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Harnessing cooling from urban trees:
Interconnecting background climates, urban morphology, and tree traits

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Abstract

Rapid increases in heat exposure in urban areas, fueled by both climate change and urban heat islands (UHI), are manifesting as a pressing concern. Planting and conserving urban trees is one of the pivotal strategies in mitigating outdoor heat and optimizing thermal comfort. We present an integrated review and meta-analysis of 131 studies conducted in recent 13 years, investigating the cooling effects of trees across 15 climate types in 85 global cities or regions. The cooling efficacy of trees is mainly determined upon interconnecting urban morphology, tree traits, and, critically, the prevailing background climates. Our meta-analysis reveals that the cooling effects of urban trees observed in hot climates are significant due to low latitudes, along with their substantial solar radiation blockage and pronounced transpirational cooling. Moreover, an optimal level of transpirational cooling can be achieved at relatively lower humidity levels. However, in tropical and arid climates, extreme conditions involving high temperatures and vapor pressure deficits may trigger stomata closure in leaves, thereby impeding transpirational cooling. Our review further underscores the guiding principles of optimizing urban morphology by arranging buildings and trees, as well as selecting suitable tree species according to their traits to enhance the cooling effects of trees in different climates. The cooling effects of trees demonstrate a nonlinear increase in correlation with higher leaf area index (LAI), leaf area density (LAD), tree canopy coverage, and, inversely, a lower sky view factor (SVF). This systematic review and meta-analysis serve as a critical resource for researchers, urban planners, and policymakers striving to mitigate urban heat by strategically using urban trees.

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Key points

- This study provides an articulated review and meta-analysis of 131 recent journal articles on the use of trees as a urban heat mitigation strategy in 85 cities or regions across 15 climate types.
- The largest variations of pedestrian air temperature reduction by trees, varying from -8.7 °C (significant cooling) to +0.4 °C (minor warming), are discovered in arid climates.
- The daily maximum air temperature change in pedestrian due to trees, attains its peak value of -3.04 °C (cooling) in arid climates, while it records a low value of -1.74 °C in temperate climates.
- An optimized design of urban morphology and tree species selection targeting an appropriately low sky view factor (SVF) can achieve more than 20% additional air temperature reduction.
- To facilitate harnessing the cooling capacity of trees, our study delivers key principal guidelines on suitable selections of urban morphology and tree traits aligning with the local background climate and provides database with an interactive map to record tree-related urban climate investigations.

Keywords: urban trees, urban heat mitigation, cooling effects, background climate, review and meta-analysis.

Introduction

Record-breaking global temperatures during summer have become the norm, largely due to human-induced climate change and changes in land cover[1,2]. Heatwaves are now persisting for extended durations and occurring with escalating frequency, which intensifies urban heat island (UHI) effects[3] and exacerbates many worrisome aspects in cities, such as increased mortality and morbidity, a surge in energy demand for space cooling[4,5], increased heat stress for city dwellers[6,7], damage to or pressure on urban infrastructure, and the propagation of heat-related societal inequity issues[8,9]. These potentially catastrophic consequences highlight the need for rapid urban heat mitigation strategies, lest we reach an irreversible tipping point.

In response to urban warming, the implementation of tree planting and conserving large existing urban trees, one of the most widely applied nature-based solutions (NBSs)[10], can provide substantial urban cooling through evapotranspiration and radiation effects. NBSs have be acknowledged as a crucial tool for supporting environmental sustainability and resilience environment and mitigate effects of climate change in the Intergovernmental Panel on Climate Change (IPCC) report [11]. Additionally, trees address many other challenges highlighted in the United Nations Sustainable Development Goals[12], for instance, improving air and acoustic quality[13,14] , supporting physical and mental health, and safeguarding biodiversity[15]. Urban forestry guidelines for green, healthy, resilient neighbourhoods are emerging, such as "3-30-300 rule"

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introduced by Cecil Konijnendijk[16]. According to this rule, it is recommended that individuals have a view of a minimum of 3 trees from their residence; each neighborhood should maintain a tree canopy covering 30% of its area; and access to a high-quality public green space should be available within a maximum distance of 300 meters[16]. In light of the myriad environmental, social, and economic benefits inherent to these initiatives, a multitude of "One Million Tree" campaigns have been inaugurated in various global cities, including, but not limited to, New York City, Paris, and Shanghai.

The mechanism by which trees provide urban cooling in cities primarily involves the blockage of shortwave solar radiation during the day, leaf evapotranspiration, aerodynamic modification of surrounding airflow, and trapping of longwave radiation from the ground surface during the night[17]as well as providing shading for humans and heat-sensitive infrastructure from direct sunlight Owing to the diurnal cycle of solar radiation and resultant leaf stomata conductance, the cooling effects of a tree typically follow a day-night pattern. Significant cooling primarily occurs in the afternoon, with minor cooling at night[18–22]. The global-scale understanding of the cooling benefit offered by trees is still not unequivocal. Background temperature and atmospheric conditions[23,24], moisture conditions[25,26], urban morphology[27], tree traits[17,28], and soil and underground characteristics among other factors, function as interconnected factors and play complex roles that ultimately determine the cooling potential harnessed from urban trees (**Figure. 1**).

In this review, we offer a comprehensive assessment of tree-related cooling effects reported in 131 studies since 2010, and meta-analyses of the data presented in these studies. We begin by introducing the scope and methodology of systematic review and meta-analysis with detailed documentation of reviewed studies listed in Appendices. After that, we synthesize understanding of background climate, urban morphology, and tree traits on cooling potential of trees. Subsequently, we conducted a quantitative meta-analysis of reported data in recent studies to support our evaluation. Finally, we explore trade-offs in employing urban trees across various dimensions, offering guiding principles for the planning of urban climate transition strategies.

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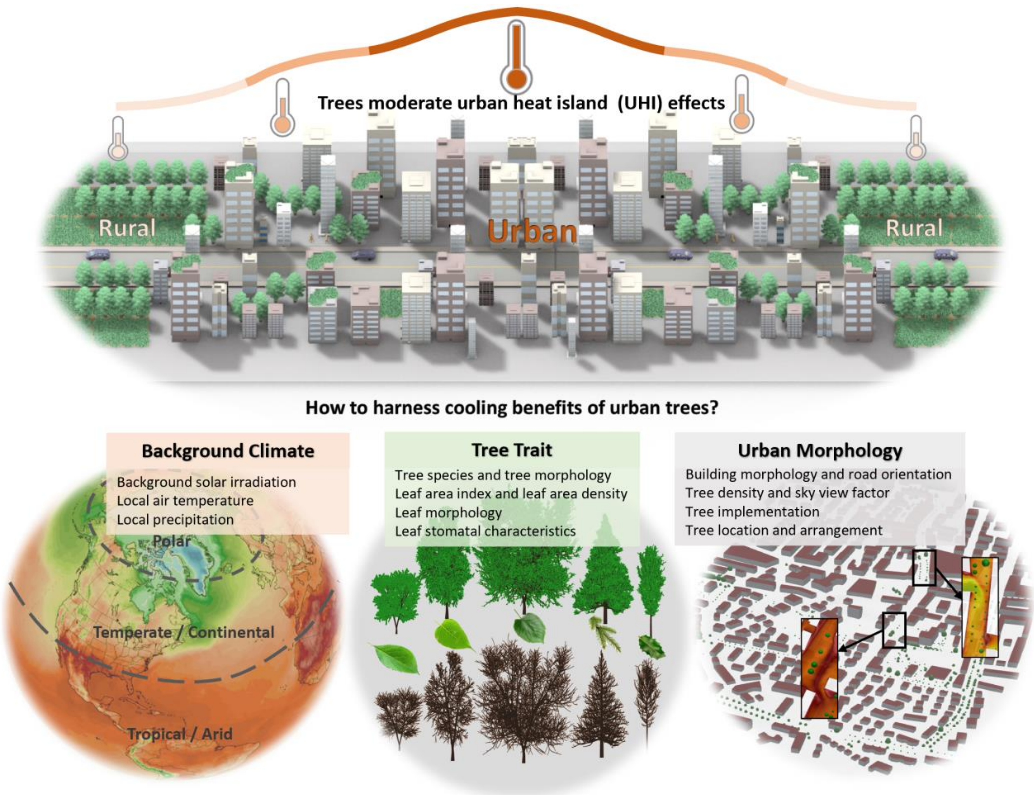

Figure 1. Urban trees are practical tools to moderate heat stress caused by urban heat island (UHI) effects. Harnessing the cooling benefits of urban trees is achieved by optimizing the interconnecting elements, background climates, tree traits, and urban morphology.

Method

Scope and methodology of the systematic review

In this study, we conducted a systematic review with a meta-analysis on the defined topic, the cooling effects of urban trees in outdoor environments. We employed Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines[29], which is a popularly used comprehensive method synthesizing the existing studies on a particularly narrowed topic, providing an objective and rigorous analysis of the available evidence. Urban trees have been utilized in various urban planning and landscape design applications, such as urban streets, roof gardens and exterior facades, residential areas, campuses, and urban parks [30]. In this study, to quantitatively assess their cooling effectiveness, we excluded the type

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of research that solely focused on trees planted in urban parks, as in such locations, the impact of tree shading on building and street surfaces is trivial. Instead, we focused on trees integrated into urban settings such as streets, building perimeters, residential areas, and buildings themselves, such as the roof gardens, where the shading of trees on the building and street surfaces are examined. On the other hand, although urban trees have been extensively studied for their environmental, social, aesthetic, and economic benefits, only studies on the cooling effects of urban trees in outdoor environments are examined in our review. We specifically focus on their heat mitigation and modification of outdoor thermal conditions, air and surface temperatures, and thermo-physiological comfort levels.

The systematic review provides a robust and transparent approach to summarizing the existing studies and results on the cooling effects of urban trees in outdoor environments. The study selection process of the systematic review involved identifying relevant scientific papers published between 2010 and May 2023 in the Web of Science Core Collection and Scopus. To achieve this, we used a combination of search terms, combining "urban trees," or "street trees," with "microclimate," "urban heat island," "outdoor thermal comfort," "outdoor cooling," or "pedestrian level comfort" to identify relevant studies on the cooling effects of urban trees in outdoor environments. The detailed steps in selecting literature follow PRISMA guidelines, based on identification, screening, eligibility, and inclusion. After a detailed selection and classification, as explained in **Appendix A**, we obtained 131 journal articles, among which, 84 studies reported quantitative changes of pedestrian level air temperature due to urban trees. An overview of the 131 reviewed studies and the description of the elements interconnecting tree traits and urban morphology are presented in **Appendix B**. A detailed documentation is listed in **Appendix C**, where we describe the author (year), method, spatial scale, climate type, city or region, country, topic, and quantitative climate indicator.

Climate indicators and classification of meta-analysis

Our meta-analysis statistically combines the results of a number of grouped studies to provide a precise estimate of the climatic effects during the daytime and nighttime. To quantify the cooling effects of urban trees, climate indicators are used to compare thermal conditions or thermo-physiological comfort indexes. As documented in **Appendix B**, Thermo-physiological comfort indices, such as the Universal Thermal Climate Index (UTCI), Physiological Equivalent Temperature (PET), and Predicted Mean Vote (PMV)[31], Standard Effective Temperature (SET)[32,33] and thermal Sensation Vote (TSV)[34], along with quantitative climate indicators, including air temperature 2 m height (T_{air}), surface temperature (T_{sur}), mean radiant temperature (T_{mrt}) are employed in the reviewed studies.

The pedestrian level air temperature (T_{air}), also known as near-surface air temperature at a height of 1.5-2 m, corresponds to the level at which people engage in walking, resting, or other physical activities in urban

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areas[35,36]. T_{air} is the most frequently used indicator, used in over 70% of reviewed studies. It is selected as the parameter for meta-analysis and for comparing the reported cooling magnitudes of trees, as presented in Eq.(1).

$$\Delta T_{air} = T_{air,tree} - T_{air} \tag{1}$$

where ΔT_{air} denotes the change in pedestrian-level air temperature resulting from the implementation of trees. $T_{air,tree}$ represents the pedestrian-level air temperature in the studied area after the implementation of trees, while T_{air} indicates the pedestrian-level air temperature in a scenario without trees, with fewer trees, or with the original settings. ΔT_{air} is usually reported in the reviewed studies on a summer day, a typical hot day, or at a typical hot time. Some studies also compare the effects of trees during summer and winter[37,38]. Among the studies that quantified ΔT_{air}, we synthesized temporal maximum, minimum, and mean reductions in pedestrian air temperature by trees on summer days or typical hot days, as represented by $\Delta T_{air,max}$, $\Delta T_{air,min}$, and $\Delta T_{air,mean}$, respectively. These three parameters are used to quantify tree effects, indicating the combined effects of daytime shading, nighttime radiation blockage, evapotranspirational cooling, and aerodynamic resistance on outdoor thermal conditions.

The climate classification is based on the Köppen climate classification (**Table 1**), determined by the background temperature and precipitation of the local sites [39]. Tropical climate is identified with an annual average temperature of 18 °C or higher, with significant precipitation. An arid climate is defined by little precipitation and at least one month with an average temperature above 10 °C. Both temperate and continental climates have at least one month with an average temperature above 10 °C. Temperate climate has the coldest month with an average temperature between 0 °C and 18 °C and continental climate has at least one month with an average temperature below 0 °C.

Table 1. Köppen climate classification. The table shows the climate types involved in the reviewed studies, explained by four main groups, names, and precipitation types.

Group	Name	Full name	Precipitation Type
Tropical	Af	Tropical rainforest climate	Fully humid
	Aw	Tropical savanna, wet	Dry winter
Arid	BSk	Cold semi-arid (steppe) climate	Steppe
	BWh	Hot deserts climate	Desert
	BWk	Cold desert climate	Desert
Temperate	Cfa	Humid subtropical climate	Without dry season
	Cfb	Temperate oceanic climate	Without dry season
	Csa	Hot-summer Mediterranean climate	Dry summer
	Csb	Warm-summer Mediterranean climate	Dry summer
	Csc	Cool-summer Mediterranean climate	Dry summer

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	Cwa	Monsoon-influenced humid subtropical climate	Dry winter
	Cwb	Subtropical highland climate or temperate oceanic climate with dry winters	Dry winter
Continental	Dfa	Hot-summer humid continental climate	Without dry season
	Dfb	Warm-summer humid continental climate	Without dry season
	Dwa	Monsoon-influenced hot-summer humid continental climate	Dry winter

Interconnecting background climates, urban morphology, and tree traits

Our study is underpinned by a thorough review of scientific papers published since 2010 that investigate the effects of urban trees on urban heat mitigation and pedestrian thermal comfort improvement. Background climates, tree traits, and urban morphology jointly determine the level of cooling benefits that trees can achieve in cities. Only a few studies synthesized the impact of background climate, more specifically seasonality and latitude, on the cooling effects of urban trees[40]. With extensive research efforts and their local investigations in different regions and climates focusing on topics relating to tree traits and urban morphology (**Figure 2**). A gap is primarily attributed to systematically study on systematically integrating background climates, tree traits and urban morphology that determines the cooling effects of urban trees. On the impact of tree traits, research has primarily focused on plant species[37,41], leaf area index (LAI), and leaf area density (LAD)[26,42]. Exploration into the influence of urban morphology has been primarily concentrated on plant arrangement and the geometric features of buildings and streets[33,43]. Maintenance and irrigation[44] and soil characteristics (SC)[45,46] are discussed in limited studies.

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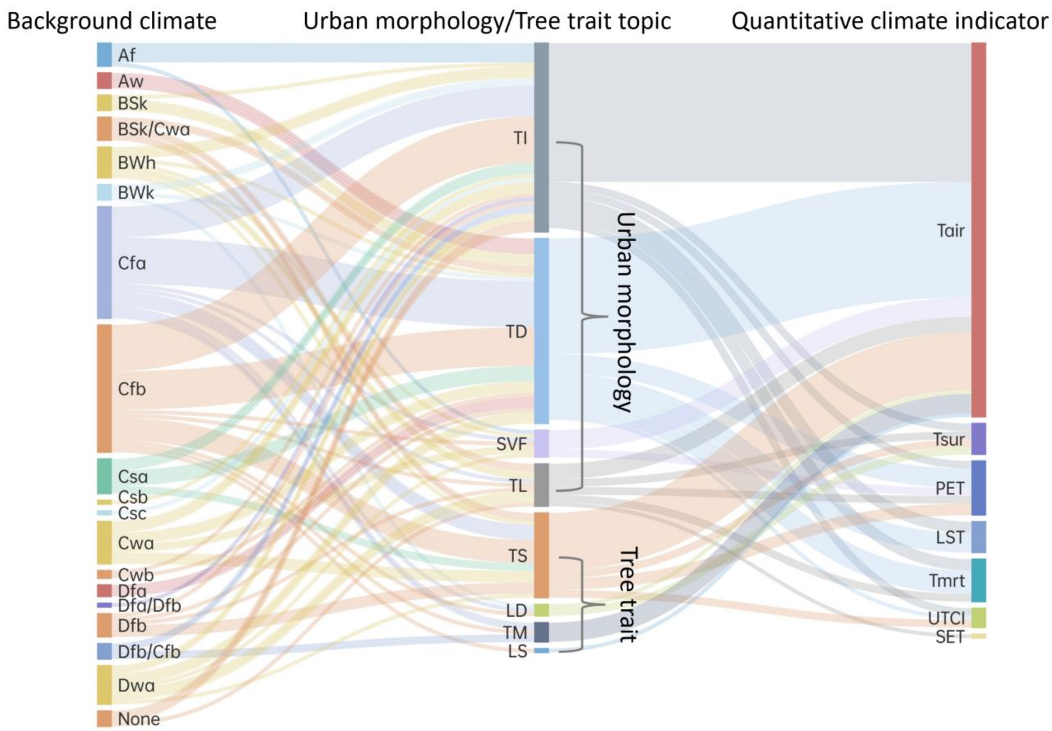

Figure 2. Interconnections of Köppen climate types and several crucial topics of urban morphology and tree traits were explored using various climate indicators. The frequently investigated topics of urban morphology and tree traits include tree implementation (TI), tree density (TD), sky view factor (SVF), tree location and arrangement (TL), and tree species (TS), LAI, and LAD (LD), tree morphology (TM), leaf morphology (LM) and leaf stomatal characteristics (LS). The frequently investigated quantitative climatic indicator include air temperature (T_{air}), surface temperature (T_{sur}), Physiological Equivalent Temperature (PET), land surface temperature (LST), mean radiant temperature (T_{mrt}), Universal Thermal Climate Index (UTCI), and Standard Effective Temperature (SET). A detailed explanation of urban morphology and tree trait factors and quantitative climatic indicators are presented in **Appendix A**.

Background climate impacts

Background climate, particularly the intensity of solar irradiance, background air temperature, and background humidity, markedly affects the magnitude of trees' cooling effects[24,44,47,48]. The cooling efficiency of vegetation is found to increase nonlinearly with an increase in air temperature and solar irradiance and a decrease in background humidity[49,50]. **Figure 3** displays a global distribution of the key findings revealed in the 131 studies, including their study sites, local climate types, and the daytime

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maximum cooling ($\Delta T_{air,max}$). The four main climates are tropical, arid, temperate, and continental. No study is located in the polar climate. A greater concentration of research is observed in temperate climate zones, especially Cfa and Cfb (according to Köppen climate classification), compared to other climate types. The reason is that Eastern Asia has been the most studied region, followed closely by Western Europe and Northern America, which are the world's largest and most densely populated areas with unique challenges and opportunities for studying urban microclimate. The tree's cooling effects are less studied in the Global South and other regions, where urban overheating issues are also urgent and severely lethal, and local climate types distinct from those most investigated regions.

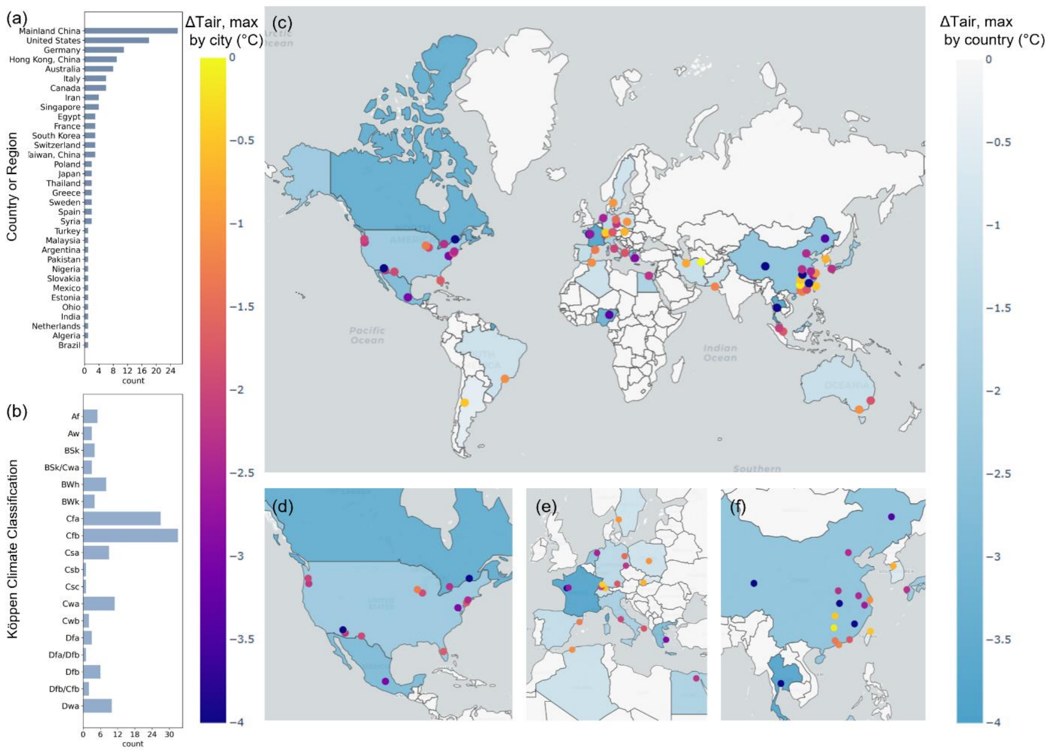

Figure 3. Geographic and climatic distributions of urban trees studies, with country- and city-level maximum reductions in air temperature highlighted in color. (a) The distribution of studies in 32 countries or regions and (b) the profile of studies in 15 climate types, according to Köppen climate classification. (c-f) The scatter plot showing the city-level averaged $\Delta T_{air,max}$ (right-axis), and the contour plot indicating the country-level averaged $\Delta T_{air,max}$ (left-axis), where (d-f) highlights the distribution of studies aggregated in the most populated areas, North America, Western Europe and Eastern Asia.

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From a global perspective, in climates with high background solar irradiance, trees can deliver substantial cooling effects through shading, reducing a large amount of solar radiation absorbed by the ground, infrastructure and surrounding surfaces. In temperate and continental climates, there are distinct seasonal variations of the tree effects with a more pronounced cooling effect during the hot summer months when peak solar irradiance reaches the surface and a reduced cooling effect during the winter when solar irradiance are lower and trees may have fewer leaves.

The cooling effects of trees increase nonlinearly, reaching peak cooling potential as the background temperature continues to rise[49]. An appropriately high temperature can enhance the transpirational cooling of urban trees by increasing the vapor pressure deficit at the stomata up to a certain level. However, when the vapor pressure surpasses a certain threshold, extreme air temperatures and water loss – usually experienced during the hottest hours of heatwaves – may trigger partial or even complete stomatal closure in plants. This stomatal closure results in a reduction of transpiration cooling[51].

In terms of the influence of background humidity levels, the cooling efficiency of urban greenery is highest in hot and dry cities where transpirational cooling is enhanced due to a high vapor pressure deficit[52]. In humid climates, however, the cooling effect may not be as pronounced, as the transpiration of trees may be less effective due to already high humidity levels. The increased humidity caused by excessively planned vegetation can exacerbate thermal discomfort issues in humid tropical cities[53]. Therefore, carefully considering these background climatic factors is crucial in designing effective strategies for using trees to mitigate the urban heat island effect.

Urban morphology impacts

Urban morphology in a broad context influences the cooling effect of urban trees through tree location and arrangement (TL), tree density (TD), tree implementation (TI), building morphology (BM), road orientation (RO), and sky view factor (SVF), plays a paramount role in determining the cooling potential offered by urban trees.

A low SVF implies that the view of the sky is obstructed by buildings, trees, or other structures, which is primarily determined by urban morphological features. This obstruction determines the amount of shortwave solar radiation blockage[54,55]. The shading, in turn, reduces the direct solar radiation reaching the ground and building surfaces during the daytime, thereby lowering surface temperatures. Conversely, a higher SVF – meaning a more open sky is visible – implies a more significant cooling potential, as trees can provide more extensive shading to the ground and building surfaces. Additionally, a higher SVF allows trees to benefit more from direct nocturnal cooling, as they can effectively emit longwave radiation during the nighttime[56].

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Effective improvement of urban morphology entails designing and managing BM, RO, TL, and TD to lower the SVF to an appropriate value effectively. A field measurement in Kuala Lumpur, Malaysia, measuring the micro-scale effects of trees on roads based on four different tree arrangements and road orientations, has proved that trees could reduce mean radiant temperature (T_{mrt}) and physiological equivalent temperature (PET) by up to 35% and 25%, respectively [57]. A denser tree arrangement leads to an improvement in the cooling benefits[58]. In Saga, Japan, a 20% increase in the density of trees resulted in a -2.27 °C reduction in air temperature at the peak temperature on a university campus[59].

Tree trait impacts

Tree traits, including tree species (TS), tree morphology (TM), LAI and LAD (LD), leaf morphology (LM), and leaf stomatal characteristics (LS), affect the cooling potential of the individual tree in complex manners. Precisely, at a smaller scale, focusing on individual plants, the species and age of a tree determine its morphology, LAI and LAD, phenology, leaf morphology, and stomatal characteristics. A proper selection of tree species can enhance the cooling benefits by maximizing shading and transpirational cooling while also improving pedestrian comfort via natural windbreaks.

Jiao et al.[60] conducted a study involving four different patches of *Ginkgo biloba* and *Populus tomentosa* trees in Beijing. Their research revealed that the optimized morphology led to a maximum transpiration rate. Moreover, taller trees offered greater benefits because the vegetation canopy, characterized by high leaf temperatures, was kept at a greater distance from the pedestrian level[25]. Furthermore, the color and texture of tree leaves can influence albedo, which impact on heat balance of trees and the surrounding area. Light-colored and glossy leaves tend to reflect more sunlight, contributing to higher albedo absorbing less heat, while darker and rougher leaves may absorb more heat.

Higher LAI and LAD values indicate denser canopies with more leaves, enhancing the interception of solar radiation[25,26]. Leaf angle distribution affects the amount of direct sunlight reaching the ground, while leaf morphology and stomatal characteristics impact transpiration rates and cooling through evapotranspiration[25]. To optimize these tree traits, urban tree species must be thoughtfully designed and selected to maximize cooling benefits and create comfortable microclimates. This involves tailoring the parameters of the aforementioned factors to the local background climate, ensuring the most effective harnessing of trees' cooling potential.

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Quantification of cooling effects in complex dimensions

Diurnal cooling effects in tropical, arid, continental, and temperate climates

Here we summarize the cooling effects of trees in terms of $\Delta T_{air,max}$ and $\Delta T_{air,mean}$ in different climates observed in 84 studies on different spatial scales (micro-scale, local scale and meso-scale) and different methods (measurement and simulation) as shown in **Figure 4**. Results in different spatial scales may exhibit disparities, as micro-scale studies are focused on individual or idealized street canyons; local scale studies investigate neighborhood areas with realistic urban morphology; while flows in the micro-scale and local scale are primarily dominated by mesoscale flows. Studies on the micro and local scales (up to 2 km) take up more than 80% of the studies, as summarized in **Appendix B**. At the micro-scale and local scale, the airflow in the street canyon plays a crucial role in facilitating ventilation, heat removal, and pollutant dispersion. Meso-scale (2 km up to 2000 km) flows are regulated by the land breeze and sea breeze circulations in coastal areas, thermally induced valley winds, and channeled flow along valleys. The meso-scale studies account for around 10% of the total reviewed studies.

In **Figure 4**, for tropical climates, observed daily maximum temperature reduction $\Delta T_{air,max}$ varies between -5 °C (cooling) and +0.8 °C (warming). On average, tropical wet climates (Aw) exhibit more significant potential benefits from the cooling of trees compared to tropical rainforest climates (Af). This is due to the higher year-round humidity levels in Af compared to Aw. The daily maximum and mean temperature reduction ($\Delta T_{air,max}$, and $\Delta T_{air,mean}$) in Aw climates are -4.19 °C and -1.82 °C respectively. In contrast, in tropical rainforest climates (Af), these values are -1.85 °C and -1.10 °C, respectively, based on micro-scale and local scale studies (see **Table 2**). Specifically, the maximum daytime cooling effects of trees can reach up to -5°C in Thailand and -3.5°C in Nigeria, both Aw climates. However, in tropical rainforest climates (Af), where humidity is higher, the cooling effect is dropped to approximately -2.00 °C.

The cooling potential of trees in arid climates is even more significant, with observed $\Delta T_{air,max}$ reaching up to -8.7 °C (cooling), as shown in **Figure 4**. The diurnal maximum and mean temperature change ($\Delta T_{air,max}$, and $\Delta T_{air,mean}$) are -3.04 °C and -1.97 °C respectively, as summarized in **Table 2**. It is worth noting that a minor warming effect can also occur during the nighttime in these arid climates.

In continental climates, the cooling potential can reach up to -5.7 °C in **Figure 4**, although nighttime warming effects are frequently reported in Dfb (humid continental) climates. After aggregating and averaging the data from the micro-scale and local scale studies, the $\Delta T_{air,max}$, $\Delta T_{air,min}$, $\Delta T_{air,mean}$ values are -2.45 °C, +0.30 °C, -1.30 °C respectively.

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These reported studies provide convincing evidence that the cooling benefits of trees during the daytime are significant in tropical, arid, and continental climates. However, minor warming effects can be observed in some cases during the nighttime in continental climates. The reduction in cooling or minor warming effects during the nighttime can be caused by stomatal closure, reduced heat removal due to aerodynamic resistance, and the trapping of longwave radiation beneath the tree canopy[20,56].

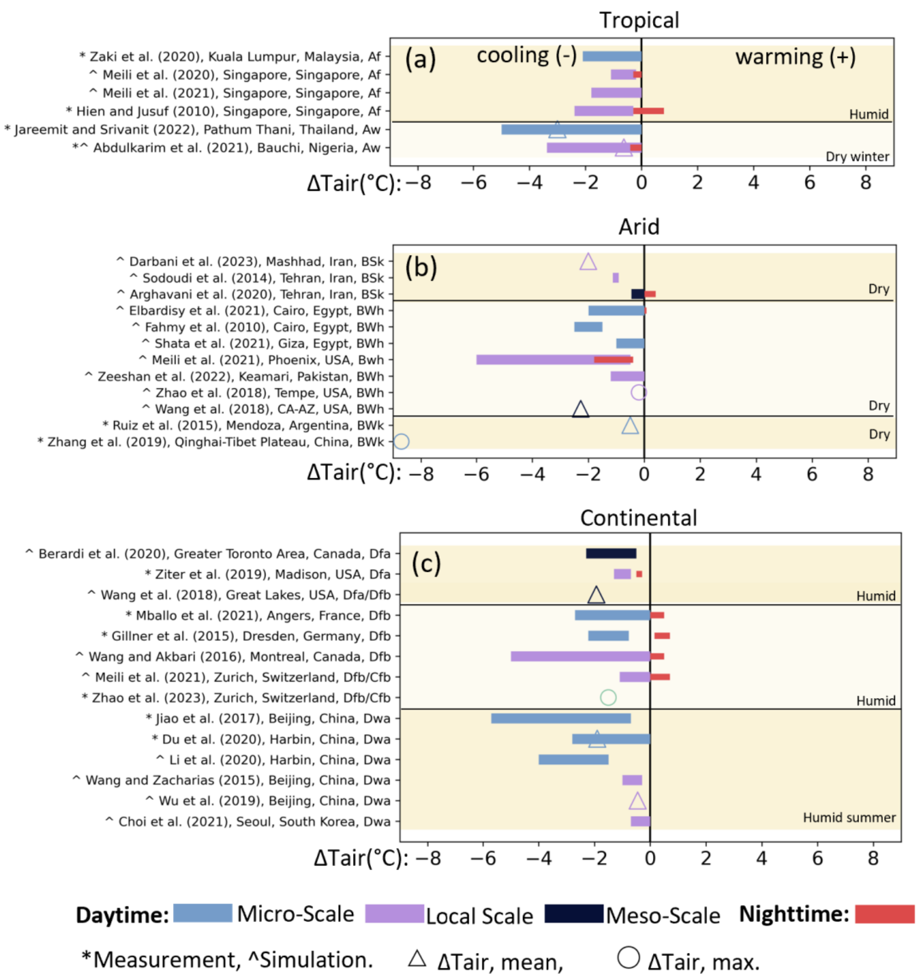

Figure 4. Diurnal variation of ΔT_{air} observed in the (a) tropical, (b) arid and (c) continental climates. The plotted bars and markers (triangle/circle) represent the cooling or warming magnitudes, and the shades in blue, purple and black colors represent the spatial scales on which the cooling or warming was observed. The nighttime tree effects are presented in red.

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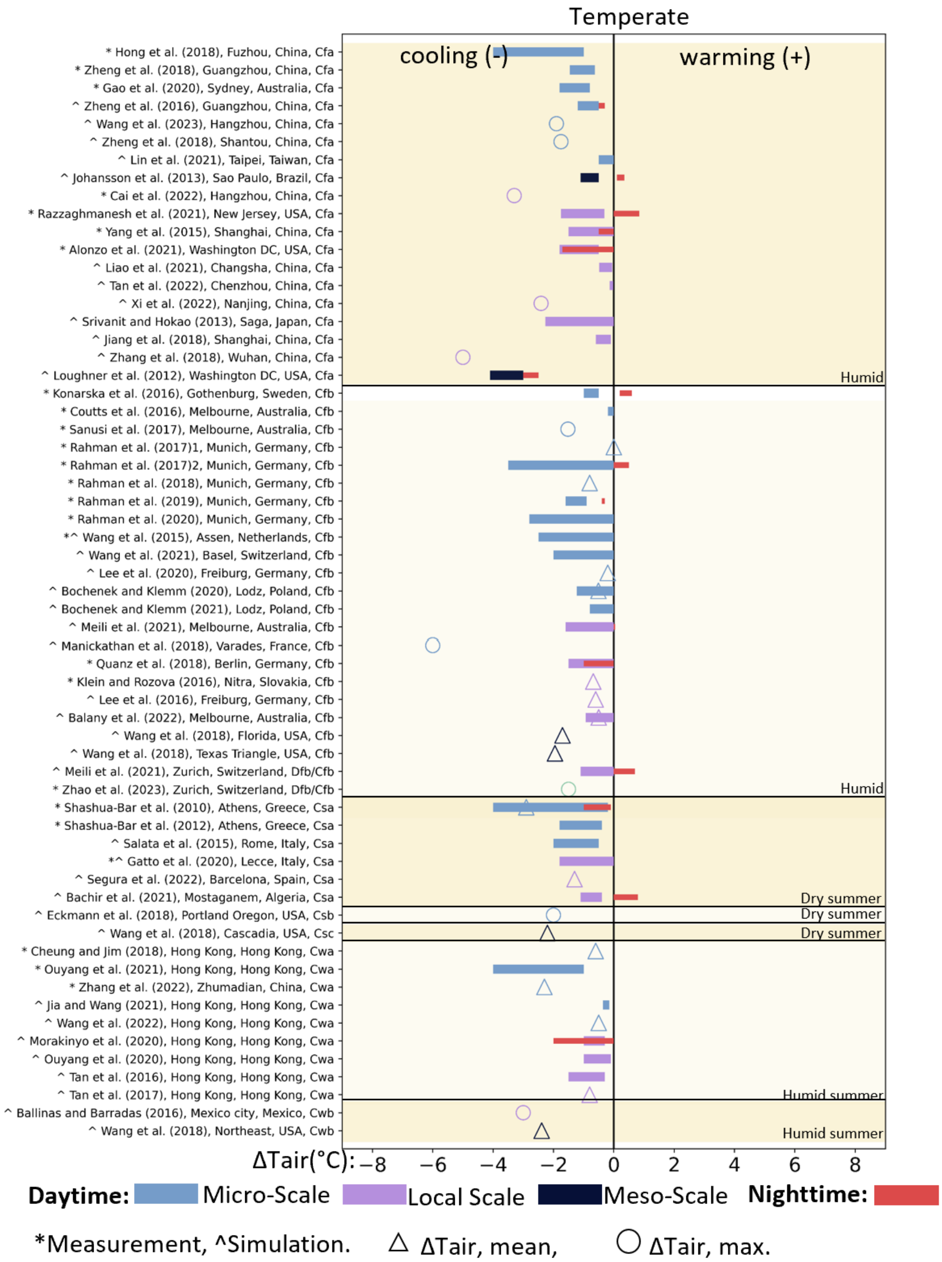

Figure 5. Diurnal variation of ΔT_{air} observed in the temperate climates. The plotted bars and markers (triangle/circle) represent the cooling or warming magnitudes, and the shades in blue, purple and black colors represent the spatial scales on which the cooling or warming was observed. The nighttime tree effects are presented in red.

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In temperate climates, the range of observed ΔT_{air} varies from -6.00 °C (cooling) to +1.50 °C (warming), as shown in **Figure 5**. On average, the maximum ($\Delta T_{air,max}$) and mean ($\Delta T_{air,mean}$) daily temperature change are -2.00 °C and -1.73 °C in dry climates, whereas in humid climates, they are -1.70 °C and -1.11 °C. The difference in $\Delta T_{air,max}$ and $\Delta T_{air,mean}$ between the temperate humid (Cfa, Cfb, Cwa, Cwb) and temperate dry (Css, Csb, Csc) climates are smaller compared to those observed in the tropical group. Specifically, in tropical climates, the $\Delta T_{air,max}$ difference between dry (Aw) and humid (Af) climates is as significant as 2.13 °C. However, in temperate climates, the $\Delta T_{air,max}$ difference between dry (Csa and Csb) and humid (Cfa, Cfb, Cwa, and Cwb) climates is negligible, at only 0.30 °C. Likewise, the difference in $\Delta T_{air,min}$ between temperate dry (Csa, Csb and Csc) and temperate humid (Cfa, Cfb, Cwa, and Cwb) climates is also minimal and negligible, at only 0.31°C.

Quantification of the cooling potential in four background climates

The comparative analysis of trees' cooling benefits in various climates (as shown in **Figure 6**) highlights their distinct contributions in tropical, arid, continental, and temperate regions. In particular, we report cooling benefits ($\Delta T_{air,max}$, $\Delta T_{air,min}$, and $\Delta T_{air,mean}$) in each city. Moreover, we compare the achievable air temperature reduction with the implementation of trees with the historically hottest month air temperature observed in recent years. Our analysis reveals that while trees in tropical and arid climates demonstrate more significant cooling effects in absolute terms, trees in continental and temperate climates offer a higher relative air temperature reduction as the local air temperature in continental and temperate climates is lower. In other words, the relative reduction of air temperature levels by trees in continental and temperate climates is more pronounced. This result can be attributed to the interplay of various climatic factors, including wind speed, humidity, and solar radiation, which influence the shading and evaporative cooling potential of trees in these regions. Therefore, future urban planning initiatives should consider both the relative and absolute impacts of trees' cooling potential concerning the local background climates. This approach will enable the implementation of targeted strategies that maximize the cooling potential of trees in respective climates.

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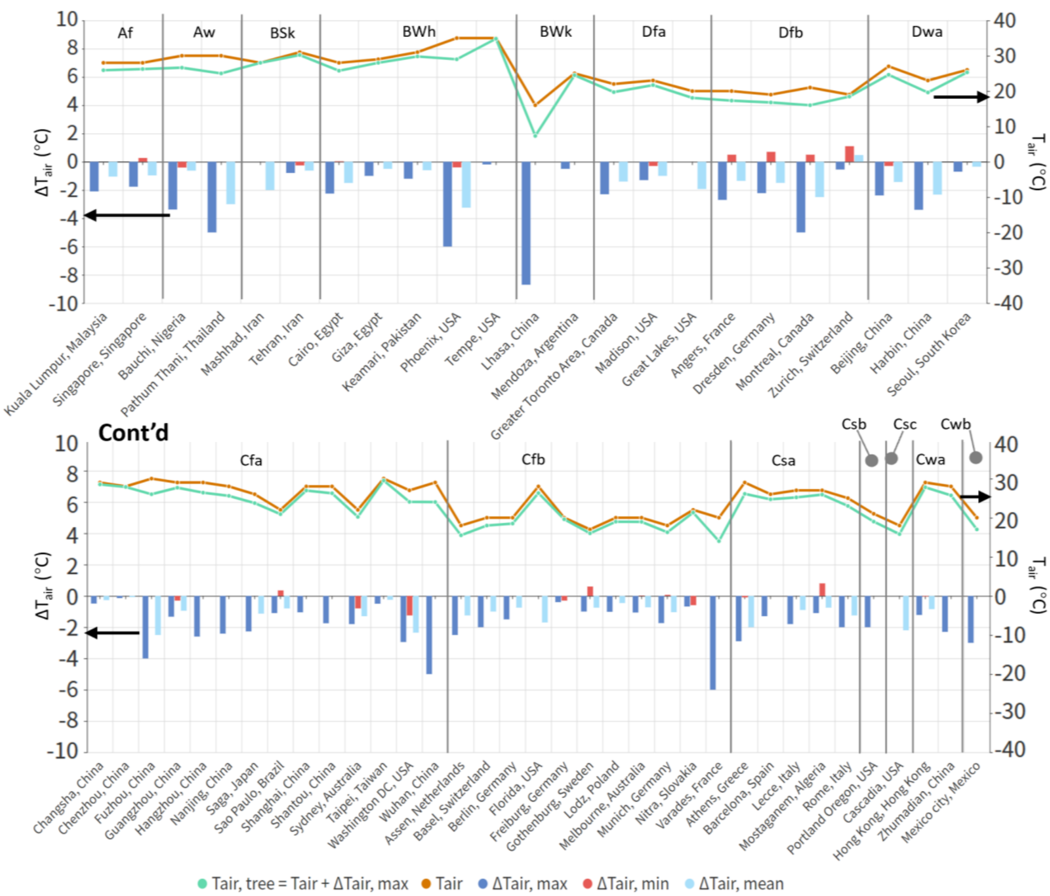

Figure 6. Achievable air temperature reductions by urban trees ($T_{air,tree}$, green line referring to the right axis) vs. the historically hottest month air temperature observed in the reviewed studies (T_{air}, orange line referring to the right axis). $T_{air,tree}$ is approximated by T_{air} and historically observed cooling capabilities of trees in respective cities ($\Delta T_{air,max}$, blue bar referring to the left axis). This figure presents a comparative analysis of the achievable air temperature reductions and the reported cooling benefits from trees ($\Delta T_{air,max}$, $\Delta T_{air,min}$, and $\Delta T_{air,mean}$, in dark blue, red, and light blue bar plot referring to the left axis) in 58 cities or regions.

The distribution of the recorded data of micro-scale and local scale studies across tropical, arid, temperate, and continental climates is presented in **Figure 7**. These results indicate significant variations in tree effects across different climates in terms of magnitude and diurnal variation. According to the 75th and 25th percentiles of the boxplot, trees exhibit distinct ranges of cooling magnitudes ($\Delta T_{air,max}$ and $\Delta T_{air,mean}$) across different climates. The local weather pattern has significant influences on the cooling magnitudes of urban trees. Large changes in temperature and rainfall can lead to extensive range of cooling magnitude. Climates

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that have distinct daily or seasonal changes in temperature and rainfall, such as arid climates and continental climates, have large ranges of cooling magnitudes. In arid climates, the cooling magnitude has an extensive range (75th and 25th percentiles are -0.60 and -5.50). The high cooling magnitudes are due to high shading potential with low latitudes and high transpirational potential with a high vapor pressure deficit[20], while low cooling magnitudes are due to its various environmental stressors such as extreme temperatures, dry air and soil, and low survival rates. On the other hand, although the temperate climate types are most studied, the distribution of the cooling magnitudes (75th and 25th percentiles) falls into a relatively focused range, between -0.80 to -2.10.

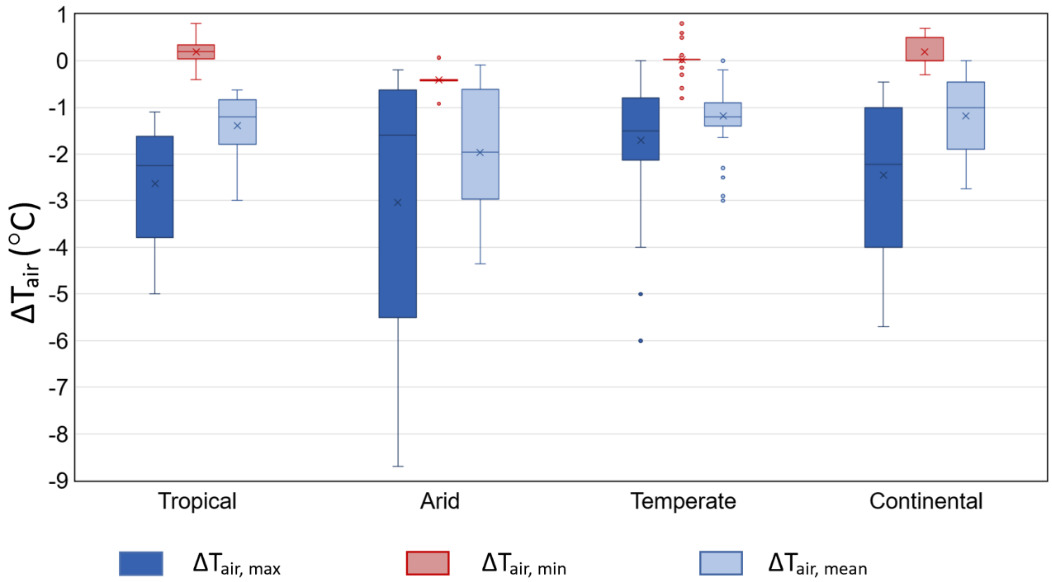

Figure 7. The distribution of the $\Delta T_{air,max}$ (dark blue), $\Delta T_{air,min}$ (red), and $\Delta T_{air,mean}$ (light blue) in tropical, arid, temperate, and continental climates was recorded from 78 micro-scale and local scale studies summarized in the **Appendix C**. In the box plot, the rectangle box covers half of the aggregated data, with the top and bottom boundaries of the box corresponding to the 75th and 25th percentiles, respectively. The lines and cross marks inside the box represent the median and mean values of the data. The whiskers extend from the box to the minimum and maximum values within 1.5 times the boundary of the box, while the dots represent the outliners.

The recorded ΔT_{air} results from micro-scale and local scale studies across tropical, arid, temperate, and continental climates are compared and summarized in **Table 2** in detail. On average (as seen in **Table 2**), the temporal mean air temperature, $T_{air,\ mean}$, shows a higher reduction (-1.39 °C) in arid climates than in

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other climates. The daily maximum reduction, $\Delta T_{air,\,max}$, also reaches its highest (-3.04 °C) in arid climates, while it is at its lowest (-1.74 °C) in temperate climates. In each climate group, we classified climate types based on their precipitation or humidity levels. Distinct patterns of daytime cooling and nighttime warming are observed in tropical climates. For instance, in the Aw climate type, $\Delta T_{air,max}$ reaches -4.19 °C, the most substantial cooling effect reported among all climate types. Conversely, in the Af climate type, which experiences higher levels of precipitation, $\Delta T_{air,min}$ is +0.80 °C, representing the most significant warming effect observed among all the climate types. Higher humidity levels may result in a low vapor pressure deficit at the stomata, which prohibits transpiration from the leaves[61].

Table 2. Summary of recorded cooling magnitudes ($\Delta T_{air,max}$, $\Delta T_{air,min}$, and $\Delta T_{air,mean}$) of 78 micro-scale and local scale studies averaged in four primary climate studies: tropical, arid, temperate, and continental. In each climate group, the cooling magnitudes are grouped based on their humidity level in the recorded period, mainly during summertime or a typical hot day.

Climate Group		**$\Delta T_{air,\,max}$ (°C)**	**$\Delta T_{air,\,min}$ (°C)**	**$\Delta T_{air,\,mean}$ (°C)**
Tropical		-2.63	+0.2	-1.39
Aw	Dry	-4.19	-0.41	-1.82
Af	Humid	-1.85	+0.80	-1.10
Arid		-3.04	-0.42	-1.97
BSk, BWk, BWh	Dry	-3.04	-0.42	-1.97
Temperate		-1.74	+0.02	-1.20
Csa, Csb	Dry	-2.00	+0.35	-1.73
Cfa, Cwa, Cfb, Cwb	Humid	-1.70	+0.04	-1.11
Continental		-2.45	+0.30	-1.30
Dfa, Dwa, Dfb	Humid	-2.45	+0.30	-1.30

Guiding principles for harnessing cooling effects of urban trees

Embedding climatic factors in urban planning

The impact of background climates on the cooling effects of urban trees is essential, as demonstrated in various studies[24,47]. By embedding climatic factors in urban planning and tailoring tree planting strategies to suit the local background climate, cities can harness and optimize the cooling potential of trees effectively, promote sustainable urban development, and enhance the overall comfort and well-being of urban residents.

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Our meta-analysis underscores this fact, revealing variations in the cooling effects of trees – specifically $\Delta T_{air,max}$, $\Delta T_{air,min}$, and $\Delta T_{air,mean}$ – across tropical, arid, temperate, and continental climates. The daytime cooling magnitude reveals that more significant cooling effects are evident in arid and tropical climates compared to temperate and continental climates in absolute terms. On the other hand, trees also exhibit pronounced cooling benefits in temperate and continental climates in relative terms, as discussed in Figure 6. Cities in arid and tropical climates are generally located at lower latitudes, subject to intense solar irradiance and high background air temperatures[20,49]. These low-latitude environmental characteristics can result in significant blockage of solar radiation and high vapor pressure deficit on tree leaves, leading to enhanced shading effects and increased transpirational cooling, respectively. Our findings align with the findings of Yang et al.[52] and Su et al.[50], demonstrating that the cooling efficiency of trees varies markedly among cities, with higher values attained in hot and dry cities. Wang et al.[62] conducted meso-scale numerical simulation modelling the near-surface temperature with/without trees across the contiguous United States. Among the six regions, i.e., CA-AZ (BWh), Florida (Cfb), Texas Triangle (Cfb), Cascadia (Csc), Northeast (Cwb), Great Lakes (Dfa/Dfb), it is found that regions in Cfb, temperate oceanic climate, have relatively lower cooling potential than in other climate types. Generally speaking, studies that locate at similar latitude and longitude values seem to have similar $\Delta T_{air,max}$ values. While in temperate and continental climates with relatively lower background temperatures, the relative air temperature reduction by urban trees is more prominent.

Our meta-analysis illustrates the significance of background humidity or precipitation on the cooling effects of trees in tropical climates [48]. Given that the vapor pressure within the stomata is near the saturation vapor pressure at the leaf temperature, the potential for transpirational cooling in hot climates is significant and, meanwhile, highly sensitive to the environmental humidity levels. Climatic factors, especially precipitation levels, are thus crucial in determining the magnitude of a tree's cooling effect.

Prior to the implementation of urban trees, it is necessary to conduct comprehensive evaluations of the potential cooling effects of trees in local climates. Moreover, given the current global warming and increasing precipitation, it is becoming increasingly imperative to investigate the cooling effects of trees in relation to both the current background climate and adaptation to future climate change-induced warming. Urban planners should consider choosing resilient species that can thrive in changing climate conditions.

Aligning tree traits with urban morphology

"Right tree, right place." The selection of appropriate tree species should be based on available space and growth requirements, aligning tree traits with urban morphology to optimize and enhance thermal comfort.

In most of the studies, cooling effects of urban trees are studies in a specific city with a specific local climate. Therefore, combining the alternations of elements of both tree traits and urban morphology to improve the overall cooling effects of urban trees (as presented in **Figure 2**) is necessary. The orientation of the street canyon, the aspect ratio, and other urban morphology features significantly influence the effects of trees [41,57,63]. For instance, in an arid climate, a substantially high $\Delta T_{air,max}$, -8.7 °C, is reported in a commercial street canyon with a H/W (aspect ratio of the street canyon) of 0.45 in Lhasa [64]. In terms of tree density and SVF, Jareemit, and Srivanit [54] studied the thermal comfort of walking through street markets in Pathum Thani, Thailand, with the intervention of roofing materials, roof shapes, and dense and sparse tree canopies. Their results indicate that the dense tree canopy offers the maximum cooling potential, accounting for 69% time of the daytime. As for tree locations and arrangements, Zhao et al.[65] discovered that in a hot arid climate, maximum cooling is achieved with two trees arranged at equal intervals, where the shading effects are optimized. The cooling effects of trees increase with canopy coverage, which in turn influences SVF[66]. Hien and Jusuf [67] explored the correlation between air temperature and SVF, revealing a slight warming effect of trees (+0.8 °C) at nighttime due to the reduction of SVF. Although a higher degree of tree canopy cover in street canyons generally results in greater cooling effects, an excessively high tree canopy cover may trap heat at the pedestrian level, especially in high-density cities[68].

Furthermore, in terms of tree trait, LAI, LAD, tree morphology, which relates to the height, size, and shape of trees and their crown, are often modeled in numerical simulations to facilitate the selection of tree species in order to achieve optimized cooling benefits. These tree trait factors determines the cooling magnitude of a single tree. While it could also influence the some key elements of urban morphology features, such as SVF under the tree crowns. Higher LAI and LAD values of trees correlate with higher cooling potential during the daytime, as the radiation blockage effects of trees can be enhanced [42,69]. The variations in air temperature and sensible heat flux, along with the enhancements in latent heat flux, exhibit a non-linear dependency on Leaf Area Index (LAI) [66]. Fahmy et al. [26] focused on the selection of tree species for cooling benefit improvement, simulating LAI values for the *Ficus elastica*, *Peltophorum pterocarpum*, and *Ficus nitida* in ENVI-met. Yang et al.[70] explored the effects of relative tree height in a symmetrical street canyon, revealing that the cooling effects increase nonlinearly with tree height. As the height of the trees in a specific layout increased, the beneficial effects began to diminish when the a threshold of SVF under tree crown reached, and ratio of tree height to building height exceeded 10:18.

However, one crucial consideration is the time trees require to reach optimal sizes for effective cooling. Specifically, trees may take decades to fully mature and deliver the full magnitude of their expected shading benefits[71,72]. Mature trees with extensive root systems have a remarkable capacity to access deeper aquifers, making them highly resilient in terms of cooling effects. By tapping into deeper water sources, they can

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maintain their lush foliage and high rates of transpiration even in times of water scarcity, offering consistent shade and evapotranspiration. This resilience makes them valuable contributors to urban and natural environments, where they play a crucial role in mitigating heat and maintaining cooling effects that benefit the local climate and ecosystem. On the other hand, young trees with smaller crown and root system may not provide expected shading, and may not even capable of surviving during hot summers. Given the urgency of global warming and its rapid consequences, this extended timeline may be impractical. Furthermore, the ongoing climate crisis may greatly reduce the future cooling effects of trees due to potential vegetation species geographic shifts, drought, and heatwaves. Therefore, when investigating urban trees, it is critical to consider enhancing cooling effects through the optimizing tree traits with the consideration of the growth time that trees required. And the selection of tree traits should consider realistic surrounding urban morphology and the local climate. Some other complementary shading and evaporation solutions, such as reflective materials, that can also provide rapid cooling results are essential in combating future detrimental urban overheating in a short term.

Avoiding cooling reduction at the hottest hours during daytime and warming effect at night

The reduced cooling effects of trees caused by extremely high vapor pressure deficit and stomatal closure at the hottest hours are reported in a few studies[20,73,74]. This phenomenon relates to the delicate relationship between tree effects and background climatic conditions. Increasing air temperature and decreasing background humidity can enhance vapor pressure deficit and promote heat dissipation through transpirational cooling. However, exceptionally high temperatures and extremely high vapor pressure deficits at the hottest hours can cause stomatal closure, which reduces transpirational cooling, particularly in tropical and arid climates. This phenomenon highly depends on the species of the plants. Some plants, for example, anisohydric species, are less influenced by the vapor pressure deficit or soil moisture[75]. Thus, tropical and arid climates should address the importance of vapor pressure deficit by selecting suitable and effective plant species to optimize transpirational cooling during the hottest hours.

The nighttime reduction of cooling, or even the occurrence of warming effects, are closely related to the stomatal closure, longwave radiation entrapment, and aerodynamic resistance. Due to stomatal closure and absence of solar radiation, transpirational cooling, and shading are reduced to minimal levels at nighttime. Improper planting of trees can increase air temperatures and thermal discomfort at the pedestrian level. An excessively high tree canopy cover results in a low SVF, which causes the trapping of longwave radiation beneath the tree foliage[76–78]. Moreover, the considerable aerodynamic resistance weakens micro-scale air ventilation, leading to worsened thermal comfort at the pedestrian level[56]. Thus, a proper urban morphology planning considering the overall layout of trees and buildings to avoid heat trapping and improve nighttime ventilation is crucial.

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Leveraging multiscale modeling to support urban planning

At the micro- and local scale, the shading, evapotranspiration, and aerodynamic influences are investigated with high resolution, using field measurement, wind tunnel measurement, and urban microclimate simulations. Simulations are performed using tools, for example, ENVI-met and OpenFOAM, for high-resolution urban microclimate modeling for a larger spatial domain of interest[79]. Urban vegetation is typically modeled as a porous medium with defined drag coefficients, thermal properties, and minimal stomatal resistance[25,80]. The Computational Fluid Dynamics (CFD) model can be solved in four coupled subdomains, consisting of radiation, air, solid, and vegetation subdomains[25]. Radiation models, such as urban canopy models, are developed to simulate radiative heat exchange between trees and surrounding urban canopies[81–84]. Krayenhoff et al. revealed significant discrepancies in the results of mitigation strategies between micro-scale models and meso-scale models, which are caused by the disparity in simplification and assumption of the boundary conditions and physical calculations[85].

At the meso-scale, the cooling effects are estimated based on the mesoscale meteorological modeling or remote sensing data. There are a few innovative studies that integrated methodologies combining different scale simulations[80,86–89]. Loughner et al. integrated modeling using Weather Research and Forecasting-Urban Canopy Models (WRF-UCM) simulations[90]. The study investigated the effects of urban trees in Baltimore, the United States, and reported that the trees led to a -4.1 °C reduction in air temperature and -15.4 °C and -8.9 °C reduction in street surface and building-wall surface temperatures, respectively. Recently, more studies have been conducted at the meso-scale. The use of remote sensing technology provides a cost-effective and non-invasive means of obtaining data on a large scale, allowing for more comprehensive assessments of the relationship between vegetation and urban thermal conditions[91]. However, it's important to note that remote sensing primarily captures data from the upper tree canopy, which may not fully represent the cooling effects provided by trees at ground level.

Limitations and future perspectives

It is important to note that the confidence of the meta-analysis results is inherently constrained by available data in the literature. As such, our aggregated results hold a higher degree of confidence for temperate climates that have been extensively studied and for which more data exist. **Figure 3** illustrates that a substantial proportion of these studies originate from Eastern Asia, Western Europe, and Northern America – regions known for their high levels of urbanization and significant research funding and institutional support. Nonetheless, in the face of rapid urbanization and burgeoning development in the Global South and other regions, it is imperative to acknowledge the importance of urban mitigation strategies across a diverse range of climates.

It is also important to underscore that our meta-analysis, based primarily on pedestrian-level air temperature changes, might not fully encapsulate the complexities of thermal comfort conditions. Thermal comfort is a multifaceted state, influenced by various environmental factors like humidity, air velocity, mean radiant temperature T_{mrt}, and personal factors such as clothing and activity level. Apart from thermal comfort properties, studies also use many other quantitative indicators, such as T_{sur}[17], sensible and latent heat fluxes[92], and radiative fluxes[93]. However, despite this potential limitation, ΔT_{air} remains the most frequently employed and well-documented climate indicator, featuring in over 70% of the studies we assessed. Furthermore, ΔT_{air} has been used to calculate vegetation cooling effectiveness (VCE), serving as an adequate means to quantify the cooling effectiveness of trees[79]. In future research, it is expected that meta-analyses will increasingly utilize more comprehensive thermal comfort metrics such as UTCI or PET for quantification purposes, given their growing popularity. We acknowledge that temperature reductions during heatwaves can vary substantially compared to typical hot days. To enhance the depth of analysis, we advise future studies to incorporate comprehensive data on meteorological conditions and detailed metadata.

Conclusion

This review and meta-analysis focus on the cooling effects of urban trees, drawing from studies that span 85 cities or regions across 15 climate types from 2010 to May 2023 based on 131 studies. Gaining a deeper understanding of the mechanisms by which trees provide shading, evoke evapotranspiration, and affect aerodynamic resistance throughout a diurnal cycle highlights the interconnection network of tree traits, surrounding urban morphology, and background climate in affecting the effects of trees. A proper selection of tree characteristics and the design of urban morphology need to be meticulously considered along with local background solar irradiance, air temperature, and humidity levels. The necessity of research on the influence of the background climate cannot be overstated. Rising background temperatures and declining humidity levels lead to a nonlinear amplification of trees' cooling effects. It is observed that hotter and drier climates exhibit greater daytime cooling magnitudes than temperate and humid climates. Drawing from the body of studies reviewed, it is apparent that the background humidity has a more pronounced impact on tropical climates than temperate climates, both in terms of daytime ($\Delta T_{air,max}$) and nighttime ($\Delta T_{air,min}$) cooling effects.

The occurrence of reduced cooling or even warming effects due to stomatal closure, longwave radiation trapping, and aerodynamic resistance is well-noted in our review. These effects remind us that there are inherent limitations and natural constraints to the cooling benefits that trees offer, and the magnitude of these effects is contingent on the background temperature and humidity of the area.

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To facilitate urban planning with optimization in trees' cooling benefits, urban planners and policymakers should tailor tree planting strategies based on our principal guidelines, with a consideration of variations in temperature, humidity, and precipitation levels across different climates and choose tree species that can thrive in changing climate conditions and are resilient to potential shifts in vegetation species geography, drought, and heatwaves. "Right tree, right place" requires tree species selection that complements the urban morphology and evaluation of the time required for trees to reach optimal sizes for adequate cooling, to balance the urgency of combating urban overheating with the extended timeline for tree maturity. Before implementing tree planting initiatives, thorough evaluations with scientific modeling at multiscale should be conducted to support urban planning decisions on local climate conditions and potential future climate change scenarios.

In summary, our detailed categorization of current research on the cooling effects of urban trees can serve as a critical resource for researchers, urban planners, and policymakers when designing effective strategies for heat mitigation.

Data availability

The detailed information of reviewed studies are recorded on an interactive map on our GitHub website.

https://97haiwei.github.io/coolingoftrees/literature_review_interactive_map.

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Appendix A. Identification, screening, eligibility, and inclusion

Following PRISMA guideline (Figure A), in identification step, a total of 3767 articles are identified through the database. After that, 1439 records remain without duplications. In the second stage of the process, we screened the titles, abstracts, and keywords of the collected articles to exclude records that were not relevant to our research question. We excluded studies that focused on building energy consumption or green parks, for example. In total, 313 research articles are excluded during the screening process.

The third stage of the process involves assessing the full-text articles for eligibility based on the type of work and research scope. We excluded review papers and non-peer-reviewed studies from our analysis. 210 research articles are viewed and assessed in full text for eligibility.

In the final stage of the process, we carefully examined the research focus and methodology of the remaining articles and reviewed their cited references.

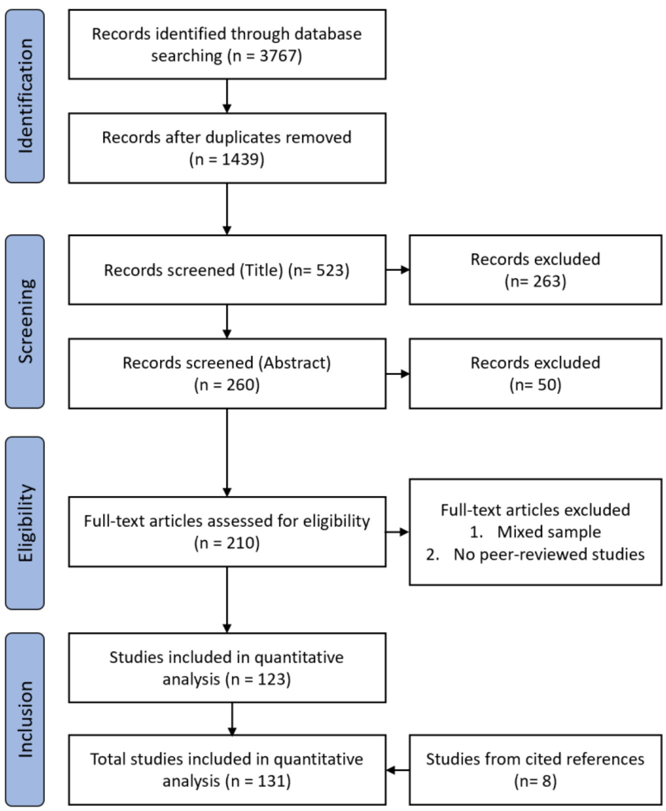

Figure A. Identification, screening, eligibility and inclusion process of papers in review.

We selected a total of 131 articles that can be tagged into our nine categories for further analysis.

(1) Year of publication;

(2) Journals;

(3) Site location;

(4) Study period;

(5) Background climate according to Köppen climate classification, as shown in **Table 1**;

(6) Methodology, including simulations, measurements, remote sensing, machine learning, and others;

(7) Spatial scales, including micro-scale with a single street canyon, local scale, and meso-scale;

(8) Topic, describing the influencing factors or optimization factors of the trees' cooling effects, including building morphology (BM), road orientation (RO), tree implementation (TI), sky view factor (SVF), tree density (TD), tree morphology (TM), tree location and arrangement (TL), tree specie (TS), LAI and LAD (LD), leaf morphology (LM), leaf stomatal characteristics (LS), soil characteristics (SC);

(9) Quantitative climate indicators, including air temperature 2 m height (T_{air}), surface temperature (T_{sur}), mean radiant temperature (T_{mrt}), Universal Thermal Climate Index (UTCI), Physiological Equivalent Temperature (PET), and Predicted Mean Vote (PMV), land surface temperature (LST) and others.

The cooling magnitude of urban trees is a complex interplay of multiple factors that need to be considered when designing and implementing urban green spaces to optimize their cooling benefits and create more sustainable and comfortable urban environments. The topics cover urban morphology influencing factors and tree traits influencing factors. Specifically, as for urban morphology, building morphology (BM) refers to the shape, height, and material composition of nearby buildings; road orientation (RO) refers to the direction of roads and streets which influence the amount of direct sunlight that reaches trees and the surrounding area; tree implementation (TI) is the general integration of trees in the urban environment; sky view factor (SVF) represents the portion of the sky visible from a particular point in space; tree density (TD) is the coverage ratio of trees relative to the open street; tree location and arrangement (TL) refers to the placement and arrangement of trees in an urban setting. In terms of the tree trait influencing factors, tree species (TS) determines the following traits of trees; tree morphology (TM) refers to the physical characteristics of trees, such as canopy shape and size, canopy volume, and tree height; LAI represents the total leaf area of trees relative to the ground area, while LAD refers to the leaf area per unit volume of the tree canopy; leaf morphology (LM) refers to the physical shape, size of leaves; leaf stomatal characteristics

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(LS) determines the transpiration characteristics of tree leaves; and related soil characteristics (SC) is the properties of the soil in which trees grow.

Appendix B. Characteristics of the reviewed literature

Our analysis is based on a thorough review of 131 scientific papers that investigate the effects of urban trees on urban heat mitigation and thermal comfort. Detailed categorization of each study is listed in **Appendix C**, describing the author (year), method, scale, climate type, city or region, country, topic, and quantitative climate indicator. **Figure B** illustrates the distribution of publication year, journal, topic, and climate indicators of the reviewed studies. It reveals a significant growth of awareness of the cooling benefits of urban trees with an increasing number of related publications in recent years. The number of articles has gradually increased since 2010, with 2021 reaching over six times the number of publications in 2010.

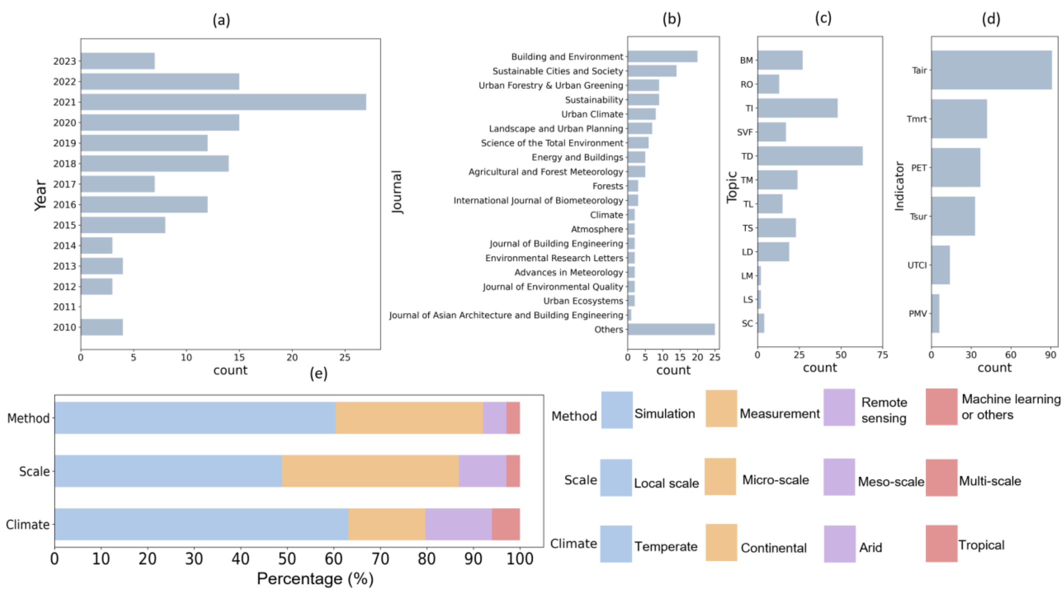

Figure B. The studies are classified by the (a) publication year, (b) publication journal, (c) topics describing the influencing factors of the trees' cooling effects and (d) quantitative climate indicator. (e) Percentage of studies classified by the methodology, spatial scale, and four main groups of Köppen climate classification of the study sites.

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In **Figure B**(c), we summarized the topics investigated in the reviewed literature that influence the trees' cooling effects. A large majority of studies focus on tree traits, including tree morphology (TM), tree species (TS), LAI and LAD (LD), leaf morphology (LM), leaf stomatal characteristics (LS), soil characteristics (SC), while studies also highlighted the importance of urban morphology, including building morphology (BM) and road orientation (RO), tree location and arrangement (TL), sky view factor (SVF), tree density (TD). The most investigated topic, tree density (TD), influences the sky view factor (SVF), which determines the amount of blockage on shortwave solar radiation[54]. To harness trees' cooling effects, an optimization of the parametric combination of the above factors with the consideration of local background climate is necessary.

Climate indicators are quantitative measures used to compare the effects of trees on thermal conditions or thermo-physiological comfort indexes. T_{air}, T_{sur}, and T_{mrt} are commonly used to reflect the objective thermal effects of trees in the thermal conditions of the environment. In terms of thermo-physiological comfort indexes, UTCI, PET, and PMV are subjective indicators that are derived from objective indicators, often considering the heat balance of a human body and taking the clothing level and physical activities into account[31]. In the context of our study, we have identified several commonly used indicators (**Figure B**d). From the statistics, T_{air} is the most frequently used indicator, which is used in 91 (over 70%) reviewed studies. Therefore, T_{air} at pedestrian level height is the most critical and intuitive climate indicator in measurements and simulations determining thermal comfort levels.

In **Figure B** (e), numerical simulation, full-scale and reduced-scale measurement, and remote sensing are the common, extensively applied methodologies for studying the thermal comfort of outdoor environments[94]. About 90% of the reviewed studies, focusing on street trees or trees adjacent to buildings, are carried out based on measurement and simulation methods. The choice of methodology depends on the research scales and available resources of the studies. Studies on the local scale and micro-scale (up to 2 km) take up more than 80% of the studies. Micro-scale studies refer to a single street canyon or idealized standard street canyon investigations, while local scale studies investigate a neighborhood area with realistic urban morphology. In street canyons, the microscale flow plays a crucial role in air ventilation, removal of heat, and dispersion of pollutants.

Appendix C. Literature in the systematic review

Table C. Classification of 131 literature according to the author (year), method, scale, climate type, city or region, country, topic and quantitative climate indicator. The topics describe the influencing factors of the trees' cooling effects, including building morphology (BM), road orientation (RO), tree implementation (TI), sky view factor (SVF), tree density (TD), tree location and arrangement (TL), tree morphology (TM),

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tree species (TS), LAI and LAD (LD), leaf morphology (LM), leaf stomatal characteristics (LS), soil characteristics (SC).

Author[ref]	Year	Method	Scale	Climate	City or Region	Country or Region	Topic	ΔTair? Or Other Climate Indicators
Zaki et al.[57]	2020	Measurement	Micro	Af	Kuala Lumpur	Malaysia	RO, TI	Yes
Meili et al.[20]	2021	Simulation	Local	Af	Singapore	Singapore	TI	Yes
Meili et al.[51]	2021	Simulation	Local	Af	Singapore	Singapore	TI	No, UTCI
Meili et al.[95]	2020	Simulation	Local	Af	Singapore	Singapore	TI	Yes
Hien and Jusuf[67]	2010	Measurement	Local	Af	Singapore	Singapore	SVF	Yes
Jareemit and Srivanit[54]	2022	Measurement	Micro	Aw	Pathum Thani	Thailand	SVF, TD	Yes
Srivanit and Jareemit[63]	2020	Simulation	Micro	Aw	Bangkok	Thailand	BM, RO, TD	No, PET
Abdulkarim et al.[96]	2020	Measurement and Simulation	Local	Aw	Bauchi	Nigeria	TD	Yes

Author[ref]	Year	Method	Scale	Climate	City or Region	Country or Region	Topic	ΔT_{air}? Or Other Climate Indicators
Darbani et al.[38]	2023	Simulation	Local	BSk	Mashhad	Iran	BM, RO, SVF, TD	Yes
Darbani et al.[97]	2021	Simulation	Local	BSk	Mashhad	Iran	BM, RO, TD	No, PET
Sodoudi et al.[98]	2014	Simulation	Local	BSk	Tehran	Iran	TI	Yes
Arghavani et al.[99]	2020	Simulation	Meso	BSk	Tehran	Iran	TD	Yes
Yang et al.[100]	2019	Simulation	Micro	BSk/Cwa	Xian	China	TD	No, PET
Yang et al.[70]	2018	Simulation	Micro	BSk/Cwa	Xian	China	TM, TL	No, PET
Zhang et al.[34]	2022	Measurement	Local	BSk/Cwa	Xian	China	TS	No, UTCI
Zhao et al.[101]	2018	Measurement	Micro	BWh	Tempe	USA	TD, TL	No, T_{sur}
Shata et al.[102]	2021	Simulation	Micro	BWh	Giza	Egypt	SVF	Yes
Elbardisy et al.[103]	2021	Simulation	Micro	BWh	Cairo	Egypt	TD	Yes
Meili et al.[20]	2021	Simulation	Local	BWh	Phoenix	USA	TI	Yes
Fahmy et al.[26]	2010	Simulation	Micro	BWh	Cairo	Egypt	TS, LD	Yes
Zeeshan et al.[104]	2022	Simulation	Local	BWh	Keamari	Pakistan	TI	Yes
Zhao et al.[65]	2018	Simulation	Local	BWh	Tempe	USA	TL	Yes

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Wang et al.[62]	2018	Simulation	Meso	BWh	CA-AZ	USA	TI	Yes
Ma et al.[64]	2019	Measurement	Micro	BWk	Lhasa	China	RO, LD	Yes
Ruiz et al.[105]	2015	Measurement	Micro	BWk	Mendoza	Argentina	BM, TD	Yes
Yahia and Johansson[32]	2014	Simulation	Micro	BWk	Damascus	Syria	BM, RO, TI	No, T_{sur}
Yahia and Johansson[106]	2013	Simulation	Micro	BWk	Damascus	Syria	BM, RO, TI	No, PET

Author[ref]	Year	Method	Scale	Climate	City or Region	Country or Region	Topic	ΔTair? Or Other Climate Indicators
Gao et al.[107]	2020	Measurement	Micro	Cfa	Sydney	Australia	TI	Yes
Chen et al.[108]	2021	Measurement	Micro	Cfa	Guangzhou	China	BM, TD, TM, TS, LD	No, PET
Chen et al.[109]	2021	Measurement	Micro	Cfa	Guangzhou	China	BM, SVF, TD, TS	No, T_{air} 0.1m
Zheng et al. [110]	2018	Measurement	Micro	Cfa	Guangzhou	China	TS	Yes
Hong et al.[111]	2018	Measurement	Micro	Cfa	Fuzhou	China	TI	Yes
Park et al.[112]	2012	Measurement	Micro	Cfa	Saitama Prefecture	Japan	TD, TL	No, T_{mrt}
Lin et al.[113]	2010	Measurement	Micro	Cfa	Taipei	Taiwan China	SVF, TD	No, PET
Wang et al.[114]	2023	Simulation	Micro	Cfa	Hangzhou	China	TD, TM	Yes
Feng et al.[42]	2021	Simulation	Micro	Cfa	Nanjing	China	TL, LD	No, T_{sur}
Lin et al.[115]	2021	Simulation	Micro	Cfa	Taipei	Taiwan China	RO, TD, LD	Yes
Zheng et al.[116]	2018	Simulation	Micro	Cfa	Shantou	China	BM, RO, TM, LD	Yes
Zheng et al.[117]	2016	Simulation	Micro	Cfa	Guangzhou	China	TS	Yes
Cai et al.[69]	2022	Measurement	Local	Cfa	Hangzhou	China	TD, TM, LD	Yes
Alonzo et al.[118]	2021	Measurement	Meso	Cfa	Washington DC	USA	TD	Yes
Razzaghmanesh et al.[119]	2021	Measurement	Local	Cfa	New Jersey	USA	RO, TD, TM	Yes
Sabrin et al.[120]	2021	Measurement	Local	Cfa	Philadelphia	USA	TI, TD	No, T_{mrt}
Yang et al.[121]	2015	Measurement	Local	Cfa	Shanghai	China	BM, TD	Yes
Chiang et al.[122]	2023	Others	Local	Cfa	Taichung City	Taiwan China	SVF	No, PET
Bartesaghi-Koc et al.[123]	2022	Remote Sensing	Local	Cfa	Sydney	Australia	SVF, TD	No, LST
Chen et al.[124]	2022	Remote Sensing	Local	Cfa	Nanjing	China	BM, TD	No, LST

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Xi et al.[125]	2022	Simulation	Local	Cfa	Nanjing	China	TI	Yes
Tan et al.[126]	2022	Simulation	Local	Cfa	Chenzhou	China	TI	Yes
Liao et al.[127]	2021	Simulation	Local	Cfa	Changsha	China	TI	Yes
Zhang et al.[37]	2018	Simulation	Local	Cfa	Wuhan	China	TD, TM, TL, LD	Yes
Jiang et al.[128]	2018	Simulation	Local	Cfa	Shanghai	China	TL	Yes
Srivanit and Hokao[59]	2013	Simulation	Local	Cfa	Saga	Japan	TD	Yes
He et al.[129]	2021	Remote Sensing	Meso	Cfa	Washington DC	USA	TD	No, LST
Loughner et al.[90]	2012	Simulation	Meso	Cfa	Washington DC	USA	BM, TI	Yes
Johansson et al.[86]	2013	Simulation	Micro and Meso	Cfa	Sao Paulo	Brazil	BM, TI	Yes

Author[ref]	Year	Method	Scale	Climate	City or Region	Country or Region	Topic	ΔTair? Or Other Climate Indicators
Rahman et al.[41]	2020	Measurement	Micro	Cfb	Munich	Germany	BM, RO, TD, TS	Yes
Massetti et al.[130]	2019	Measurement	Micro	Cfb	Florence	Italy	LD	No, T_{sur}
Rahman et al.[21]	2019	Measurement	Micro	Cfb	Munich	Germany	TS	Yes
Rahman et al.[45]	2018	Measurement	Micro	Cfb	Munich	Germany	TS, SC	Yes
Rahman et al.[46]	2017	Measurement	Micro	Cfb	Munich	Germany	TS, SC	Yes
Sanusi et al.[131]	2017	Measurement	Micro	Cfb	Melbourne	Australia	TD, TS, LM	Yes
Rahman et al.[22]	2017	Measurement	Micro	Cfb	Munich	Germany	TM, SC	Yes
Coutts et al.[58]	2016	Measurement	Micro	Cfb	Melbourne	Australia	BM, TD	Yes
Konarska et al.[132]	2016	Measurement	Micro	Cfb	Gothenburg	Sweden	BM, SVF, TD	Yes
Wang et al.[133]	2015	Measurement and Simulation	Micro	Cfb	Assen	Netherlands	TI	Yes
Lachapelle et al.[93]	2023	Simulation	Micro	Cfb	Vancouver	Canada	RO, TD, TL	No, T_{mrt}
Bochenek and Klemm[134]	2021	Simulation	Micro	Cfb	Lodz	Poland	TD	Yes
Azcarate et al.[135]	2021	Simulation	Micro	Cfb	Bilbao	Spain	SVF	No, PET
Wang et al.[66]	2021	Simulation	Micro	Cfb	Basel	Switzerland	TI	Yes
Meili et al.[20]	2021	Simulation	Local	Cfb	Melbourne	Australia	TI	Yes
Bochenek and Klemm[136]	2020	Simulation	Micro	Cfb	Lodz	Poland	TD	Yes
Lee et al.[137]	2020	Simulation	Micro	Cfb	Freiburg	Germany	BM, TD, TM	Yes

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Manickathan et al.[25]	2018	Simulation	Micro	Cfb	Parametric, Validation in Varades	Parametric, Validation in France	TD, TM, LD, LM, LS	Yes
Napoli et al.[138]	2016	Simulation	Micro	Cfb	Florence	Italy	TM, TS, LD, SC	No, T_{sur}
Quanz et al.[139]	2018	Measurement	Local	Cfb	Berlin	Germany	RO, SVF, TD	Yes
Klein and Rozova[140]	2016	Measurement	Local	Cfb	Nitra	Slovakia	BM, TI	Yes
Sung[141]	2013	Remote Sensing	Local	Cfb	Woodlands Township	USA	TI	No, LST
Briegel et al.[142]	2023	Simulation	Local	Cfb	Freiburg	Germany	TI	No, T_{mrt}
Balany et al.[143]	2022	Simulation	Local	Cfb	Melbourne	Australia	TI	Yes
Aminipouri et al.[144]	2019	Simulation	Local	Cfb	Vancouver	Canada	TD	No, T_{mrt}
Aminipouri et al.[145]	2019	Simulation	Local	Cfb	Vancouver	Canada	TD	No, T_{mrt}
Morille and Musy[146]	2017	Simulation	Local	Cfb	Lyon	France	TI	No, UTCI
Lee et al.[147]	2016	Simulation	Local	Cfb	Freiburg	Germany	TI	Yes
Lindberg et al.[148]	2016	Simulation	Local	Cfb	Goteborg	Sweden	TD	No, T_{mrt}
Ketterer and Matzarakis[149]	2015	Simulation	Local	Cfb	Stuttgart	Germany	TI	No, PET
Morabito et al.[150]	2021	Remote Sensing	Meso	Cfb	Italy	Italy	TD	No, LST
Wang et al.[62]	2018	Simulation	Meso	Cfb	Florida	USA	TI	Yes
Wang et al.[62]	2018	Simulation	Meso	Cfb	Texas Triangle	USA	TI	Yes
Meili et al.[20]	2021	Simulation	Local	Dfb/Cfb	Zurich	Switzerland	TI	Yes
Zhao et al.[56]	2023	Measurement	Local	Dfb/Cfb	Zurich	Switzerland	BM, TD, TM	Yes

Author[ref]	Year	Method	Scale	Climate	City or Region	Country or Region	Topic	ΔTair? Or Other Climate Indicators
Shashua-Bar et al.[151]	2012	Measurement	Micro	Csa	Athens	Greece	BM, TD	Yes
Shashua-Bar et al.[152]	2010	Measurement	Micro	Csa	Athens	Greece	BM, TD, TS	Yes
Gulten et al.[153]	2016	Simulation	Micro	Csa	Elazığ	Turkey	TI	No, T_{sur}
Thom et al.[154]	2016	Simulation	Micro	Csa	Adelaide	Australia	TD	No, T_{mrt}
Salata et al.[155]	2015	Simulation	Micro	Csa	Rome	Italy	TI	Yes
Gatto et al.[156]	2020	Measurement and Simulation	Local	Csa	Lecce	Italy	TD, TS	Yes
Segura et al.[157]	2022	Simulation	Local	Csa	Barcelona	Spain	SVF, TD	Yes

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Bachir et al.[158]	2021	Simulation	Local	Csa	Mostaganem	Algeria	SVF, TD	Yes
Duncan et al.[159]	2019	Remote Sensing	Meso	Csa	Perth	Australia	TI	No, LST
Eckmann et al.[160]	2018	Simulation	Micro	Csb	Portland Oregon	USA	TI	Yes
Wang et al.[62]	2018	Simulation	Meso	Csc	Cascadia	USA	TI	Yes
Zhang et al.[161]	2022	Measurement	Micro	Cwa	Zhumadian	China	TD, TM	Yes
Ouyang et al.[162]	2021	Measurement	Micro	Cwa	Hong Kong	China	TI	Yes
Cheung and Jim[163]	2018	Measurement	Micro	Cwa	Hong Kong	China	TI	Yes
Wang et al.[164]	2022	Simulation	Micro	Cwa	Hong Kong	China	TM, TL, TS, LD	Yes
Jia and Wang[165]	2021	Simulation	Micro	Cwa	Hong Kong	China	TI	Yes
Raman et al.[166]	2021	Simulation	Local	Cwa	Patna	India	BM, TD	No, T_{mrt}
Ouyang et al.[167]	2020	Simulation	Local	Cwa	Hong Kong	China	BM, TD	Yes
Tan et al.[168]	2017	Simulation	Local	Cwa	Hong Kong	China	SVF	Yes
Tan et al.[169]	2016	Simulation	Local	Cwa	Hong Kong	China	SVF	Yes
Morakinyo et al.[88]	2020	Simulation	Micro and Local	Cwa	Hong Kong	China	SVF, TD, TM, LD	Yes
Morakinyo et al.[87]	2017	Simulation	Micro and Local	Cwa	Hong Kong	China	BM, TM, TS, LD	No, PET
Yang et al.[100]	2019	Simulation	Micro	BSk/Cwa	Xian	China	TD	No, PET
Yang et al.[70]	2018	Simulation	Micro	BSk/Cwa	Xian	China	TM, TL	No, PET
Zhang et al.[34]	2022	Measurement	Local	BSk/Cwa	Xian	China	TS	No, UTCI
Ballinas and Barradas[170]	2016	Simulation	Local	Cwb	Mexico city	Mexico	TD	Yes
Wang et al.[62]	2018	Simulation	Meso	Cwb	Northeast	USA	TI	Yes

Author[ref]	Year	Method	Scale	Climate	City or Region	Country or Region	Topic	ΔTair? Or Other Climate Indicators
Ziter et al.[171]	2019	Measurement	Local	Dfa	Madison	USA	TD	Yes
Park et al.[172]	2021	Remote Sensing	Local	Dfa	Columbus	USA	TD	No, LST
Berardi et al.[89]	2020	Simulation	Micro and Meso	Dfa	Greater Toronto Area	Canada	TD	Yes
Wang et al.[62]	2018	Simulation	Meso	Dfa/Dfb	Great Lakes	USA	TI	Yes
Mballo et al.[173]	2021	Measurement	Micro	Dfb	Angers	France	TI	Yes

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Speak et al.[28]	2020	Measurement	Micro	Dfb	Bolzano	Italy	TM, TS, LD	No, T_{sur}
Gillner et al.[174]	2015	Measurement	Micro	Dfb	Dresden	Germany	TS, LD, LS	Yes
Millward et al.[175]	2014	Measurement	Micro	Dfb	Toronto	Canada	TM, TL, TS, LD	No, T_{sur}
De Luca[176]	2022	Simulation	Micro	Dfb	Tallinn	Estonia	TD	No, UTCI
Wang and Akbari[177]	2016	Simulation	Local	Dfb	Montreal	Canada	TD, TM, TS, LD	Yes
Meili et al.[20]	2021	Simulation	Local	Dfb/Cfb	Zurich	Switzerland	TI	Yes
Zhao et al.[56]	2023	Measurement	Local	Dfb/Cfb	Zurich	Switzerland	BM, TD, TM	Yes
Du et al.[178]	2020	Measurement	Micro	Dwa	Harbin	China	TI	Yes
Jiao et al.[60]	2017	Measurement	Micro	Dwa	Beijing	China	TL, TS	Yes
Li et al.[179]	2020	Simulation	Micro	Dwa	Harbin	China	SVF	Yes
Park et al.[180]	2019	Simulation	Micro	Dwa	Seoul	South Korea	TI	No, T_{mrt}
Park et al.[181]	2019	Simulation	Micro	Dwa	Seoul	South Korea	TM, TL	No, T_{mrt}
Hong and Lin[33]	2015	Simulation	Micro	Dwa	Beijing	China	BM, TL	No, SET
Zhang et al.[182]	2023	Simulation	Local	Dwa	Qingdao	China	TM, TS, LD	No, PET
Choi et al.[183]	2021	Simulation	Local	Dwa	Seoul	South Korea	TD	Yes
Wu et al.[43]	2019	Simulation	Local	Dwa	Beijing	China	BM, TD	Yes
Wang and Zacharias[184]	2015	Simulation	Local	Dwa	Beijing	China	TD, TM	Yes
Tien et al.[185]	2021	Simulation	Micro	None	None	None	TD, TL	Yes
Yang et al.[52]	2022	Remote Sensing	Meso	None	None	None	TI	Yes
Marando et al.[186]	2022	Remote Sensing	Meso	None	Europe	Europe	TI	Yes
Wang et al.[187]	2019	Remote Sensing	Meso	None	USA	USA	TI	No, LST

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