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Urban green belt outdoor thermal evaluation via leaf area index

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1. Introduction

Urban greening is a mean that can meet the leisure demands of residents resided in fast-growing sub-tropical cities by increasing plantation and the coverage percentage of vegetation. It is also a strategy to counteract the urban heat island. Gago et al. [1] proposed a solution in reducing the adverse effect of urban heat island (UHI) by increasing greenery spaces, trees and vegetation. Increasing urban greenery area is considered an effective method to alleviate UHI in Taiwan. Outdoor open space is important for the sustainability of a city, as it accommodates pedestrian's traffic and outdoor activities, it also contributes to livability and vitality of the city. Providing pleasurable thermal comfort experience is an important thing that should be taken into account when designing the outdoor space. Nikolopoulou's [2] survey was one of the first outdoor thermal comfort studies to address people's behavior, and discovered that the comfort conditions generally implied that there are more people willing to use the space.

A comfortable thermal environment of pedestrian sidewalks or greenery corridors must to be ensured during urban design process. Some studies have discussed the topic of thermal comfort for pedestrian street spaces in humid climate zones. Ali-Toudert and Mayer [3] indicated the pedestrian areas of shading was the primary strategy to alleviate pedestrians' heat stress in summer. Johansson and Emmanuel [4] suggested to allow a more compact urban form with deeper street canyons and to provide additional shade within street canyons during the hours around noon by utilizing large tree canopies, covered walkways, pedestrian arcades, etc. Zeng and Dong [5] conducted micrometeorological measurements in a pedestrian precinct and recorded number of people passing through measurement locations in Chengdu, China. The authors found that streets with no trees have longer and greater discomfort, and fewer people were observed passing through the street when thermal index values were higher. In view of this, the objective of this study is trying to establish a quick evaluation tool via leaf area index (LAI) in assessing thermal qualities of the plantation of urban greenery belts.

2. Materials and Methods

2.1 Studying area description

As reflected in the literature, outdoor thermal comfort in urban spaces is a complex issue and is becoming an increasingly prominent and hotly debated topic. Many field studies on outdoor thermal comfort have been conducted under different climates over years. Fieldwork studies in Japan and Taiwan [6, 7], where the ideal appreciation of beauty is fair skin, found that most of the visitors in the urban public place sought shade at higher temperature conditions to prevent from getting sun tanned. The leaves of roadside trees can obstruct solar radiation and provide the necessary shade. Exactly in line with the habit that Taiwanese residents tended to avoid the sun when doing outdoor activities. Therefore, it's crucial to diagnosis the sufficiency of trees' shading condition in providing a comfortable environment in the pedestrian area in Taiwan. To develop a diagnosis tool, sections of primary urban green belts located in Taichung city (central Taiwan) were selected as studying area.

2.2 The shadowing effect of L

Under the tree shadow, albeit the air temperature reduction caused by street trees is limited, the shortwave and longwave radiation, hereinafter referred to as global radiation, are substantially diminished, and thus, the physiologically equivalent temperature (PET) is significantly decreased. As a result, street trees play a major role in human thermal comfort during hot summer days. Knowledge about the appropriate value of transmissivity of global radiation through the canopy of trees is important for modelling PET, while little attention has been paid to the transmissivity of global radiation through the canopies of urban trees. Based on several literatures, it appears that LAI is suitable as an indicator of the interaction between plants and climate responses. Ling [8] develop an empirical equation by using LAI to estimate the reduction ratio of urban trees on global radiation:

$$RI=\exp(-0.0054*LAI^3+0.1083*LAI^2-0.9504*LAI) \qquad (1)$$

where RI is the ratio of global radiation measured below the canopy of the tree to that of radiations above it. The model is applicable for the range of LAI<10. According to Ying, the global radiation is reduced to 20% when the LAI rises to 2.1, and 10% at LAI=4.0. Note that urban trees may affect the reduction ratio of global radiation differently depending on the actual type of tree geometry and that the relationship in Eq. (1) carries a certain degree of uncertainty in real contexts. However, the above equation is used to give a first approximation for a general representation of solar radiation transmissivity through tree crowns and is helpful in assessing the predicted impact on thermal comfort of different walkway trees.

2.3 Calculation of PET under tree-shaded area

Thermal comfort outdoors is affected by both weather and human factors. Radiation and air temperature dominate most of influential factors in regards to thermal comfort, since radiation that reaches the human body activates the same mechanisms as air temperature does. PET is defined as the air temperature at which in a typical indoor setting (without wind and solar radiation) the heat budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions. The main advantages of PET are that it is expressed in a widely known unit (˚C) and that it is related to thermal comfort in indoor conditions, with which people are more familiar. PET can be calculated through models like RayMan, which has been used in the present study. Matzarakis, Rutz and Mayer established RayMan model, which can calculate PET value by entering radiation of specified measuring point [9]. In this study, we calculate the annual hourly operating temperatures from the meteorological data provided in Typical Meteorological Year (TMY3) of Taichung. Air temperature, wind velocity, cloud cover, relative humidity, and solar radiation in TMY3 were imported into the RayMan model to simulate the year-around PET. However, the transmissivity of obstacles is not taken into account in the current regular version of RayMan model. Thus, in this study, the solar radiation from weather data is firstly modified by using Eqn. (1) and then is submitted into RayMan model in order to obtain PET under the canopies of trees.

3. Results and discussion

3.1 Outdoor thermal perceptions for Taiwan

Based on the data from field surveys of 759 interviewees in a city park, Lin et al. used wet-bulb globe temperature (WBGT) as the thermo-physiological index to analyze outdoor thermal comfort. The finding shows that the upper and lower limits of 80% acceptability are 26°C WBGT and 20°C WBGT, respectively [6]. Meanwhile, the maximum likelihood probit models for the percentages of unacceptability due to hotness and coldness are given in that work. Resulting from thermal acceptability analysis on the database obtained from a field study of 1,644 interviewees in the outdoor environment, Lin and Matzarakis gave 21.6-35.4°C PET for 80% acceptability and identified the classification of PET ranges for various thermal perceptions (See Table 1) [10].

Table 1 PET range versus TSV for Taiwan

thermal perceptions	range (°C)
very cold	PET<14
cold	14≦PET<18
cool	18≦PET<22
slightly cool	22≦PET<26
neutral	26≦PET< 30
slightly warm	30≦ PET <34
warm	34≦PET <38
hot	38≦PET< 42
very hot	42≦PET

3.2 Thermal comfort level in sunlit versus shaded outdoors

As known, the shading effect of urban trees contributes to the benefit of mitigating outdoor heat stress in summer by reducing the impact of solar radiation. In winter, however, limited solar access has considerable negative influence on thermal comfort in street canyons. Before discussing the relationship between the degree of shading trees and outdoor thermal comfort, sunlight and full shaded conditions in outdoor thermal environment in Taichung were presented to describe two extreme conditions. According to the equation (1), when the LAI equals to 10, the solar radiation received under the penetration of tree canopy is lower than 0.02. Therefore, LAI=10 is regarded as full shading. The analysis results for sunlit and full shaded outdoors are comparable from in figure 1 and figure 2.

It can be found that a very high proportion of overheating probability in summer without shading exists. During May to October, the percentage of PET higher than 34°C (slightly warm) were more than 50%. That indicates outdoor space in the summer of overheating risk is quite intense in Taichung. From figure 2 of full-shaded case, the PET observed is significantly improved. During the hottest months in Taichung (June, July, and August), the overheating situation is almost disappeared, and the highest proportion of thermal perceptions is neutral, suggesting a great contribution from tree shading.

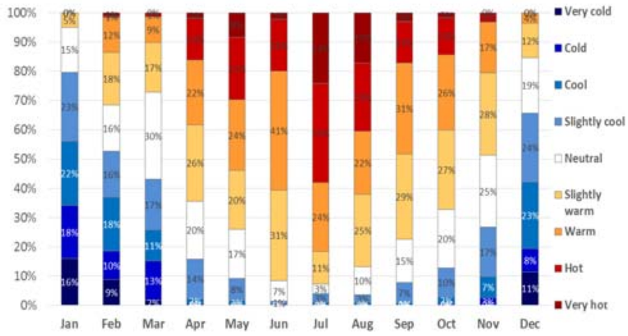

Fig. 1 Sunlit (LAI=0)

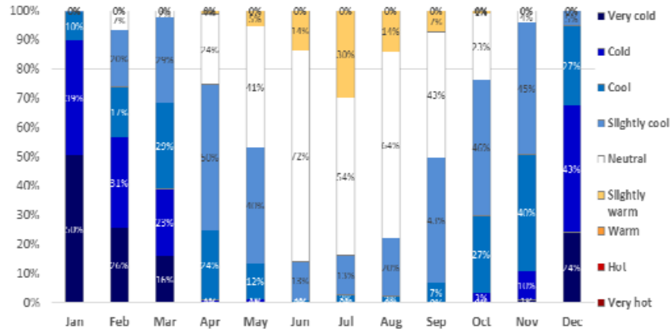

Fig. 2 Shaded (LAI=10)

3.3 Overheating risk assessment

In order to address precisely about how the effect of tree shading is improving the overheating environment, data gathered before 9:00 after 15:00 were omitted for the reason that at that period the walkways are perhaps shaded by adjacent buildings. Furthermore, hours of rainy or heavily clouded sky were also excluded from the analysis in the following sections because the direct radiation was decreased so sharply. By estimating from eq. (1), when the LAI is larger than 4.0, which equivalents to 90% solar shielding effect, the solar shielding effect did not change significantly and the percentages of solar radiation reducing effect will be approaching to constant as LAI further increases. The shielding effect changes significantly when the LAI is between 2.0 to 0. Consequently, this study selected ten various levels of LAI being 0, 0.25, 0.5, 0.75, 1.0, 1.5, 2.0, 3.0, 5.0, 10.0 for the analysis of overheating severity comparison. The frequencies of overheating occurrence, defined as PET greater than 34°C, were monthly analyzed against various degrees of LAI as shown in figure 3.

The above figure shows that when LAI changes from 0 to 1.0, the cooling effect is obvious and the occurrence frequency of PET>34°C is reduced significantly as LAI increases. In addition, a suggested design value of LAI being over 3.0, the PET will be fully controlled below 34°C resulting no probability in overheating occurrence in the hot season from May to October. It suggests that the overheating outdoors may be prevented in summer.

When the outdoor PET is exceeding the comfort temperature, the higher degrees of temperature it surpasses, the stronger thermal sensation one would feel, these differences are connected with the nonlinear relationship. In order to quantify the human's feelings to the thermal environment, we take 34°C as the upper boundary of comfortable zone. In an overheated situation is occurring, a difference of PET to the upper boundary temperature was taken. Then, each difference was multiplied by the number of hours when overheating occurs. At last, the summation of each squared difference was calculated as square of degree-hour for describing the severities of overheating to mimic the thermal endurances a human is encountering. The monthly cumulative square of degree-hours against various levels of LAIs is illustrated as figure 4.

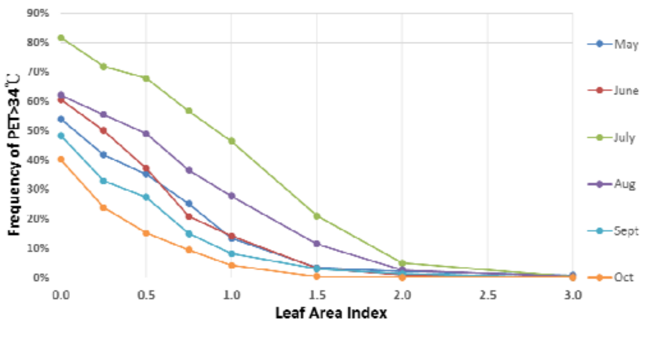

Fig. 3 The frequency of PET>34℃

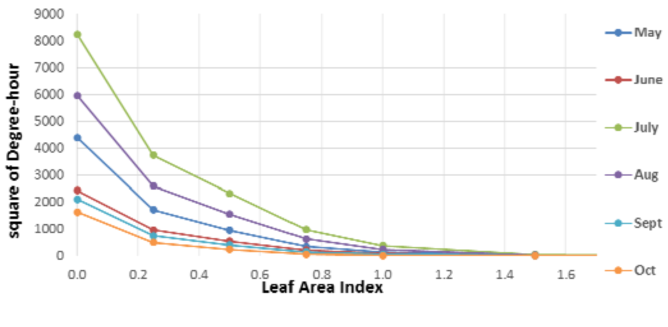

Fig. 4 The square of degree-hour of overheating

In this study, we considered both the intensity and the frequency of overheating as Criteria I and Criteria II to determine whether overheating is occurring in outdoor spaces. Criteria I assesses the overheating frequency of PET greater than 34°C as Criteria II evaluates the cumulative square of degree-hour of PET greater than 34°C. A concept of overheating risk was introduced for devising a guidance of the lowest design LAI for outdoor overheating prevention. The overheating risk is defined as the percentage of overheating hours during total diurnal hours in summer season. As listed in table2, eight levels of the probabilities of overheating risk were with the corresponding lowest suggested LAI for plantation in pedestrian area were proposed. From the table 2, if we want to control the overheating risk below 2.5%, the LAI should be lower than 2.05 in criteria I and it should be lower than 1.05 in criteria II, that is criteria I is obviously stricter than criteria II in terms of overheating risk. Consequently, criteria I was taken as evaluating index for outdoor overheating assessment.

Table 3 shows the monthly lowest LAI under a given ratio of overheating risk. Take the hottest month, July, as an example, as we want to maintain the overheating risk no more than 2.5%, the greenery density in terms of LAI should be kept higher than 2.48; when the target ratio of overheating risk is 5.0%, the LAI should be higher 1.98. By means of this reference table, one could easily estimate the lowest LAI they should maintain or design in preventing overheating occurrences over a certain risk probability during urban greenery planning/designing processes.

Table 2 Overheating risk and the corresponding LAI in two criteria

overheating risk	Criteria I		Criteria II	
	Hours	Leaf area index	Square Degree Hours	Leaf area index
2.5%	20	2.05	619	1.05
5%	40	1.91	1237	0.94
7.5%	60	1.76	1856	0.84
10%	80	1.62	2474	0.74
12.5%	100	1.49	3093	0.70
15%	120	1.43	3711	0.66
17.5%	140	1.37	4330	0.62
20%	160	1.30	4949	0.57

Table 3 Overheating risk and corresponding LAI from May to October

	Leaf area index					
overheating risk	May	June	July	August	September	October
2.5%	1.80	1.60	2.48	2.00	1.63	1.21
5%	1.41	1.40	1.98	1.84	1.29	0.95
7.5%	1.28	1.28	1.89	1.69	1.04	0.83
10%	1.15	1.16	1.81	1.53	0.92	0.72

4. Conclusions

According to the analysis of the severity and the frequency of overheating from May to October, we can discover that the comfort level of the unshaded outdoor space will be largely improved immediately by adding shaded trees. The results also confirmed the overheating environment could be improved efficiently by providing some tree shadings. The magnitude of the improved thermal comfort increased with the increasing of LAI. Another phenomenon we discovered is that the improvement of thermal comfort do not change a lot as the LAI is larger than three, suggesting a plantation density with average LAI equals to three is sufficient enough to achieve outdoor thermal comfort in the context of Taichung's urban climate.

Since there is no international standard for evaluating overheating condition in outdoor environment. In the study, we proposed the overheating frequency, the square of degree-hour along with overheating risk concept in assessing the outdoor thermal conditions via LAI. To take human's thermal perception into consideration PET was adopted as physical quantities in constructing outdoor overheating criteria. The lowest suggested LAI values corresponding to the different rate of overheating risk were proposed. By means of this, one can utilize these data as a reference in designing urban outdoor green spaces for a greater comfort outdoor environment. Planting properly chosen trees with adequate LAI in urban design process, the risk of outdoor overheating could be controlled. By properly design an urban green belt system in overheating perspective, it will not only let residents having more willing to use outdoor space for doing outdoor activities in summertime, it can also have mitigation effect on UHI by enhancing urban outdoor thermal comfort.

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