensional factor indicating trees' geometry, since trunk height (TH) might affect their canopying degree (Karna et al., 2019), despite of same crown size (TCR). Trees with lower TH cause higher canopying degree if they have the same TCR (TH₁ was canopied more densely than TH₂ in Fig. 1). For simplified evaluating them, the ratio of TCR to TH (R/TH) was proposed, which has the similar significance with D/PH (D, the crown diameter; PH, the branching point height) (Zhang & Gou, 2020); θ in Fig. 1 is directly correlated with R/TH geometrically. Generally, TCR directly affects tree cover, which used to be proved in a variety of thermal relevant studies (Zhang, Gou, & Lu, 2019). TH has rare effect on tree cover, which might be thermal irrelevant. For confirming their difference, TCR and R/TH were respectively analysed for comparing their difference of thermal performances.

2.1.2. WinSCANOPY

Microclimate is also correlated with other environmental factors, such as space openness, apart from trees. Meanwhile, as the existence of gaps among leaves and the crown layers, a tree's geometric size cannot cover its total climatic performance. A tree crown with denser leaf create more solid shades (with fewer sunlight spots). These aspects are not involved by TCR and TH. To compensate the limitation of geometry, WinSCANOPY (2017) was utilised as a supportive tool. WinSCANOPY (2017) is a diagram analyser for digitally analysing canopies and sunlight. It measures SVF, LAI (leaf area index), and much more, which is conducted by hemispherical images

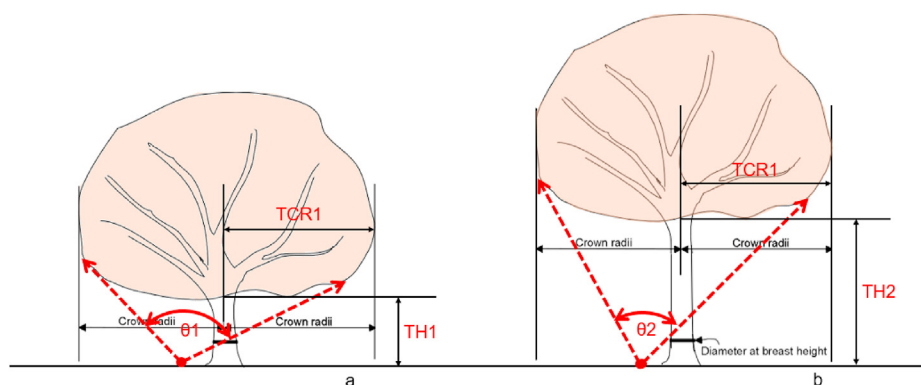


Fig. 1. Illustration of tree crown radius (Larsen, 2020) and canopying degree variation due to different trunk height (TH₁ < TH₂); TH₁ causes higher canopying intensity than TH₂, for $\theta_2 < \theta_1$.

that photographed via a fisheye imager. SVF means the hemispheric visible sky ratio on a fisheye image, ranging from 0 to 1 (Zeng et al., 2018) (Fig. 2a). LAI means the values of total leaf area in any unit ground area (Fig. 2b). It is the ratio of total leaf area to the ground area of certain location. LAI calculation is complex due to the diversity of parameter involvement, which includes leaf GFr (gap fraction), Plth (path length), leaf orientation distribution etc. Despite of LAI's diversity of parameters and complexity of calculation process, some studies have simplified that, which is the multiplication of leaf layer index (Zhang et al., 2020) and tree view factor (Yang, 2009). Values of both SVF and LAI can be directly acquired through WinSCANOPY (2017). There are several types of LAI values in WinSCANOPY (2017), generally Lin and Log, which also contain a number of subtypes. This study selected LAI Log 2000 for LAI calculation (Peper & McPherson, 1998).

SVF of the area under a tree is correlated with its crown size and leaf gap fraction (GFr). Larger size and/or lower GFr cause lower SVF. In contrast, LAI involved one more factor, which is leaf layer. This property mitigates the ignorance of leaf shade overlapping on SVF. Hence LAI is positively correlated with TCR, leaf density, and tree canopy height (TCH). Compared with TCR and SVF, LAI involves one extra factor relating to cooling, which is biological effect efficiency. It is correlated with leaf quantity. Further, SVF and LAI are not specific factors supporting tree studies. They just express physical characteristics of one certain location, which is different from TCR and R/TH. Therefore, for full evaluating tree crown characteristics, the three parameters are commonly functional.

2.1.3. Research questions

This investigation studies thermal effect of tree crown characteristics on sunny summer days. There were several parameters used, TCR, R/TH, SVF, and LAI. TCR, R/TH, and LAI were the specific parameter measuring trees. SVF measures characteristics of both location environment and the tree (porosity of the crown). They commonly affect a tree canopied site's microclimate. To find cooling effect of each tree, this study utilised objective field measurement to collect weather data. To approach the aim of finding the relationship between tree crown characteristic parameters and microclimatic indicators, they were associated by some data analysis methods. Meanwhile, as the TCR and R/TH were more specific for trees, their detailed microclimatic effects were compared interactively and with some existed factors (SVF and LAI) through significance comparison.

2.2. Site selection

Xindu (30.8 °N, 104.2 °E) is located to the north of Chengdu, Southwest of China, which is known as a satellite city of Chengdu (Fig. 3). Satellite city is a national symbol of China, which is a precinct at a level between the town and city. It usually belongs to a provincial city politically. Satellite cities create an advantage that avoids the metropolitan high pressure and high living cost but not far away from the central economical circle, which provides advantageous suitability and liveability. Hence it attracts a large number of residents to inhabit and work. Meanwhile, most researchers selected main capital cities for case studies, such as Hong Kong (Cheung & Jim, 2018b), Peking (Amani-Beni et al., 2018), and Shanghai (Li et al., 2011). Small-scale cities were rarely involved. Selecting satellite cities well compensated the limitations of earlier studies. Xindu is located at the north of Chengdu Plain (CDP). CDP is a geographical typical region of China with a long history and special local culture. Due to the rich nutritiousness of soil, it is a productive region with

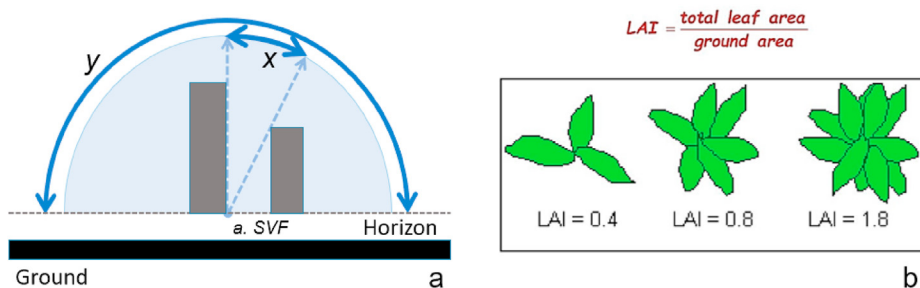


Fig. 2. SVF (a) and LAI (b): $SVF = x/y$ (Nasrollahi & Shokri, 2016); $LAI = (\sum_{i=1}^n S) / S_{\text{ground}}$, S refers to the area of one leaf (Trimble, 2021).

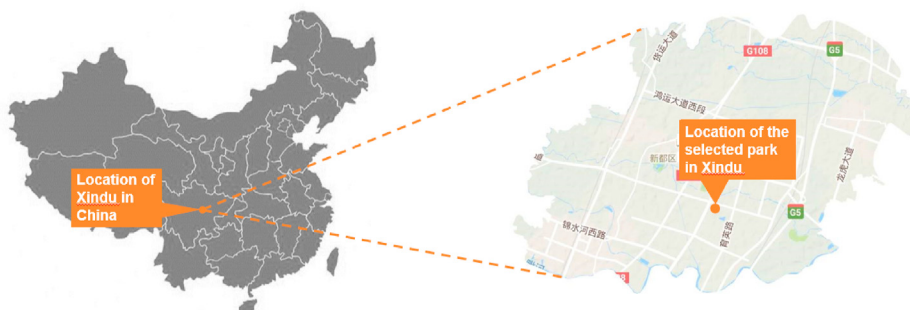


Fig. 3. Location of Xindu in China and the selected park in Xindu.

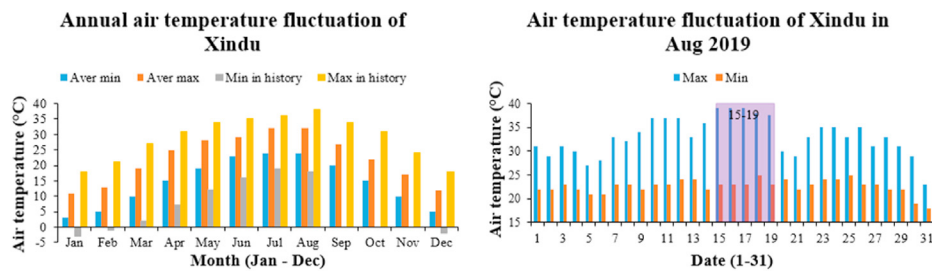


Fig. 4. Annual and Aug 2019's air temperature fluctuation records in Xindu (Weather).

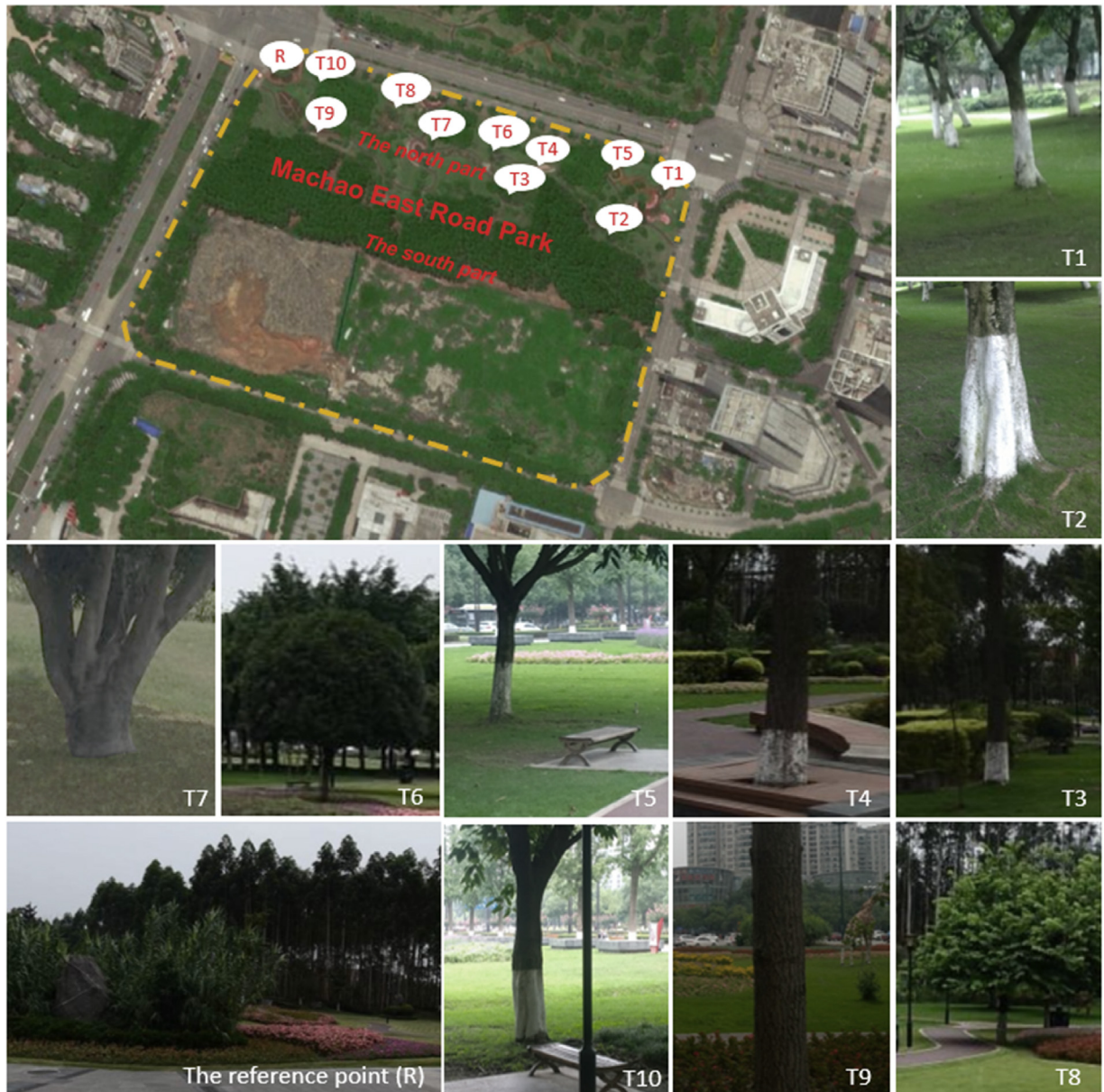


Fig. 5. Location of the ten trees and reference as well as their surrounding environments.

abundant harvesting of temperate climate farming crop every year, which rises people generation by generation (Zeng, 2016). Nevertheless, side effects of its climate are also important. This region is located within Sichuan Basin which has very extreme climates, especially in hot seasons. Sichuan Basin Climate (SBC) refers to a special climate with lower air temperature but higher humidity in summers compared with other same latitude cities, which is very sultry (Guo et al., 2008). Due to the effect of SBC, Xindu has very hot and humid summers from July to August every year, which causes very poor urban microclimate. Annual air temperature record of Xindu is listed in Fig. 4. It can be seen from that, August is the annual hottest month. Hence it was selected for the field measurement.

2.3. Field measurement

Urban Park of Machao East Road is located at the city centre of Xindu (Fig. 3), which is selected for the field measurement. It is well vegetated by trees of varying species and dense lawn, which creates optimistic natural environments and strikes many local people to attend. This park is composed by two fields, south and north. Relatively, the north field is open, which is composed by footpath, gardens, and sparse trees. It is available for pedestrians. In contrast, the south one is densely forested by tall trees, which is lack of open space for people attendance. As a result, the measurement was carried out at the north field (Fig. 5).

There were ten individual trees with different characteristics selected. A clear location of the ten trees and their surrounding environments were listed in Fig. 5. For ensuring the measurement accuracy, each sample tree is independently standing with little space sharing and shade overlapping with surrounding obstructs. Meanwhile, for avoiding errors resulting from sample location environment variation, SVF was used as another site variable for analysis. Due to the humanity design of this park, there are some chairs posited under some trees for pedestrians' staying and resting, which is where the measurement took place and fisheye image photographed (Fig. 5).

The measurement took place during August 2019, which is the annual hottest month of Xindu (Fig. 4). There were three sets of instruments (Testo) supporting the whole measurement. One for reference and the rest two for measuring. Every tree was measured for a full daytime. During the measurement, the referencing one was placed at a fixed location at the entrance square of the park for evaluating the daily weather change (temperature fluctuation), whereas the rest ones were at two sample trees for conducting the measurement. Therefore, within every full day, two trees were completely measured. The ten trees took five days (15th to 19th Aug. 2019, Fig. 4) for completing the measurement. Meanwhile, due to the sun position change of the day, there was some slight move of the instrument location, which ensures that they were within tree shades. This operation strengthened the accuracy of tree cooling investigation.

2.4. Thermal comfort indicator

Thermal comfort correlating with microclimate is a comprehensive feeling impacted by many climatic indices, including AT (air temperature), RH (relative humidity), radiation, AV (air velocity), clothing insulation and so on (De Dear & Brager, 1998). Air temperature, a widely used weather index, cannot complexly express people's thermal feeling. For standardising and simplifying the evaluation, some indicators that comprehensively cover these factors were proposed, such as PET (Höppe, 1999), UTCI (Urban & Kysely, 2014), and MRT (Tan et al., 2013). PET is a complex important thermal comfort indicator calculated by AT, RH, AV and MRT. AT (°C), RH (%), GT (°C) and AV (m/s) could be provided by the instruments, while MRT (°C) needs to be calculated by the following equation:

$$MRT = \left[\left(\langle GT \rangle + 273 \right)^4 + \frac{1.01 \times 10^8 \langle AV \rangle^{0.6}}{\epsilon D^{0.4}} \left(\langle GT \rangle - \langle AT \rangle \right) \right]^{0.25} - 273 \text{ (}^\circ\text{C)} \quad (1)$$

Where ϵ (emissivity) and D (diameter of the globe thermometer, m) were 0.95 and 0.15 respectively (Thorsson et al., 2007).

PET is defined to equal the air temperature in a particular indoor environment and heat balance that the human body exists with a work metabolism of 80W when conducting light activity and a clothing insulation of 0.9 clo (Höppe, 1999). It suits a wide range of practical outdoor environments, although PET is the equivalent temperature under a virtual indoor environment. PET is utilised to predict thermal element varying for regional climates. Despite of involving parameter diversity, its values could be calculated from RayMan, which simplifies the process of data acquisition.

Testo (Global-Test, 2018) was the selected instrument for microclimatic data collection. It is able to collect data relevant to MRT and PET calculation, including air temperature, air velocity, and globe temperature. Property of each sensor was listed in Table 1.

2.5. The data analysis

Artificial neural network (ANN) is a series of algorithms that mimic the operation of a human brain to recognise relationship between vast amounts of data (Lee et al., 2016). They can be used in forecasting, fraud detection and risk assessment, which is expressed by the importance values of several independent variables towards the dependent variable. There were several layers interconnected nodes

Table 1

Detailed components and their functions of the instrument.

Sensors	Measurement range	Accuracy	Resolution
Air temperature sensor	−100 to 400 °C	±0.3 °C	0.01 °C
Globe temperature sensor	−200 to 1370 °C	±(0.3+0.1% measurement value)	0.1 °C
Air velocity sensor	0 to 20 m/s	±0.3 m/s	0.01 m/s

contained. This study utilised PET as the dependent variable, while thermal affecting parameters (R/TH etc.) as independent variables (covariates). Factor is functional for clustering groups of data with certain commonness. In PET analysis, as weather condition fluctuated, time was used as the factor defining weathers. Additionally, neural networks just express the relative importance among the input variables, their total correlation significance and change trends are ignored (sometimes the variables were not linear correlated). As a compensation, binary linear regression was used, which finds the correlation between two continuous variables. Respectively, the relationship between model predicted values and the original measured ones (testing) and that between thermal indicators and any tree characteristic indicator were regressed. The regression was used for reliability test of neural network models and quantitative contribution presenting of the most significant microclimate influential factor.

3. Results

3.1. Original data description

This subsection describes data that process the independent variable (PET) calculation. Fig. 6 shows the original collected data of the reference instrument. It can be seen clearly that daily weather illustrated a warming trend during each measurement timespan (8:00 to 17:00), which is explained by the increase tendency of air temperature. There was slight difference among the five-day general weathers. The 18th and 19th were the hottest, while the 15th had more considerable change (air temperature was increased by more than 5 °C). In contrast, air velocity did not show remarkable trend as time going on the four days, which was irregular.

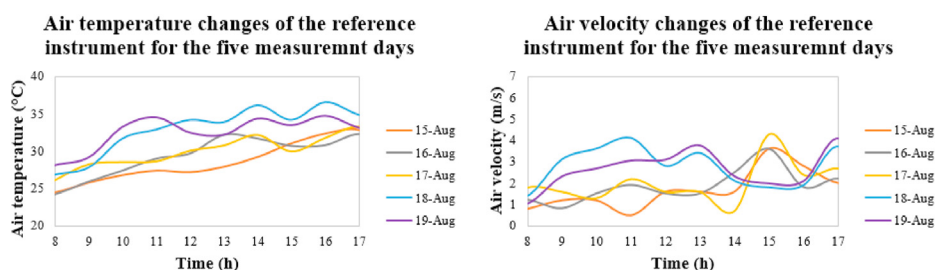


Fig. 6. Collected original data of the reference instrument.

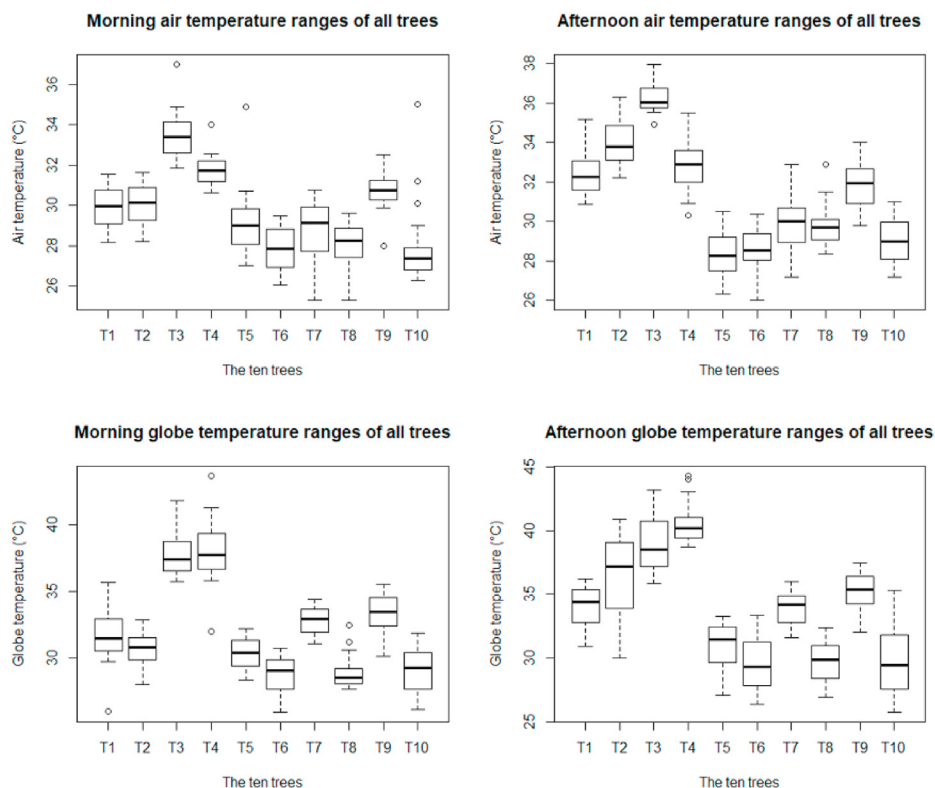


Fig. 7. Original temperature ranges of the ten trees.

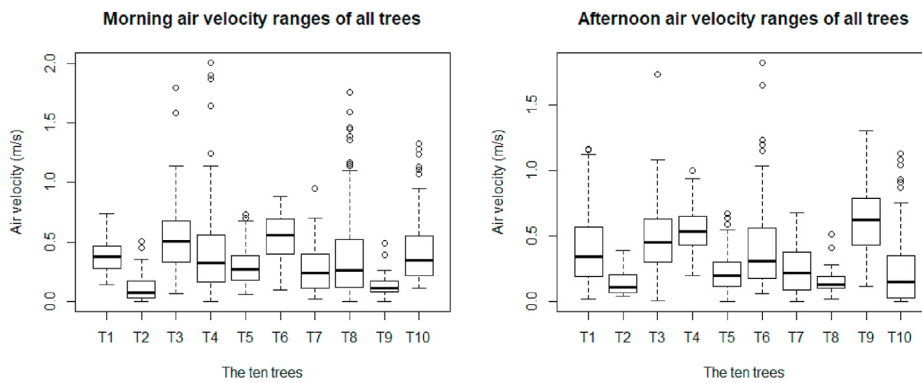


Fig. 8. Air velocity ranges of the ten trees.

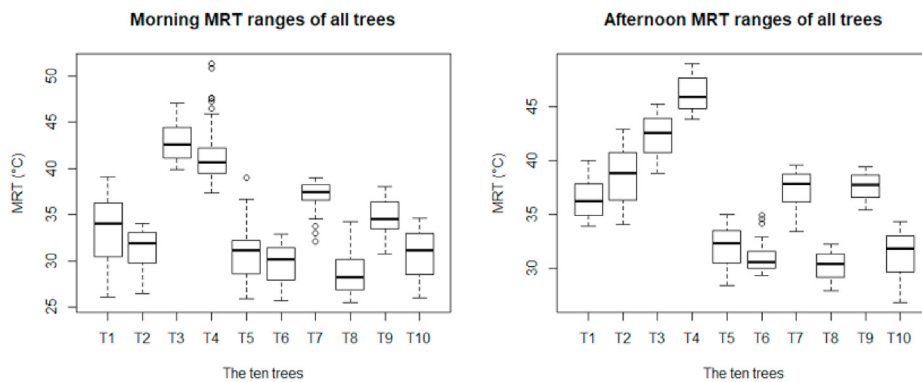


Fig. 9. MRT ranges of the ten trees.

Figs. 7 and 8 illustrate the original data ranges of all selected trees, it can be seen clearly that all trees showed varying ranges. As to air temperature, T10 (26 °C in minimum) had the lowest value in the morning, which was followed by T6; while T3 (peaked at 36 °C) and T4 (peaked at 34 °C) were relatively warm. The afternoon air temperature was similar with that in the morning, T3 was still the warmest, reaching 38 °C, which was nearly 10 °C warmer than T10. Air velocity did not show quite noticeable regulars for they were generally low. Fluctuation trends of globe temperature were not totally same with the air temperature although T3 and T4 still showed higher values (around 40 °C in the afternoon). The temperature data illustrated a fact that afternoon was warmer than morning.

Fig. 9 illustrated the MRT ranges of all trees. T3 and T4 respectively had the highest values in the morning (43 °C in average) and afternoon (45 °C in average). There were four trees relatively cool, which was T5, T6, T8, and T10. Their mean MRT values were all nearly 30 °C.

3.2. Primary analysis

This study focused on tree crown characteristics. ANN models were established to find their effects on canopied sites. There were several tree crown parameters affecting the microclimate, which was used as independent variables in the model. Also, owing to the periods of measurement (five days), temperature fluctuation caused by weather changes cannot be ignored. Therefore, the parameter evaluating current weathers, air temperature (AT) from the reference instrument, was used as another variable. For microclimatic parameters fluctuated by time, the time (h) was used as the factor. Meanwhile, TH might affect site thermal comfort. For confirming that, TCR and R/TH were analysed in separation in two models. The models outputted Tables 2 and 3. It can be seen clearly that TCR and R/TH expressed significant effects on site thermal comfort. Their importance was 0.285 and 0.303 respectively. The rest factors were also important, time was more significant, due to temperature fluctuation regarding time. Physically, R/TH had more significant effect than TCR thermally, its importance values was higher by 0.018 nearly.

3.3. Further analysis

Tree characteristics (size and ratio) were found being the most significant climatic affecting factor among all in the models. Hence their independent thermal performances need to be further analysed. Linear regression was used for this analysis, which separately associates TCR and R/TH with the mean value of PET at each site. Meanwhile, due to the noticeable difference between morning and afternoon temperatures, data of two periods were regressed in separation. Fig. 10 illustrates that TCR and R/TH were significantly

Table 2

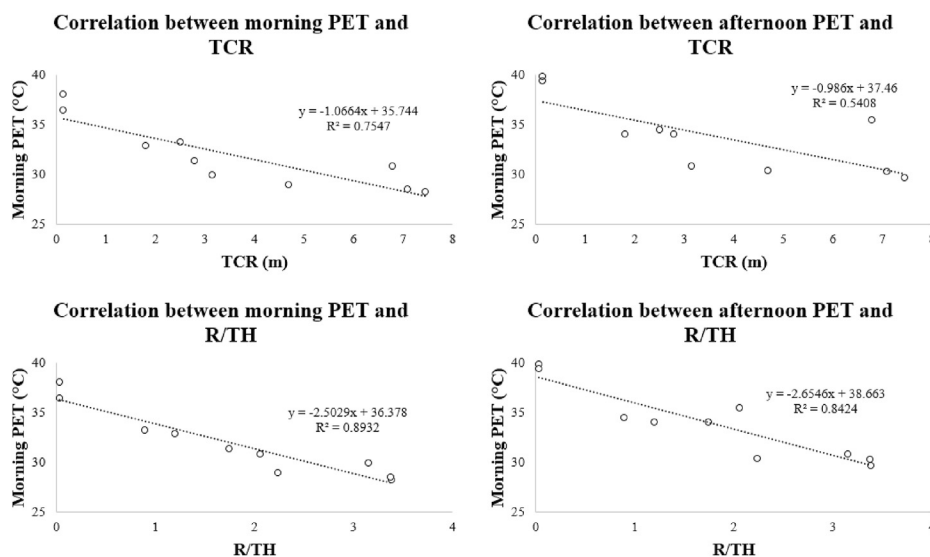
Importance and normalised importance of all independent variables for TCR model.

Independent variable	Importance	Normalised Importance
TCR	0.285	100.0%
Time	0.284	99.5%
LAI	0.191	67.0%
AT	0.274	96.1%
SVF	0.250	87.7%

Table 3

Importance and normalised importance of all independent variables for R/TH model.

Independent variable	Importance	Normalised Importance
R/TH	0.303	100.0%
Time	0.301	99.3%
LAI	0.228	75.2%
AT	0.252	83.1%
SVF	0.218	71.9%

**Fig. 10.** Correlation between PET and TCR in each period of the day.

negatively correlated with PET. Increasing TCR from 1 to 8 can reduce PET by 8 °C in maximum; a similar reduction degree was found through the R/TH increment of around 3.5. Meanwhile, R/TH ($R^2 > 0.8$) expressed more significant correlation than TCR ($R^2 < 0.76$). That is to say, TH might be also thermal relevant, R/TH was more thermal significant than TCR.

3.4. Reliability test

Neural network models only express the relative importance among all independent variables. Total model significance was ignored. For compensating this limitation, reliability tests were needed, which is processed through associating the predicted PET values with the original measured ones. Fig. 11 illustrates that the predicted data was significantly correlated with the original ones ($R^2 > 0.8$). Hence these models were reliable.

4. Discussion

This study found that tree crown characteristics had significant statistical correlation with their thermal affecting performances. This finding was reasonable and similarly proved by previous studies. Generally, effects of trees on microclimate improvements have been broadly approved (Coutts et al., 2015; de Abreu-Harbach et al., 2015; Ellison et al., 2017). Their effect varied for several canopied relating factors, including size, scale, and cover. Tree canopied size (TCR), geometry characteristics (R/TH), site openness (SVF), and leaf density (LAI) were the main involved parameters. These parameters were cooling performable with different significance. The climate relating model established based on them presented very high reliability ($R^2 > 0.8$).

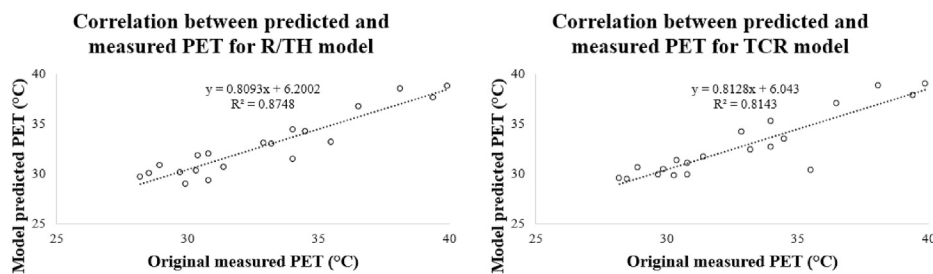


Fig. 11. Correlation between model predicted PET and the original one.

An increase of TCR by 1 m can reduce PET by nearly 1 °C in maximum (Fig. 10). TCR defines a tree's horizontal canopying size. Geometrically, a tree with large size contributes to high tree (vegetation) cover, which might be cool. This fact used to be rarely unconfirmed (Chapman, 2018). Cooling effects of TCR expressed that of vegetation cover in another way. Time had very high importance, which is understandable, for temperatures fluctuated considerably by time (Fig. 4). Additionally, canopying size was not the only thermal influential factor. Geometrical characteristics (the ratio of TCR to TH) ($R^2 > 0.8$) showed more significant cooling effect than the size ($R^2 < 0.76$). Increasing R/TH by 1 could help to decrease PET by above 2.5 °C. It means that TH might be negatively cooling effective, for a high TH causes low canopying intensity. SVF and LAI were less significant compared with tree geometry. In this study, SVF and LAI were supportive for the evaluation of crown porosity, site openness, and leaf density, respectively, under the condition of a fixed crown geometry. During the leaf dense season (summer), sunlight spot through the porosity caused little thermal influence. Meanwhile, during the daytime, tree cooling mostly results from shading instead of biological effects (Lin & Lin, 2010), which could explain the slight effects of LAI.

Some limitations cannot be ignored despite of novel findings acquired. Some studies have found that tree cooling effects were more significant during the evening (Zhang, Gou, & Shutter, 2019). Nevertheless, this study only involved daytime (8:00 to 17:00) micro-climatic data instead of full day, which shows the necessity of study continuation. This limitation might be addressed in future studies.

5. Conclusion

This study has explored the characteristics of tree crowns and their performances on cooling intensity locating around a satellite city of China. Outdoor thermal comfort studies relating to urban microclimate was rarely explored through detailed tree component characteristics and highlighted their thermal recreation function on outdoor thermal comfort. This study compensated this limitation of some earlier researches through studying tree crown. Significantly, this study decomposed crown characteristics of a tree through four parameters, tree crown radius, trunk height, leaf area index, and sky view factor. Relevant study outcomes could be used for future landscaping and planting projects for microclimate improvement. The findings were concluded as follows:

- Tree canopying size (the crown radius) would have significant cooling effect, every metre of TCR increase can reduce PET by approximately 1 °C in both morning and afternoon;
- Tree geometry characteristics (R/TH) might be more thermal effective, every increase of R/TH can reduce PET by nearly 2.5 °C in both morning and afternoon;
- Trunk height might be negatively cooling effective for its increase could reduce crown canopying degree;
- SVF and LAI had relatively insignificant thermal effect due to the season of dense leaves.

Generally, this study has found that trees with wider crowns and/or shorter trunks create optimal microclimate in summer, which provides optimistic approaches for further urban design and planning for climate adjustment.

Ethics declaration

The authors declare no competing interests.

Declaration of competing interest

There is no conflict of Interest.

Acknowledgement

This study was completed with the help of students from Deyang Installation Technician College. Thanks for their participation and efforts in the field measurement. All authors (王静、吴伟等) contributed equally for the manuscript. Some images are acquired from Google satellite maps and three-dimensional street view.

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