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Review

Heat Mitigation Benefits of Urban Trees: A Review of Mechanisms, Modeling, Validation and Simulation

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Abstract: Modeling, validating, and simulating are three essential parts in investigating the heat mitigation benefits of urban trees (BUT). Therefore, 81 relevant studies from the last ten years are reviewed, analyzed, and summarized in this study. Three main ways for urban trees to adjust the environment are summarized, including shade creation and radiation modification, cooling effects of transpiration, and airflow blocking and modification effects. Research works are analyzed with regard to four categories: (1) heat and moisture exchange mechanisms and their mathematical modeling; (2) verification of modeling predictions based on measurements; (3) thermal performance simulation and prediction; and (4) environmental assessment and human thermal comfort analyses. Future research opportunities are discussed: (1) conduct real-time and in-depth measurements to analyze the mechanisms of heat and moisture transfer of trees in different areas; (2) develop tree radiation attenuation, airflow resistance, and transpiration models to accurately describe heat and moisture transfer processes in the urban environment; and (3) establish a three-dimensional numerical simulation method that can accurately simulate the urban thermal environment with trees. This review provides researchers with an overview and potential research opportunities on the thermal effects of urban trees.

Keywords: human thermal comfort; microclimate; tree; urban heat island; radiation modification

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1. Introduction

The urban heat island (UHI) reduces the quality of life of urban dwellers [1], changes the local hydrology and subsurface structure [2], and causes several ecological problems [3,4]. Recent research indicates that a rational vegetation layout is an effective means for alleviating the UHI and preventing the mortality burden [5], reducing energy consumption, and providing better outdoor thermal comfort [6]. Wong et al. [7] evaluated the potential of green infrastructure as a mitigation strategy and found that greenery on the ground reduces the peak surface temperature by 2–9 °C, while green roofs and green walls reduce the surface temperature by 17 °C. Bowler et al. [8] used a systematic review methodology and meta-analysis to evaluate the available evidence on whether greening interventions affect the air temperature of an urban area and found that, on average, a park with trees was 0.94 °C cooler in the day. Thus, focusing on climatic adaptive design that combines elements of landscape with microclimatic factors is an important way to deal with urban ecological problems and to improve the urban thermal environment [9,10].

Trees, as one of the most important urban landscape elements, play a crucial role in mitigating the UHI [11]. Radiation attenuation and transpiration are important tree factors for the balance of surface energy and the water vapor cycle of the hydrosphere–atmosphere–biosphere [12]. Through canopy shading and transpiration [13], trees can adjust the outdoor radiant heat, affect the heat and moisture balance of the surrounding environment [14], and change the outdoor microclimate and urban environment. Trees can also reduce wind speed, enhance airflow turbulence [15], change outdoor wind flow characteristics, reduce convective heat and mass transfer coefficients [16], and further affect the heat and moisture balance between trees and the surrounding environment.

The physical properties of trees, such as diameter at breast height, crown width, and leaf area index (LAI), are paramount factors in regulating the microclimate and increasing user comfort [17–19]. Due to the significant differences in root depth, crown width, LAI, tree morphology, and leaf reflectance among different tree species, the cooling performance of different tree species varies greatly under different climate conditions. The complexity of the heat exchange process of trees and the climatic particularity of "wind, heat, rain, and humidity" in different areas ensure that the heat and mass transfer between trees and the environment is a coupled and complex process. How to accurately describe this process has become an urgent problem in disciplines such as architectural technology, landscape architecture, urban planning and design, and urban climatology.

Of particular importance to this review, the latest progress in urban climate modeling indicates that it is crucial to incorporate urban trees into urban canopy models (UCMs) so as to realistically capture the surface energy budget and achieve an accurate simulation of the urban thermal environment [20–23]. However, as the modeling of tree radiation attenuation, tree airflow resistance, and tree transpiration is still lacking [19,24,25], the current urban thermal environment assessment tools cannot achieve accurate simulations of tree heat and moisture transfer processes and, thus, cannot accurately predict the urban energy balance, natural ventilation, and outdoor thermal comfort in the presence of trees, nor can they predict the thermal environment performance of design plans. Numerical simulations under certain assumptions or simplifications cannot yield accurate and universal models and need to be further developed and improved.

Previous related reviews have mainly focused on urban green space cooling effects [26–29], such as threshold size [29], cooling potential [28], contribution to ambient air cooling [27], and enhancement of human comfort [26], with limited insights on trees, particularly their heat and moisture exchange mechanisms and their mathematical modeling. It is, therefore, the purpose of this paper to present a comprehensive review and analysis of recent developments involving the heat mitigation benefits of urban trees, including (1) impact mechanisms of urban trees on the urban thermal environment; (2) heat and moisture transfer mechanisms between trees and the environment and related mathematical models. This study focuses on the experimental testing of trees, theoretical methods, mathematical models, numerical simulations, and validations. The opportunities to expand research on the thermal effects of urban trees will also be presented.

2. Data and Methodology

To understand to what extent the available guidelines of tree heat and moisture exchange mechanisms and their mathematical modeling could fulfill researchers' real needs, we attempted a condensed literature survey for the last ten years in the tropics. We developed a four-step workflow that serves as the analytical framework: (1) reviewing the mechanism of urban trees' influence on the urban thermal environment; (2) reviewing the mechanism of heat and moisture exchange and its mathematical modeling; (3) reviewing and analyzing the research results of recent years on heat mitigation by trees; and (4) reviewing pending problems in the heat and moisture transfer mechanism and related modeling. The eligibility criterion "tropics" was defined by cities located at 23.5° S–23.5° N and the criterion "subtropical" was defined by cities located at 23.5–35° S and 23.5–35° N latitudes.

In the literature review, the Web of Science was chosen for the literature search. The keywords "tree", "human thermal comfort", "microclimate", "urban heat island", and "radiation modification" were used as the topics for the literature search. The literature was limited to the last 10 years. The total number of articles that emerged from the initial review was 136. All articles were subsequently manually reviewed, and only those field and modelling studies closely related to the impact of urban trees on urban microclimate were selected. All selected field measurements studies needed to include basic information, such as date, time, tree's species country name, city name, number of stations, locations of stations, measurement type, and measured variables. Based on the topics discussed in the paper, more relevant keywords, such as "influence mechanism", "exchange mechanism", "mathematical modeling", "simulation", "ENVI-met", and "modelling" were selected to limit the search. Finally, 81 papers were included in the in-depth analysis. A flowchart of Paper Retrieval Research is shown in Figure 1. The four-part framework analysis and article citations are described specifically in the following sections.

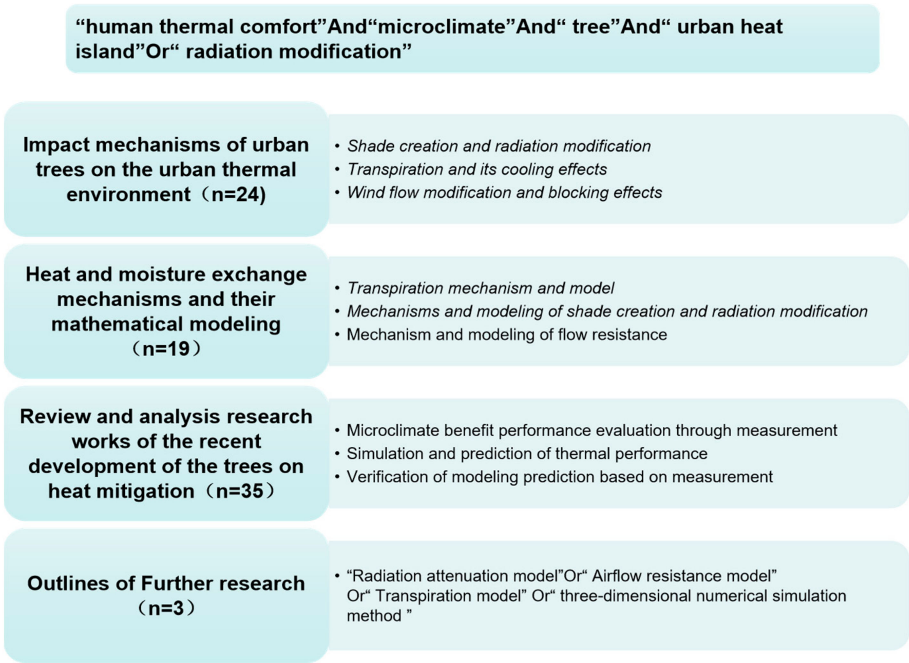

Figure 1. Flowchart of Paper Retrieval Research.

3. Impact Mechanisms of Urban Trees on the Urban Thermal Environment

The heat mitigation benefits of urban trees have complex internal and external causes. It is necessary to consider not only their physical characteristics, such as tree species, crown albedo, leaf reflectance, transpiration rate, and leaf area index, but also the impacts of different microclimatic parameters on a tree's heat and moisture transfer processes.

There are three main ways for trees to adjust the environmental microclimate [29]: (1) due to the unique albedo and absorptivity of the tree crown, trees can reduce solar heat reaching the ground by absorbing and reflecting solar radiation; (2) the transpiration of trees can reduce surface and ambient temperatures; and (3) trees can guide and control the airflow by blocking and filtering it.

3.1. Shade Creation and Radiation Modification

The attenuation of solar radiation by the tree canopy is a crucial way to reduce the UHI, affecting the surface energy balance and improving the urban microclimate [28]. The canopy can reduce solar radiation, modify heat exchanges between buildings and the surrounding environment, and affect human outdoor thermal comfort [27]. Trees can also indirectly reduce surface temperatures by modifying ground radiation [30]. The ability of trees to attenuate the UHI is mainly related to a reduction in direct solar radiation, especially visible and near-infrared light [11,31–33]. Current research is mainly focused on tropical, arid, and temperate regions and their native tree species. Little is known in humid and hot climates [13,34].

3.2. Transpiration and Its Cooling Effects

The transpiration of trees is the main reason for the cooling and humidification effects [35,36]. The transpiration process of trees can convert heat energy into latent heat, increase the humidity, and reduce the temperature of the surrounding environment [37,38]. In a hot dry climate, trees can evaporate about 100 gallons of water per day [36]. On a typical summer weather day, because of the transpiration, approximately 33% of incoming solar radiation is converted into latent heat [39]. Quantifying the cooling and humidification effects caused by trees requires accurate tree transpiration rates [40].

3.3. Wind Flow Modification and Blocking Effects

Trees also have significant implications for wind flow, which significantly impacts outdoor thermal comfort [41,42], energy efficiency [3,43], urban pollutant dispersion [22], and urban heat island mitigation [44]. The insulation effect of trees in terms of windward and leeward wind speed reduction is related not only to their physiological characteristics, such as spacing, size, porosity, and orientation, but also to their location and surrounding environment. Shahidan [18] found that, in a typical urban area, a tree's physical parameters (leaf area index, crown width, and branches, etc.) have significant implications for airflow and wind environment, and that the leaf area index (LAI) and crown width are the main factors affecting the outdoor wind environment. Zheng et al. [45] found that the control of wind speed and direction by trees further affects air temperature. In the mainstream wind direction, the distance from a tree influencing air temperature is about five-times its height, but only two-times in the case of a non-mainstream direction.

4. Heat and Moisture Exchange Mechanisms and Their Mathematical Modeling

Through canopy shading and transpiration, trees can reduce solar radiation, affect the heat and moisture balance of the surrounding environment, and change the outdoor microclimate. At the same time, trees can also reduce wind speed, enhance airflow turbulence, change outdoor flow field characteristics and wind field distribution, and further affect the heat and moisture balance between trees and the surrounding environment. In order to realistically capture and present these phenomena, the common method is to load the tree's radiative heat transfer, convective heat transfer, and transpiration latent heat into the boundary layer's energy balance equations when discussing the regional heat balance. The goal is to control the energy balance of the body [46,47].

4.1. Transpiration Mechanism and Model

There are three evapotranspiration models commonly used in the agriculture and hydrology fields: Priestley–Taylor, Penman–Monteith, and Shuttleworth–Wallace (S-W) [48–50]. Only the S-W model can be used for urban trees as it comprehensively considers the canopy and soil source evapotranspiration processes [51–54].

The S-W model calculations are as follows [50]:

$$\lambda \mathrm{ET} = \mathrm{C_c ET_c} \times \mathrm{C_s ET_s} \tag{1}$$

$$\mathrm{ET_c} = \frac{\Delta(\mathrm{R_n} - \mathrm{G}) + \{\rho \mathrm{C_P}(\mathrm{e_s} - \mathrm{e_a}) - \Delta \mathrm{r_a^c}(\mathrm{R_n^s} - \mathrm{G})\}/\mathrm{r_a^a} + \mathrm{r_a^c}}{\Delta + \gamma\{1 + \mathrm{r_s^s}(\mathrm{r_a^a} + \mathrm{r_a^c})\}} \tag{2}$$

$$\mathrm{ET_s} = \frac{\Delta(\mathrm{R_n} - \mathrm{G}) + \{\rho \mathrm{C_P}(\mathrm{e_s} - \mathrm{e_a}) - \Delta \mathrm{r_a^s}(\mathrm{R_n^s} - \mathrm{G})\}/\mathrm{r_a^a} + \mathrm{r_a^s}}{\Delta + \gamma\{1 + \mathrm{r_s^s}(\mathrm{r_a^a} + \mathrm{r_a^s})\}} \tag{3}$$

$$C_C = \frac{1}{1 + (R_s R_a)/[R_s(R_c + R_a)]} \quad (4)$$

$$C_s = \frac{1}{1 + (R_s R_a)/[R_c(R_s + R_a)]} \quad (5)$$

$$R_a = (\Delta + \gamma) r_a^a \quad (6)$$

$$R_c = (\Delta + \gamma) r_a^c + \gamma r_s^c \quad (7)$$

$$R_s = (\Delta + \gamma) r_a^s + \gamma r_s^s \quad (8)$$

The nomenclature of Equations (1)–(8) is presented in Table 1.

Table 1. Nomenclature of Equations (1)–(8) of the S-W model.

Symbol	Full Name	Unit
ET	Total evapotranspiration	$J/m^2 \cdot s$
λ	Latent heat of water vaporization	J/kg
ET_C	Canopy transpiration	$J/m^2 \cdot s$
ET_C	Bare surface evaporation	$J/m^2 \cdot s$
C_C and C_S	Weight coefficients of ET_C and ET_s	-
R_n	Canopy net radiations	$J/m^2 \cdot s$
R_n^s	Soil surface net radiations	$J/m^2 \cdot s$
G	Soil heat flux	$J/m^2 \cdot s$
γ	Air humidity constant	kPa/°C
e_s	Saturated water vapor pressure	kPa
e_a	Actual water vapor pressure	kPa
r_s^c	Canopy stomatal resistance	s/m
r_a^c	Canopy boundary layer resistance	s/m
r_s^s	Soil surface resistance	s/m
Δ	Water vapor pressure-temperature curve	J/kg

The heat transfer structure of the S-W model is present in Figure 2. The S-W model integrates two source terms of evapotranspiration from the soil and the plant canopy by introducing soil resistance and canopy resistance parameters. It has been widely used in recent years.

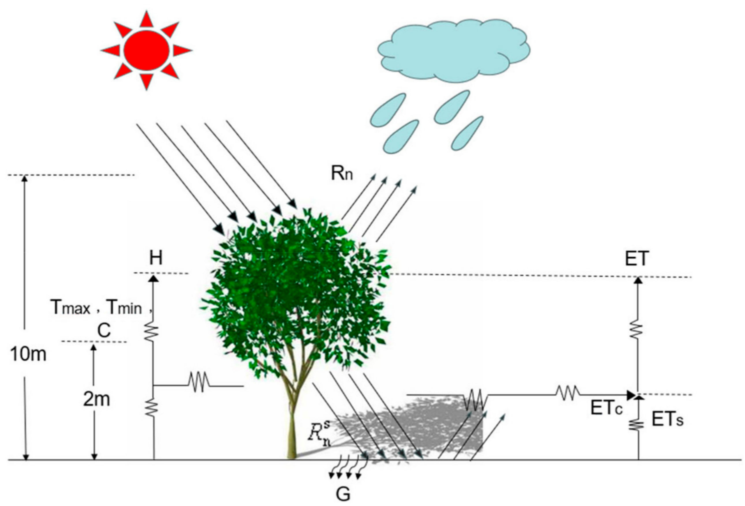

Figure 2. Schematic diagram of the S-W model [50].

4.2. Mechanisms and Modeling of Shade Creation and Radiative Properties Modification

In order to calculate the shielding effect of the canopy on solar radiation, there are two common calculation methods: transmittance and numerical simulation. The transmittance method obtains the solar radiation transmittance (σ) of the canopy by measuring the solar radiation (S_0) and incident solar radiation (S_t) under the tree, as shown in Figure 3. According to Zheng et al. [19] and Shahidan et al. [18], the solar radiation transmittance of single-layer leaves is quite different: 10% of visible radiation and 30% of infrared radiation (Figure 4).

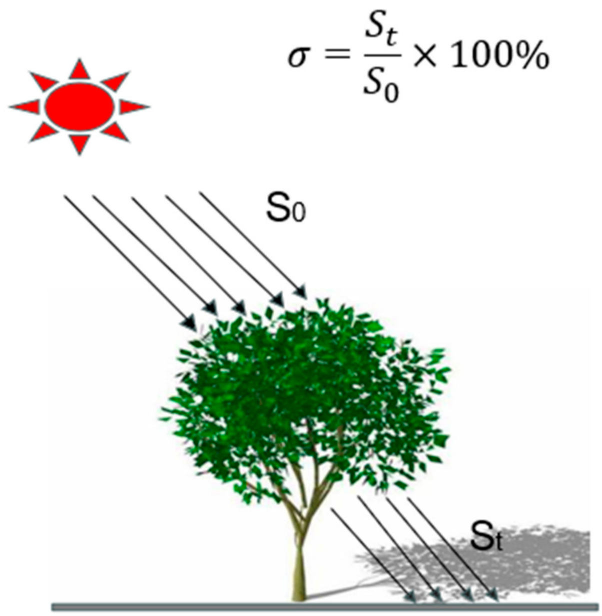

Figure 3. Calculation of the solar radiation transmittance of trees.

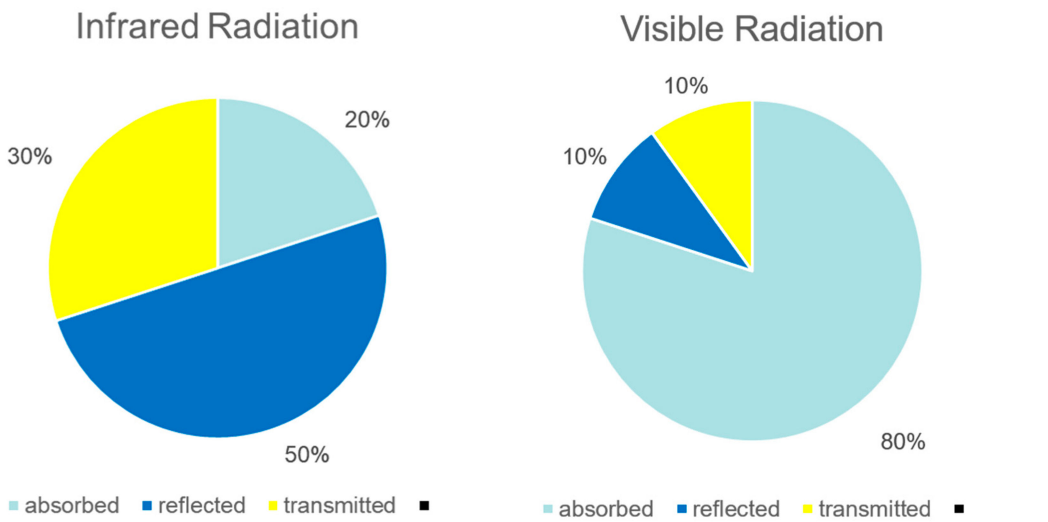

Figure 4. Optical properties of leaves (transmission, absorption, and reflection of visible and infrared radiation, respectively) [17,18].

Only a part of solar radiation (>0.38 μm) has thermal effects on trees [55,56]. From a biological viewpoint, solar radiation <4 μm can be divided into three parts: ultraviolet radiation (UV), photosynthetically active radiation (PAR), and infrared radiation. The thermal effects of this radiation are provided in Table 2, which shows that UV does not have a thermal effect on trees. Near-infrared radiation has mainly thermal effects and can be absorbed by water in the stems of the leaves. Far-infrared radiation can only warm the tree.

Table 2. Thermal effect of solar radiation on the canopy at different wavelengths [55].

Type of Radiation	Wavelength (µm)	Proportion (%)
UV	0.29~0.38	0~4
PAC	0.38~0.71	21~46
Near-infrared	0.71~4.0	50~79
Far-infrared	>4.0	-

4.3. Mechanism and Modeling of Canopy Flow

The influence of trees on the airflow field is related to their enhancing turbulence and reducing wind speed. In numerical simulation, in order to facilitate research, a tree's physical model is divided into two parts: trunk and crown (Figure 5). The crown is considered as a porous medium because of its air permeability. In order to reflect the obstruction effect of trees on airflow, current microclimatic models generally modify the three-dimensional momentum equation by adding source terms [45,57].

$$F_d = -\frac{1}{2}C_d \eta a u_i \left(\sum u_i^2\right)^{0.5} \quad (9)$$

where F_d is the resistance source term caused by the tree, and C_d is the drag coefficient.

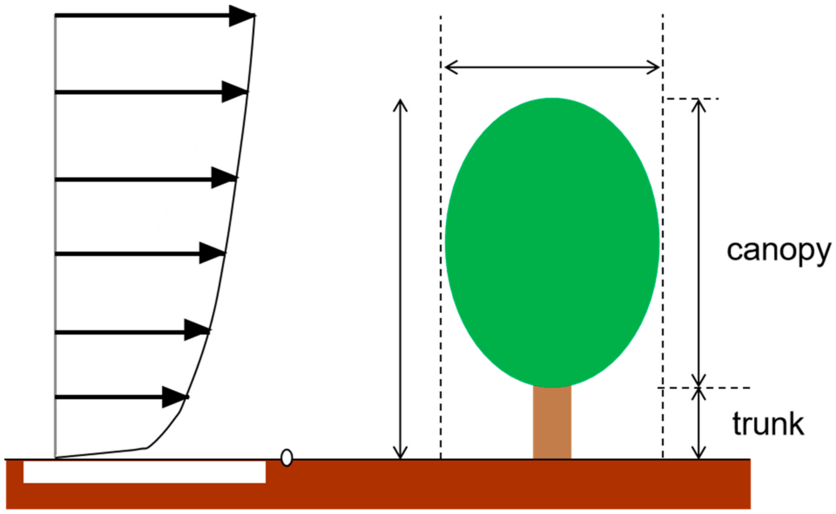

Figure 5. Physical models of trees [57].

The key for this method is to obtain the drag coefficient. Because the resistance coefficient of trees is difficult to obtain, most of these models use empirical resistance coefficients to simplify the exchange of momentum between the trees and their environment. It is assumed that the empirical resistance coefficient is constant and independent of wind speed and direction. In temperate regions, the empirical resistance coefficient usually varies between 0.1 and 0.3. Therefore, the default drag coefficient in the ENVI-Met tree model was set at 0.2 [58]. However, the latest research [57] shows that the actual resistance coefficient of trees in different climatic regions differs greatly from the empirical resistance coefficient in the actual situation, and the drag coefficient decreases with increasing wind speed, as shown in Figure 5 [57]. In addition, the drag coefficient is quite different in different areas. The resistance coefficient of common trees is 0.6 in the Mediterranean climate [59] and 0.8 in tropical regions [60]. In order to accurately simulate the momentum exchange between the tree and its environment, it is necessary to obtain the real drag coefficient in a given area.

For a scaled tree model, the aerodynamic performances of real trees in the wind, such as reconfigurations and the change in the projection area of a tree crown against incoming wind, are difficult to simulate. Based on wind tunnel experiments, Manickathan et al. [59] and Cao et al. [60] found that the reconfiguration phenomenon is mainly affected by the branch stiffness and wind speed. This phenomenon affects the characteristics of tree forces and tree forms, especially the frontal area of trees (the area of the orthographic projection of the tree on a plane perpendicular to the wind direction) and drag coefficients. The frontal area of trees and drag coefficient decrease with increasing wind speed (U) (Table 3). The negative exponential relationships between drag coefficients and wind speed (U) can be expressed by the formulas $C_d = a \times U^{-b}$ [60].

Table 3. Variations in the drag coefficients (C_d) of four tree species with wind speed (U) [57].

Species	Leaf Area Density (m^2/m^2)	Drag Coefficient (C_d)
Ficus microcarpa	4.97	$C_d = 1.07 \times U^{-0.075}$
Mangifera indica	4.79	$C_d = 1.0 \times U^{-0.05}$
Michelia alba	2.88	$C_d = 1.0 \times U^{-0.19}$
Bauhinia blakeana	4.27	$C_d = 0.89 \times U^{-0.069}$

5. Review and Analysis of Recent Research Works on Heat Mitigation by Trees

In this section, recent works on the heat mitigation benefits of urban trees (HMBUT) are reviewed and analyzed in the order of the publication year. Works associated with HMBUT were found to be substantial and were analyzed along the following themes: (1) microclimate benefit performance evaluation through measurement; (2) thermal performance simulation and prediction; (3) verification of modeling prediction based on measurement; and (4) environmental assessment and human thermal comfort analyses.

5.1. Microclimate Benefit Performance Evaluation through Measurement

The experimental research on trees in the field of urban microclimate mainly concerns microclimatic data (air temperature, humidity, solar radiation, wind direction, and wind speed, etc.) at measurement points and compares them with a tree's physiological parameters (three-dimensional green quantity, leaf area index, canopy cover, canopy closure, plant coverage, average leaf inclination, etc.), as presented in Figure 6 and Table 4 [61,62]. Some scholars have also combined thermal environment simulation software, such as Envi-met 4.2 and Airpak 3.0, to analyze the impact of landscape design methods on the microclimate [63–65].

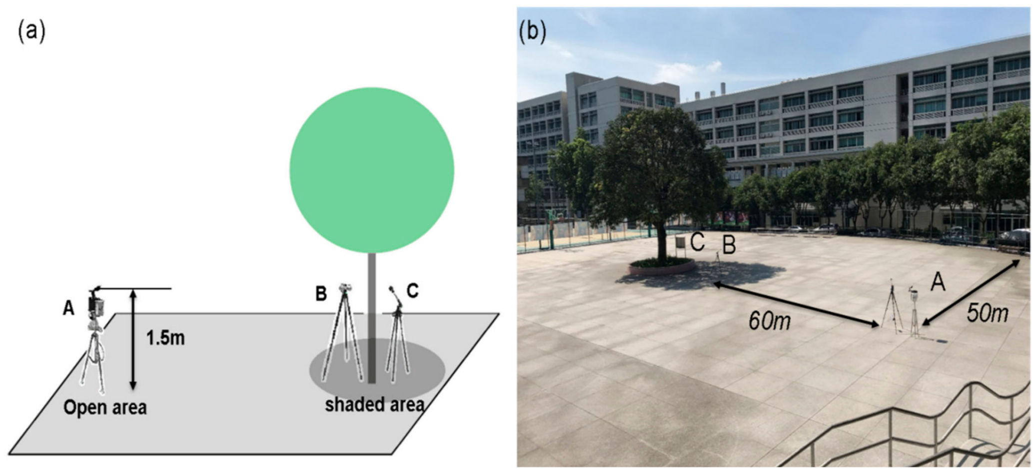

Figure 6. Layout of measuring points and instruments to obtain trees' cooling effects. (**a**) is a schematic diagram; (**b**) is field measurement chart. A: weather station to obtain meteorological parameters in open areas; B and C: sensors to obtain meteorological parameters in shaded areas [30].

Table 4. Commonly used microclimatic measuring parameters and instruments [58].

Test Parameter	Test Equipment	Factory Owners	Accurate	Test Range
Air temperature Relative humidity	HOBO pro v2 data logger (U23-001)	Onset Computer Corporation, Bourne, MA, USA	±0.2 °C (0~50 h)	−40~70 °C
Wind Speed, Wind Direction Black sphere temperature	Ultrasonic anemometer sensor (Model 81000)	M. Young Company, Traverse, MI, USA	±1% ± 0.05 m/s	0~40 m/s
Meteorological parameters	Davis Vantage Pro2	Davis Company, Boston, MA, USA	±0.5 °C (Ta) ±5% (v)	−40~65 °C (Ta) 0–1800 W/m^2 (S)
Transpiration rate Leaf surface temperature	Photosynthesis apparatus Li-6400	Decagon Company, Pullman, WA, USA	±0.007 mmol/mol	0~75 mol
Solar radiation Long-wave radiation	4-component net radiation sensor NR01	Hukseflux Company, Delft, The Netherlands	7–25 µV/W/m^2	0~2000 W/m^2
Soil temperature	T type thermocouple	Sensors Company, Wuxi, China	±0.05 °C	−200~260 °C
Thermal imaging	Thermal infrared imager	Kaise Company, Ueda, Japan	±2 °C	−40~500 °C
Leaf reflectance	Spectrophotometer (U-4100)	Hitachi Company Tokyo, Japan	/	175~2600 nm
Root depth, root width and root density	Tree Radar (TRU-100)	Tree Radar Company, Silver Spring, MD, USA	1 cm	/

There are three main ways in which trees adjust the environmental microclimate: solar radiation modification, transpiration, and blocking effect on airflow.

The solar radiation attenuation by the canopy is mainly affected by physical factors, such as branches and leaves, which differ somewhat across tree species. Therefore, the solar radiation attenuation performance of different tree species varies greatly, especially in different climate regions. Kotzen et al. [17] tested this attenuation effect for street trees common in tropical regions, and they analyzed the effects of solar radiation intensity, incident angle characteristics, and canopy leaf area density on solar radiation attenuation. Based on measured data, Akbari [26] discussed radiation occlusion and transmission mechanisms, indicating that planting design needs to take into account tree canopy density, tree height, canopy transmittance in different seasons, and canopy structure levels.

The transpiration of trees is an important influencing factor on the surface energy balance and cooling effects [66,67]. In order to quantify the cooling and humidification caused by trees, we need to accurately obtain a tree's transpiration rate. At present, there are two main methods for measuring tree transpiration rates [26,68]: measuring the convective mass transfer coefficient (a) and air humidity on the blade surface. However, it is difficult to obtain the convective mass transfer coefficient in heterogeneous urban environments. Another is the trunk runoff method, which can use the trunk runoff meter to measure the liquid flow for a long time, but the instrument is usually very expensive and causes significant damage to the tree. Due to the limitations of the above methods, there are few experimental studies on tree transpiration rates. Akbari [26] found that trees can evaporate about 100 gallons of water per day in dry and hot climates. If evapotranspiration is combined with proper layout and shade, the temperature drop caused by nearby trees can reach 9 °C. Chen et al. [69] established a regression model for calculating the biomass of garden plants by measuring the daily transpiration rates of common trees in Beijing. Han [70] tested the transpiration rate, ecological effect, and utilization of light energy of common tree species in severely cold areas. By simplifying the calculation of the transpiration heat transfer, the cooling effect of different tree species in different months was obtained.

A tree's blocking effects on airflow are not only related to its location and surrounding environment but also to the tree's characteristics, such as size, orientation, porosity, and canopy density. Many researchers at home and abroad have conducted studies on the effects of trees on the near-surface wind environment. Shahidan et al. [18] found that, in a typical urban area, the physical parameters (leaf area index, crown width, and branches, etc.) of different trees yield large differences in impacts on airflow, and they also have a great impact on the wind environment, especially the leaf area index (LAI) and crown width. Heisler [71] found that the canopy blocking effect on wind speed in residential areas depends on the density of the canopy. Increasing the density by 10% can reduce wind speed by 10% to 20%, and increasing it by 30% can reduce wind speed by 15% to 35%.

In addition, the control of wind pressure and direction by trees will further affect the urban microclimate. Zheng [45] found that, if a site is located in the downwind direction of the plant coverage area, trees can play a role in reducing wind speed and wind pressure. Planting a dense row of trees can concentrate and strengthen the airflow under the canopy and improve ventilation conditions at the ground level under the trees. Dimoudi and Nikolopoulou [46] found that in the mainstream wind direction, the influencing distance of a tree on temperature is about five-times its height, and a rational tree layout can effectively improve the thermal comfort of pedestrians around a building. However, when the tree is in the non-mainstream wind direction, the impact is not obvious. Therefore, many studies have suggested that pedestrian comfort should be improved by combining urban greening with the main ventilation channels of urban areas.

5.2. Simulation and Prediction of Thermal Performance

In recent years, with the continuous improvements in computer performance, numerical simulation has become the main research method for the quantitative prediction and evaluation of urban thermal environments. It is necessary to include urban trees in numerical simulations to accurately calculate the urban surface energy balance and achieve accurate simulation of the UHI [19,36]. Because of the complexity of trees' heat and moisture transfer processes and the diversity of their geometric shapes and spatial locations, it is very difficult to create 3D tree models in a given urban street environment, accounting for their spatial locations and sizes [36]. In order to meet this challenge, the commonly used approach is to use existing simulation software.

ENVI-met and ANSYS Fluent are CFD models that are widely used in microclimate simulation and outdoor thermal comfort studies. ENVI-met is a three-dimensional urban microclimate simulation software developed by Bruse and Fleer in 1998. It is based on heat transfer and computational fluid dynamics, and it is mainly used to simulate at the urban block scale, across ground, buildings, vegetation, and the atmosphere [72,73]. ANSYS Fluent, a general-purpose CFD platform based on the Finite Volume, provides comprehensive modelling of fluid flows under steady or transient conditions [74]. Since ANSYS Fluent requires the user to formulate a specific problem via user-defined functions, it requires a high level of physics expertise [75]. Until now, most numerical simulations of the impact of trees on the outdoor thermal environment have been carried out using ENVI-met. Zhang [67] used ENVI-met to simulate the arrangement of eight tree species in residential areas in summer and winter and found that the tree spacing ratio is essential to improve the outdoor thermal environment. Duarte [66] used ENVI-met to explore the influence of trees on air temperature and found that densely planted street trees are cooler than central and pocket parks. Chen [76] studied the impact of common tree species in humid and hot areas by coupling the energy consumption simulation software EQUEST 2.0 with ENVI-met 4.2.

However, because of the complexity of trees' impact on the outdoor environment, ENVI-met simplifies the tree model as follows [19,57,58]: (1) in terms of solar radiation, ENVI-met only considers the attenuation of direct solar radiation by the tree canopy and does not consider the influence of trees on long-wave radiation and heat transfer between trees and the surrounding environment; (2) ENVI-met adopts an empirical resistance coefficient (0.2), which cannot be modified according to the actual species. These simplifications may cause ENVI-met to inaccurately simulate heat and mass exchanges between a tree and its surrounding environment.

5.3. Verification of Modeling Prediction Based on Measurement

Many researchers have evaluated the ENVI-met tree model in their own climate zones [72,73,77]. Zheng et al. [19,57] verified ENVI-met accuracy in hot and humid areas, showing that ENVI-met greatly simplifies the calculation processes of radiation, convection, and transpiration between trees and the environment, with large deviations in the simulation of radiation attenuation, wind speed, and transpiration rate. The root mean square error between the simulated and measured values of solar radiation under a tree reaches 256 W/m^2.

With the development of computational fluid dynamics (CFD) technology, some studies have represented the effect of trees on airflow and heat and moisture transfer by adding source terms to the Navier–Stokes (N-S) equation [78]. Upreti [79] studied trees' radiation attenuation, canopy flow, and heat and mass transfer, using the Monte Carlo method to calculate solar radiation and long-wave radiation attenuation by the tree canopy with a structured grid, simplifying the calculation of canopy radiation transmission by the method of spherical crown envelope surface. Gao and Long [80] coupled the CFD simulation of airflow with outdoor radiation calculation but did not calculate long- and short-wave radiation, nor did they involve the coupling of the tree canopy energy equation with the convection, heat transfer, and radiation equations of the surrounding environment. Argiro [46] simplified the microclimate model of trees by using fixed solar transmittance and transpiration rates. Using this model, they analyzed the microclimatic benefits of trees in the urban environment and conducted a parameter sensitivity analysis of the simplified tree model, which assumes that the sunlight transmittance of a tree canopy is constant and does not consider long-wave radiation.

6. Outlines of Further Research

Tree canopy shading, transpiration, and airflow obstruction have important effects on solar radiation [81], water circulation [82], air temperature [83], and wind environment, as widely recognized by scholars around the world [84–87]. However, there are still several pending problems related to heat and moisture transfer mechanisms and related modeling, as detailed below.

6.1. Conducting Comprehensive and In-Depth Measurements to Analyze the Mechanisms of Tree Heat and Moisture Transfer in Different Areas

Although recent research on the impact of trees on the urban thermal environment has achieved fruitful qualitative results [88–91], there are few studies on tree heat and mass transfer under the coupling of radiation, convection, and transpiration. Also, current relevant research is mainly concentrated on tropical, dry, and temperate regions, with little known about common trees in humid and hot areas [92–95]. The native tree species growing in humid and hot areas have completely different tree shapes and philological characteristics, as compared with trees in other areas. More research is needed to determine their own heat and moisture transfer laws and mechanisms.

6.2. Developing Tree Radiation Attenuation, Airflow Resistance, and Transpiration Models to Accurately Represent Heat and Moisture Transfer Processes in Urban Environments

6.2.1. Radiation Attenuation Model

Previous radiation attenuation models have not included long- and short-wave radiation calculations, or they have only calculated tree canopy radiation in the one-dimensional case [96–98]. As a result, it is impossible to accurately simulate the occlusion, reflection, transmission, and absorption of short-wave solar radiation by the tree canopy and the long-wave radiation heat transfer with the surrounding environment. This hinders further research on the heat mitigation benefits of urban trees.

6.2.2. Airflow Resistance Model

The obstruction of airflow by urban trees affects the urban wind environment and ventilation, which, in turn, affects urban pollutant diffusion, energy distribution, and outdoor thermal comfort [99–102]. In order to reflect the obstruction effect of trees on airflow, current microclimatic models generally modify the three-dimensional momentum equation by adding source terms [103–106]. The key to this method is to obtain the drag coefficient, which varies across different trees. It is urgent to obtain the actual resistance coefficient of the tree species in a given area to specify a flow resistance model and then accurately simulate the resistance characteristics of the trees and the momentum exchange with the environment.

6.2.3. Transpiration Model

The commonly used transpiration models (P-M, P-T and S-W) have all been established and widely used in agriculture. A transpiration model is also urgently needed to accurately represent the urban tree transpiration process and its impact on the heat island effect [107–110]. However, due to differences in plant and soil properties between urban trees and crops, the transpiration model established in the agricultural field may not accurately represent the transpiration process of urban trees. It is an urgent problem to establish a transpiration model suitable for urban trees.

6.3. Establishing a Three-Dimensional Numerical Simulation Method That Can Accurately Simulate the Urban Thermal Environment with Trees

At present, the existing urban thermal environment evaluation tools either do not fully consider radiation attenuation, airflow resistance, and transpiration of trees or cannot accurately simulate the thermal environment with trees [111–115]. Zheng et al. [8,56,59] assessed the commonly used simulation software ENVI-met 4.2 and found that it cannot accurately simulate trees' solar radiation, flow resistance, and transpiration rate. Therefore, in order to accurately simulate the heat and moisture transfer of trees in urban environments and to improve the predictability of the energy balance, natural ventilation, and outdoor thermal comfort [116–122], a three-dimensional numerical simulation model that can accurately simulate the urban thermal environment with trees is urgently needed.

7. Conclusions

Urban trees' thermal effects play a key role in mitigating the UHI, reducing residential energy consumption, and improving outdoor thermal comfort. A critical review of urban trees' thermal effects was carried out, and the influencing mechanisms of urban trees' thermal effects were described, as well as their classifications into (1) shade creation and radiation modification, (2) transpiration and its cooling effects, and (3) wind flow modification and its blocking effects, based on urban trees' heat and moisture exchange mechanisms. Mathematical equations and models for radiation modification, transpiration, and wind flow modification were presented.

Research opportunities related to urban trees' thermal effects are numerous, but the major points lie in the following: (1) heat and moisture exchange mechanisms and their mathematical modeling; (2) verification of modeling predictions based on measurements; (3) thermal performance simulation and prediction; and (4) environmental assessment and human thermal comfort analyses. In view of the current research status and outstanding problems, further research opportunities are outlined as follows: (1) conducting comprehensive and in-depth measurements to analyze the mechanisms of heat and moisture transfer of trees in different areas; (2) developing tree radiation attenuation, flow resistance, and transpiration models to accurately describe the heat and moisture transfer processes of trees in the urban environment; and (3) establishing a three-dimensional numerical simulation method that can accurately simulate the urban thermal environment with trees.

This review focused on urban trees. Less relevant types of green spaces, such as green roofs and green walls, could be considered in a future review.

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