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Cooling efficacy of trees across cities is determined by background climate, urban morphology, and tree trait

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Urban planners and other stakeholders often view trees as the ultimate panacea for mitigating urban heat stress; however, their cooling efficacy varies globally and is influenced by three primary factors: tree traits, urban morphology, and climate conditions. This study analyzes 182 studies on the cooling effects of urban trees across 17 climates in 110 global cities or regions. Tree implementation reduces peak monthly temperatures to below 26 °C in 83% of the cities. Trees can lower pedestrian-level temperatures by up to 12 °C through large radiation blockage and transpiration. In tropical, temperate, and continental climates, a mixed-use of deciduous and evergreen trees in open urban morphology provides approximately 0.5 °C more cooling than a single species approach. In arid climates, evergreen species predominate and demonstrate more effective cooling within compact urban morphology. Our study offers context-specific greening guidelines for urban planners to harness tree cooling in the face of global warming.

Record-breaking global temperatures during summer have become the norm, primarily due to human-induced climate change and changes in land cover and land use[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[4–6], increased heat stress for city dwellers and urban infrastructure[7,8], and the propagation of heat-related societal inequity issues[9–12]. 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, planting and conserving existing urban trees, the most widely applied nature-based solutions (NBSs)[13], can provide substantial urban cooling through evapotranspiration and shading effects. NBSs have been acknowledged as a crucial tool for supporting environmental sustainability, enhancing environmental resilience, and mitigating the negative effects of climate change in the Intergovernmental Panel on Climate Change (IPCC) report[14]. Additionally, trees address many other challenges, as highlighted in the United Nations Sustainable Development Goals (SDGs), such as improving air and acoustic quality[15,16], supporting physical and mental health, and safeguarding biodiversity[17]. Urban forestry guidelines for green, healthy, resilient neighbourhoods are emerging, such as 3-30-300 rule introduced by Cecil Konijnendijk[18]. In light of the myriad environmental, social, and economic benefits inherent to these initiatives, multiple One Million Tree campaigns have been inaugurated in various global cities, including New York City, Paris, and Shanghai.

Background climate[19–21], urban morphology[22–24], and tree traits[25,26], among other factors, function as interconnected factors and play complex roles that ultimately determine the cooling potential harnessed from urban trees (Fig. 1). Maximizing cooling from urban trees can be achieved by selecting optimal trees and strategically placing them, which requires a comprehensive understanding of the cooling mechanisms and these interconnected factors. Trees provide urban cooling in cities via several key mechanisms. During the day, trees provide shading by blocking shortwave solar radiation; their leaves perform evapotranspiration; and the foliage also modifies the surrounding airflow aerodynamically[27–30]. At night, spacious crowns of trees can trap longwave radiation from the ground surface[25,29,31]. Owing to the diurnal cycle of solar radiation and resultant leaf energy balance[27], the cooling effects of a tree typically follow a day-night pattern. Large cooling potential primarily occurs in the afternoon with minor cooling during nighttime[32–36].

Past studies have compared various urban green strategies[37–42], with the majority comparing various green and blue infrastructures[43–46]. These greening strategies, however, involve fundamentally different cooling mechanisms, and past reviews have only provided general comparisons. Research has focused on specific climates or regions, such as temperate[46] or tropical climates[47], South Africa[37,41], and Asia[44]. A meta-analysis on tree

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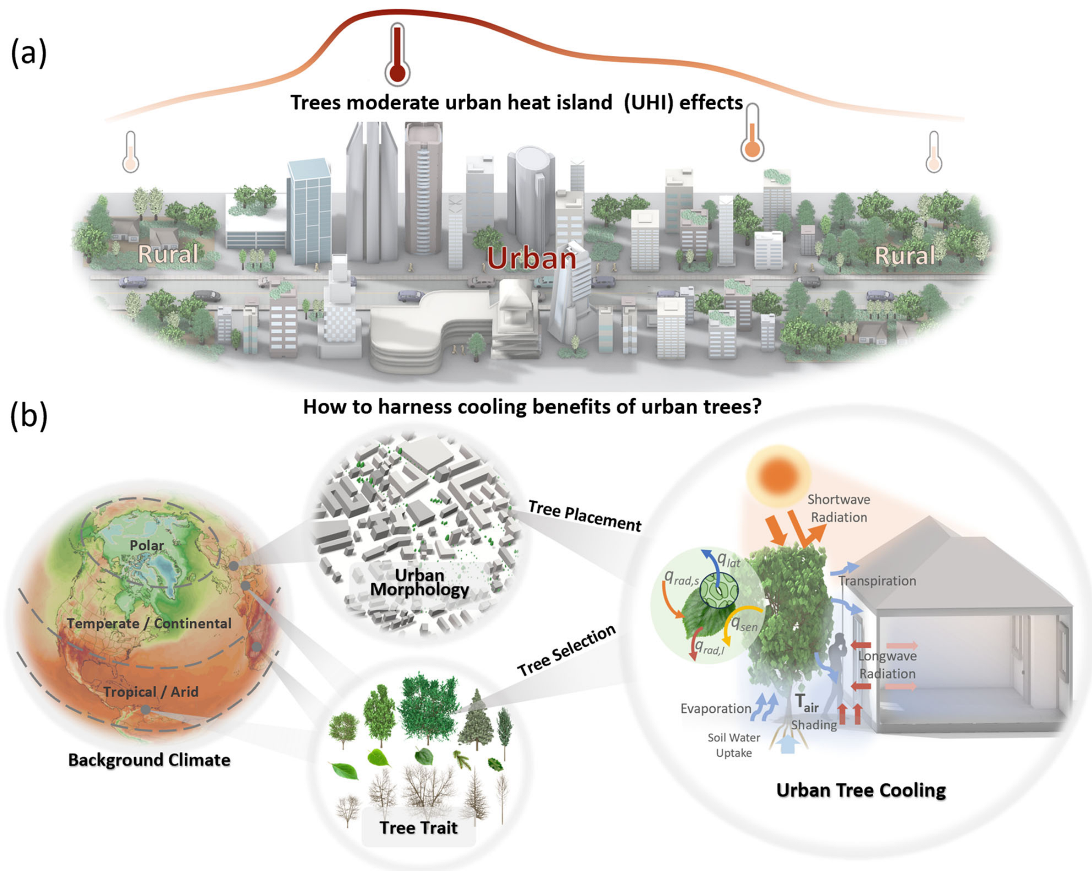

Fig. 1 | Harnessing the cooling benefits of urban trees to mitigate urban heat island effects. **a** Urban trees moderate urban warming caused by urban heat island (UHI) effects. **b** Interconnecting factors determine the cooling benefits of urban trees. Maximized cooling from urban trees is achieved by selecting the optimal trees and their placement, with an articulated understanding of the interconnecting elements: background climates, tree traits, and urban morphology. The cooling effect of urban trees is determined by a combination of mechanisms, such as shading (shortwave radiation blocking) and transpiration. On the leaf and its stomata scale, the leaf energy balance can be represented by q_{sen} (sensible heat flux) $+q_{lat}$ (latent heat flux)$=q_{rad,l}$ (net longwave radiation) $+$ $q_{rad,s}$ (net shortwave radiation).

traits has highlighted that tree canopy density influences cooling benefits, with notable variations based on climate, tree size, ground surface cover, and leaf traits[25]. A recent systematic study has pointed out a lack of quantification regarding the impact of local climate zones and land cover[39].

There remains a notable gap in understanding the cooling potential of urban trees, especially considering their unique cooling mechanisms and interactions with urban features, such as substantial contributions to shading and evapotranspiration. Although background climate[25,39,48,49], urban morphology[43,49,50], and tree traits[25,45,46,48] are frequently mentioned in numerous case studies, they are often discussed in a fragmented manner without adequate quantification or synthesis related to cooling potential. With the growing body of case studies on the cooling effects of urban trees, our research fills the gap by offering cooling efficacy estimations and guiding principles for urban tree strategies across diverse global contexts. This synthesis of factors represents a comprehensive approach to quantitatively understanding urban tree cooling efficacy, allowing for more generalizable and actionable principles that can be applied across different urban contexts worldwide.

In this study, we offer a comprehensive global assessment of tree-related cooling effects reported in 182 journal articles since 2010, with a meta-analysis of the data presented in these studies. We begin by introducing the background and motivation of the study. After that, we discuss core findings for the impacts of background climate, urban morphology, and tree traits. Subsequently, we present a meta-analysis of the reported data with quantitative analyses to show the interconnections between influencing factors. This is followed by the guiding principles section, which elaborates on the results and provides strategic, integrated recommendations for urban planners and policymakers. Finally, the article concludes by summarizing the research findings.

Factors influencing urban tree cooling efficacy

Our study is underpinned by a thorough analysis of scientific papers that investigate the effects of urban trees on pedestrian-level heat mitigation and thermal comfort improvement. Extensive research efforts and local investigations in different regions and climates have focused on individual topics relating to tree trait comparison, species selection[35,51–58], plant arrangement and the geometric features of buildings and streets[23,59–64]. Maintenance, irrigation[65] and soil characteristics (SC)[56,66] are discussed in only a limited number of studies. A few studies synthesized the impact of background climate, more specifically seasonality and latitude[67].

Among all the climate indicators used to represent cooling efficacy of trees, pedestrian-level air temperature (T_{air}) is the most frequently used indicator, appearing in over 70% of studies (Supplementary Note 1). It is selected as a major parameter for meta-analysis and for comparing the

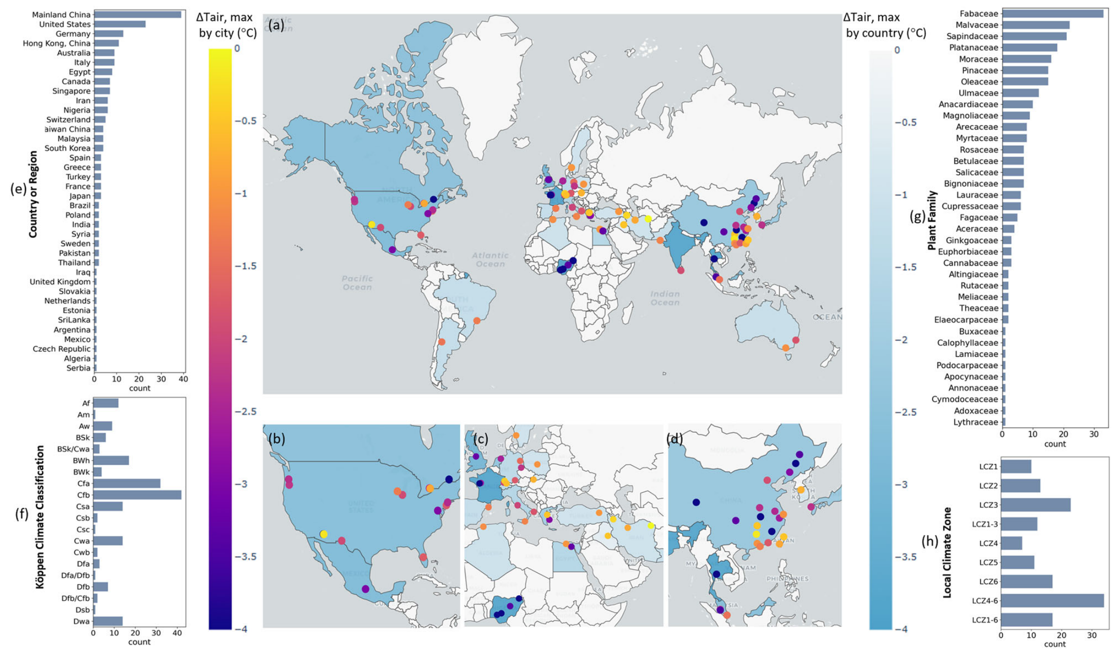

Fig. 2 | Geographic distributions of urban tree heat mitigation studies, with country- and city-level maximum reductions in air temperature highlighted. **a** Distribution of studies in 32 countries or regions, and (**b–d**) highlights the distribution of studies aggregated in the most populated areas, (**b**) North America, **c** Western Europe and Northern Africa, and (**d**) Eastern Asia. Countries are color-coded by country-level $\Delta T_{air,max}$ (left-axis), and cities are color-coded by city-level $\Delta T_{air,max}$ (right-axis). **e–h** Overview of the number of studies in (**e**) major countries, (**f**) climate types (represented by Köppen climate classification), (**g**) plant species, and (**h**) urban morphology (represented by local climate zones).

reported cooling efficacy of trees, as presented in Eq. 1.

$$\Delta T_{air} = T_{air,tree} - T_{air} \quad (1)$$

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. Among the studies that quantified ΔT_{air}, we synthesize 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.

Background climate impacts

Background climate, particularly the intensity of solar irradiance, background air temperature, and background humidity, markedly affects the efficacy of trees' cooling effects[20,65,68,69]. Figure 2 displays a global distribution of the analyzed studies, including their study sites, local climate types, and the daytime maximum cooling ($\Delta T_{air,max}$), along with the species used and local climate zone (LCZ) for these studies. The four main climates are tropical, arid, temperate, and continental. A greater number of studies have been conducted in temperate climate zones, especially Cfa and Cfb (according to Köppen climate classification)[70–73], compared to other climate types. Eastern Asia is the most studied region[74–78], followed closely by Western Europe and Northern America[79–84], the world's largest and most densely populated areas with unique challenges and opportunities for studying urban microclimate.

The cooling efficacy of trees is found to increase nonlinearly with an increase in air temperature and solar irradiance and a decrease in background humidity[85,86]. 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 in tree effects, with a more pronounced cooling effect during the hot summer months and a reduced cooling effect during the winter.

The cooling effects of trees increase nonlinearly, reaching peak cooling potential as the background temperature continues to rise[85]. 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 transpirational cooling[87].

In terms of the influence of background humidity levels, the cooling efficacy of urban trees is highest in hot and dry cities where transpirational cooling is enhanced due to a high vapour pressure deficit[88]. 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.

Urban morphology impacts

Urban morphology influences the cooling effect of urban trees mainly by building morphology, road orientation, tree location and arrangement, and tree density. Sky view factor (SVF) and LCZ have been commonly used in studies to represent urban morphology.

A low SVF, as seen in, e.g., LCZ 1-3, implies that the view of the sky is obstructed by buildings or other urban elements. This obstruction determines the amount of shading or shortwave solar radiation blockage[89,90]. Shading reduces the direct solar radiation reaching the ground and building surfaces during the daytime, thereby lowering surface temperatures. However, it can also contribute to the entrapment of hot, humid air below the tree canopy. Excessively planted trees or planted in enclosed spaces with a humid climate can result in low cooling efficacy or thermal discomfort,

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increasing PET by up to 2 °C under high humidity and stagnant air conditions[47,91–93].

Conversely, a higher SVF, as seen in, e.g., LCZ 4-6 open area, which means a more visible open sky, implies a greater tree cooling potential. Planting trees in such areas can provide more extensive shading to the ground and building surfaces. The greater spacing between buildings allows for better air circulation and longwave radiation exchanges, enhancing the cooling effects of trees[94]. Additionally, higher SVF and LCZ 4-6 open urban forms enable trees to benefit more from direct nocturnal cooling, as they can effectively emit longwave radiation during the nighttime[29].

Tree trait impacts

For the impact of tree traits, research has primarily focused on plant species[35,51–53,58,95], leaf area index (LAI), and leaf area density (LAD)[24,96,97], which affects the cooling potential of individual trees. At a smaller scale, focusing on individual plants, the species and age of a tree determine its crown and trunk morphology, LAI and LAD, phenology, leaf morphology, and stomatal characteristics. *Robinia pseudoacacia* L. (Fabaceae) and *Tilia cordata* Mill. (Malvaceae) are the most commonly used plants in the analyzed studies (Fig. 2g).

Proper selection of tree species can enhance the cooling benefits by maximizing shading and transpirational cooling while also improving pedestrian comfort via natural windbreaks. For example, Jiao et al. revealed that the optimized tree crown morphology led to a maximum transpiration rate[98]. Higher LAI and LAD values indicate denser canopies with more leaves, enhancing the interception of solar radiation[27,96]. Moreover, taller trees offered greater benefits because the tree canopy, with high leaf surface temperatures, is kept at a greater distance from the pedestrian level[27].

Leaf retention type typically indicates the characteristics of leaf and crown shape, leaf texture, and seasonal variations in leaf density. Deciduous trees, such as *Quercus robur* L., *Tilia cordata* Mill., and *Acer pseudoplatanus* L., which often have dense and wide crowns, are found to provide large shading and high transpiration rates during the daytime, especially in summer[36,46,66]. As deciduous trees shed their leaves from summer to winter, the solar radiation blockage of dense canopies can decrease from about 90% to 50%[25,46]. Evergreen or coniferous trees, such as *Pinus halepensis* Mill. and *Magnolia grandiflora* L., are found to provide year-round shading benefits, maintaining consistent cooling effects[46]. Furthermore, the color and texture of tree leaves can influence albedo, which impacts the energy balance of trees and the surrounding area. Evergreens, especially coniferous trees with higher leaf thickness and LAI, generally show higher radiation blockage effects compared to deciduous trees. At the same time, the thicker and waxy leaves of evergreen trees lead to lower stomatal opening and increased stomatal resistance, resulting in a lower transpiration rate than common deciduous species with thinner leaves[25].

Interconnections between climate, urban morphology, and tree traits

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

We synthesize the key case studies for meta-analysis in Fig. 3. The cooling effects of trees in these studies are quantitatively analyzed in terms of $\Delta T_{air,max}$ and $\Delta T_{air,mean}$ across different climates, spatial scales (micro, local, and meso), and methods (measurement and simulation). Selected factors are also summarized in Fig. 3, including leaf retention type as a tree trait and local climate zone (LCZ) as an urban morphology characteristic.

For tropical climates, observed daily maximum temperature change $\Delta T_{air,max}$ varies between −12 °C (cooling) and +0.8 °C (warming). Specifically, the maximum daytime cooling efficacy of trees can reach up to −5 °C in Thailand[89], −5.6 °C in India[99], and −12 °C in Nigeria[100], in Aw climate. However, in tropical rainforest climates (Af), where humidity is higher, the cooling effect drops to approximately a mean value of −2 °C. The cooling potential of urban trees in arid climates is also prominent, with observed $\Delta T_{air,max}$ reaching up to −9.3 °C (cooling), as shown in Fig. 3. It is worth noting that a minor warming effect (+ 0.4 °C) can occur during the nighttime in these arid climates. In continental climates, the cooling potential can reach up to −5.7 °C (Fig. 3), although nighttime warming effects are frequently reported in Dfb (humid continental) climates[101,102]. In temperate climates, the range of observed ΔT_{air} varies from −6.00 °C (cooling) to +1.50 °C (warming).

The precipitation difference among the sub-climate types affects the cooling of trees. On average, tropical wet climates (Aw) exhibit more cooling benefits from trees compared to tropical rainforest climates (Af). This is due to the higher year-round humidity levels in Af. The $\Delta T_{air,max}$ difference between dry (Aw) and humid (Af) climates is as high as 2.12 °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 0.28 °C.

Studies show that a higher diversity of plant use, particularly the mixed use of various sizes of evergreen and deciduous trees, is linked to open urban forms (LCZ 4-6), often resulting in more cooling in tropical, temperate, and continental climates. The combined use of deciduous and evergreen trees generally results in 0.5 °C higher cooling compared to studies using only deciduous or evergreen trees in these climates. In arid climates, studies with solely evergreen trees show higher tree cooling potential.

These studies provide convincing evidence that the cooling benefits of trees during the daytime are prominent in tropical, arid, and continental climates. However, the reduction in cooling or minor warming effects observed in some cases 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[29,34].

Results in different spatial scales with different methods may exhibit disparities (Fig. 3), as micro-scale studies focus on individual or idealized street canyons, while local scale studies investigate neighborhood areas with realistic urban morphology. Flows on micro- and local scales are primarily dominated by mesoscale flows[7,39]. Meso-scale (2 km up to 2000 km) flows are regulated by land and sea breeze circulations in coastal areas, thermally induced valley winds, and channeled flow along valleys[103].

Studies on the micro and local scales (up to 2 km) take up more than 80% of the studies (Supplementary Note 1). Figure 4 highlights the estimated urban tree cooling potential based on micro and local scale studies. In particular, we report cooling benefits ($\Delta T_{air,max}$, $\Delta T_{air,min}$, and $\Delta T_{air,mean}$) in each city. After the implementation of trees, in 83% of cities, the air temperature of the hottest month was reduced to below 26 °C, meeting the thermal comfort threshold[104].

When comparing absolute temperature reduction (ΔT_{air}) and relative temperature reduction ($\Delta T_{air} T_{air}^{-1}$), trees in tropical and arid climates demonstrate more cooling effects in absolute terms, while trees in continental and temperate climates offer a higher relative air temperature reduction. In other words, the proportional reduction of air temperature by trees in continental and temperate climates is more pronounced.

Quantification of tree cooling effects influenced by interconnected factors

Background climate, urban morphology, and tree traits are highly interconnected and can collectively determine urban tree cooling potentials (Fig. 5). Among the studies, urban trees in tropical climates are predominantly evergreen. In compact urban forms (LCZ1-3), all studies involve evergreen trees, while in open urban forms (LCZ4-6), 27% of studies involve evergreen trees, 57% involve deciduous trees, and 16% involve mixed species (Fig. 6). Deciduous trees in tropical and arid climates shed their leaves typically in response to dry seasons rather than cold temperatures[105]. In arid climates, evergreen trees are dominant; around 80% of studies involve evergreen trees, and 20% involve deciduous trees. In temperate and continental climates, there is a mixed use of deciduous and evergreen trees. Tree traits, whether evergreen, deciduous, or a mix of both, are linked to various types of urban morphology, showing a broad distribution across compact, open, and mixed urban forms (Fig. 5). About 25% of the articles neither report urban morphology information nor specify tree types.

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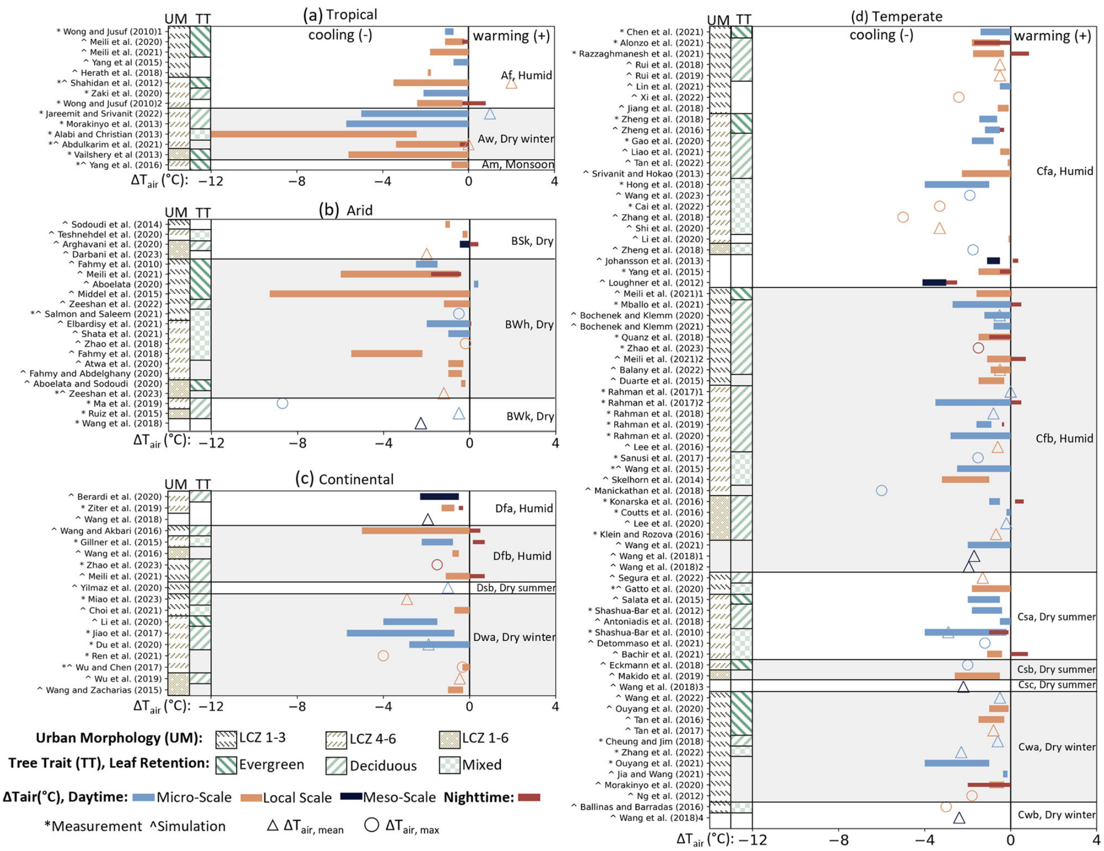

Fig. 3 | Impact of tree traits and urban morphology on diurnal variation of tree cooling efficacy ΔT_{air}, across different climate zones. Observed tree cooling efficacy ΔT_{air} in studies conducted in (**a**) tropical climates, (**b**) arid climates, (**c**) continental climates, and (**d**) temperate climates. The plotted bars and markers (triangle/circle) represent the cooling or warming efficacy, and the shades in blue, orange and black colors represent the spatial scales on which the cooling or warming was observed. The nighttime effects caused by trees are presented in red. The studies are also classified based on urban morphology (represented by LCZ), tree traits (represented by leaf retention types), scale (micro, local or mesoscale) and methodologies (measurement or simulation).

The cooling effects from trees are quantified in complex dimensions. These results indicate large variations in tree effects across different climates in terms of cooling efficacy (Fig. 6). According to the 75th and 25th percentiles of the boxplot, trees exhibit distinct ranges of cooling efficacy ($\Delta T_{air,max}$ and $\Delta T_{air,mean}$) across different climates, which are affected by local weather patterns. In arid climates, the cooling efficacy has an extensive range. The high cooling efficacy is due to high shading potential with low latitudes and high transpirational potential with a high vapour pressure deficit[34], while low cooling efficacy is due to various environmental stressors such as extreme temperatures, dry air and soil, and low tree survival rates[106].

From Fig. 5, urban tree cooling is primarily quantified by air temperature reduction (ΔT_{air}, 126 case studies). In addition, 30% of studies mainly focused on thermal comfort or thermo-physiological comfort analysis, often using indicators, such as *UTCI* (25 studies) and *PET* (48 studies). As an example, *UTCI* calculation (Eq. 2) incorporates air temperature (T_{air}), and additional meteorological variables such as relative humidity (*RH*), wind speed (V_{air}), and mean radiant temperature (T_{mrt})[107].

$$UTCI = T_{air} + f(T_{air}, T_{mrt}, V_{air}, RH) \tag{2}$$

Moreover, a few meso-scale remote sensing studies quantified cooling from trees solely based on land surface temperature (*LST*). The *UTCI* changes can reach up to −6 °C, with most changes ranging from −4 °C to −2 °C. Similarly, the *PET* changes can reach up to −8 °C, typically ranging from −8 °C to −4 °C. Studies, in general, show stronger urban tree cooling in open and low-rise areas in dry climates (Fig. 6). With open urban form LCZ 4-6, the cooling can be improved by about 0.4 °C (Table 1). This is mainly due to the availability of larger spaces that allow for greater canopies, higher biodiversity, and more extensive green coverage. On average, the temporal mean air temperature, $T_{air,mean}$, shows a higher reduction (−2.14 °C) in arid climates with LC Z4-6, while it is at its lowest (−1.03 °C) in temperate climates with LCZ 1-3 (Table 1). Case studies with mixed-use trees in open zones (LCZ4-6) yield more cooling efficacy than those in compact zones (LCZ1-3), especially in hot and warm dry climates. These results emphasize the importance of strategic urban planning that incorporates diverse tree types and extensive green spaces to maximize cooling benefits, especially in arid and high-temperature regions.

Guiding principles for harnessing cooling effects of urban trees

An integrated approach: aligning tree selection and placement with urban morphology and climate

Right tree, right place. The selection of appropriate tree species and their placement in appropriate locations should be based on the available space, growth requirements, and suitable climate conditions to maximize the cooling impact.

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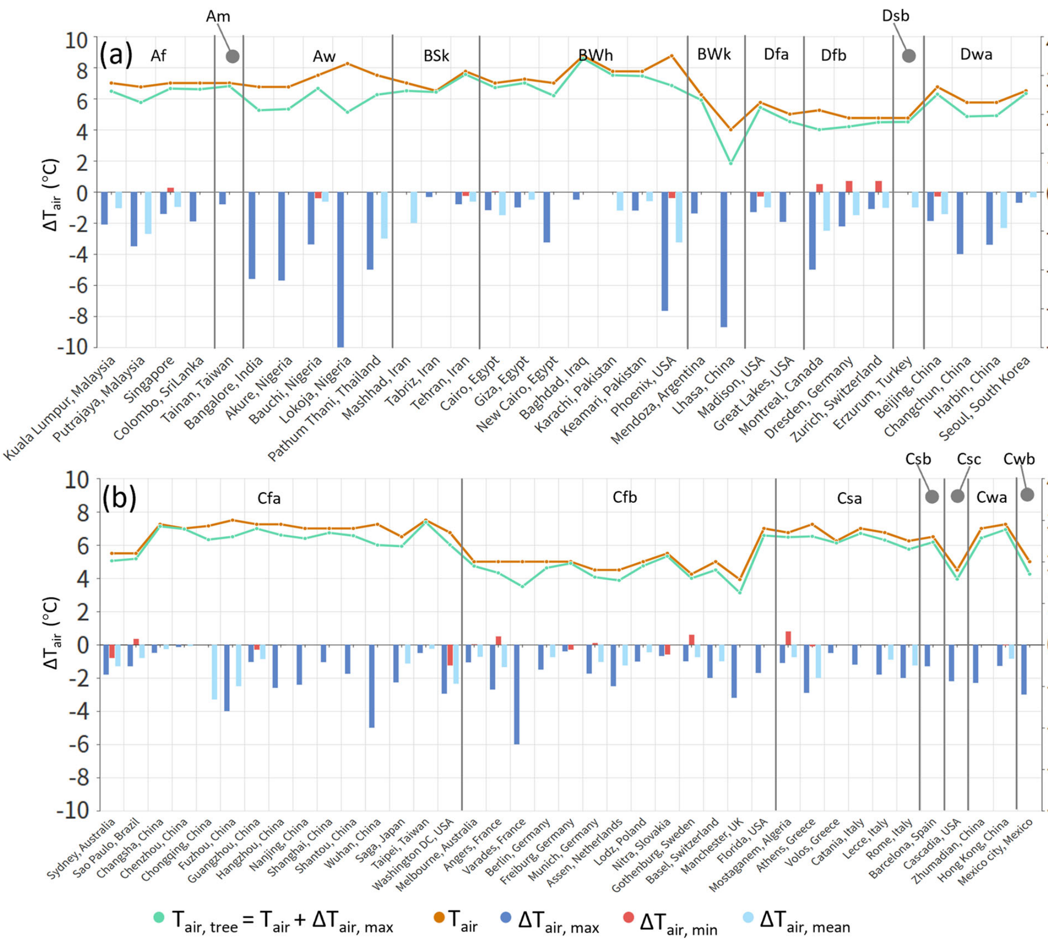

Fig. 4 | Estimated urban tree cooling potential in 71 major cities or regions. Lowest air temperature achieved with urban trees observed in the analyzed studies ($T_{air,tree}$, green line referring to the right axis) is compared with the historically hottest monthly air temperature (T_{air}, orange line referring to the right axis) in (**a**) tropical, arid and continental climates and (**b**) temperate climates. $T_{air,tree}$ represents a lower air temperature cooled by trees, which equals the sum of the historically hottest month air temperature observed (T_{air}, orange line referring to the right axis) and achievable air temperature reductions ($\Delta T_{air,max}$, blue bar referring to the left axis). Bars in dark blue, red, and light blue represent the reported cooling benefits characterized by $\Delta T_{air,max}$, $\Delta T_{air,min}$, and $\Delta T_{air,mean}$, respectively.

This approach ensures that local species can thrive and provide maximum cooling benefits. In tropical, temperate, and continental climates, studies show higher biodiversity with various heights of deciduous and evergreen trees. The mixed-use of various species can balance seasonal shading and sunlight, providing three-dimensional cooling at various heights[108,109]. From the studies, low stomatal resistance species, such as *Ulmus americana* can maximize transpiration, though these species are less common in arid climate zones[65]. In high-temperature climates, small-leaved, heat-resistant species such as *Gleditsia triacanthos* L. and *Metasequoia glyptostroboides* are recommended[25]. In dry climates, prioritizing drought-resistant evergreens that maximize shading and tree-trait-driven cooling is crucial[102]. Higher LAI and LAD values of trees correlate with higher cooling potential during the daytime, as the radiation blockage effects of trees are enhanced[24,110]. Variations in air temperature and sensible heat flux, along with the enhancements in latent heat flux, exhibit a non-linear dependency on LAI[111]. The cooling effects also increase nonlinearly with tree height in symmetrical street canyons[112].

Furthermore, the selection of species and tree placement needs to comply with the urban forms. The orientation of the street canyon, LCZ, aspect ratio, SVF, and other urban morphology features that influence the effects of trees should be carefully considered[51,60,113]. The cooling effects of trees increase with tree canopy coverage, which in turn influences SVF beneath trees[111]. Nevertheless, a denser tree arrangement can lead to improved cooling benefits[114]. For example, 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[115].

Although a higher degree of tree canopy cover in street canyons generally results in more cooling effects, excessively high tree canopy cover may trap heat at the pedestrian level, especially in LCZ 1-3 compact zones with high background temperature climates[116]. Due to stomatal closure and the absence of solar radiation, transpirational cooling and shading are minimal at nighttime. Improper extensive planting of trees can result in low SVF and weakened micro-scale air ventilation, which causes the trapping of longwave radiation beneath the tree foliage[108,117,118]. Therefore, in compact urban zones, narrow species and sparse planting strategies are recommended. Recent research has demonstrated that integrated greenery provides effective cooling effects and is of vital importance, especially in densely built urban areas[119–121]. Trees on building roofs or terraces can cool surfaces through shading and evapotranspiration, providing a 1.8–4 °C cooling effect at roofs and up to 15 °C for indoor temperature reduction[119].

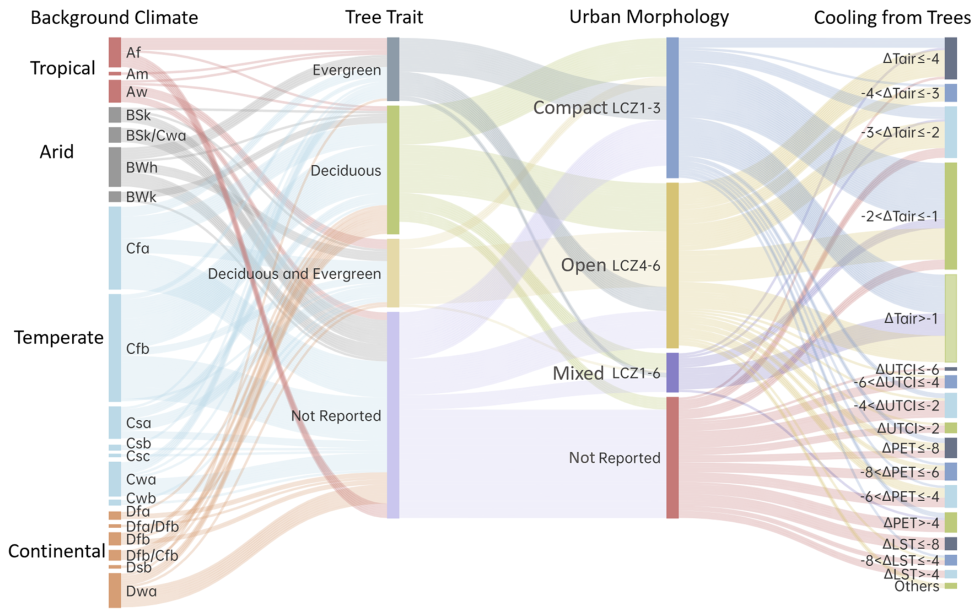

Fig. 5 | Hidden interconnections of background climate, tree traits, urban morphology characteristics, and the corresponding cooling potentials. This Sankey diagram illustrates how different background climates (tropical, arid, temperate, and continental) influence the selection of tree traits and urban morphology types. The tree traits are characterized by leaf retention types (evergreen, deciduous, deciduous and evergreen) and the urban morphology characteristics are characterized by local climate zone (LCZ, compact, open, mixed). The cooling potential is evaluated using indicators including ΔT_{air}, Universal Thermal Climate Index ($\Delta UTCI$), Physiological Equivalent Temperature (ΔPET), and Land Surface Temperature (ΔLST).

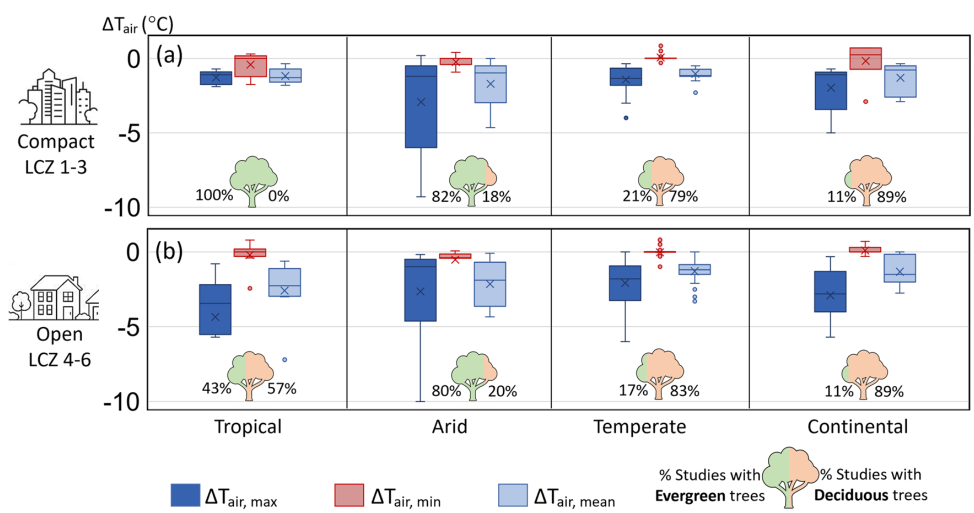

Fig. 6 | Cooling potential of urban trees evaluated across complex dimensions. The box plots synthesize cooling efficacy of trees reported in tropical, arid, temperate, and continental climates and the use of evergreen and deciduous trees for (**a**) compact urban morphology and (**b**) open urban morphology. Cooling efficacy of trees is represented by maximum ($\Delta T_{air,max}$, dark blue), minimum ($\Delta T_{air,min}$, red), and mean ($\Delta T_{air,mean}$, light blue) pedestrian-level air temperature reductions. The box plot's rectangle covers the interquartile range (25th to 75th percentiles). Inside, lines mark the median, and a cross marks the mean. Whiskers extend to the data's minimum and maximum within 1.5 times the interquartile range.

Urban trees for heat mitigation in a warming climate

As one of the key factors in the integrated approach, background climates are essential to the cooling effects of urban trees[20,68], which regulate the cooling efficacy and influence the selection of appropriate species.

Our meta-analysis illustrates the significance of background temperature and precipitation on the cooling effects of trees in tropical climates[69]. Cities in arid and tropical climates, generally located at lower latitudes, are subject to intense solar irradiance and high background air temperatures[34,85]. Our findings align with those of Yang et al.[88] and Su et al.[86], demonstrating that the cooling efficacy of trees varies markedly among cities, with higher values attained in hot and dry cities. Wang et al.[122] found that regions in temperate oceanic climate have relatively lower cooling

Table 1 | Summary of reported cooling efficacy ($\Delta T_{air,max}$, $\Delta T_{air,min}$, and $\Delta T_{air,mean}$) of studies averaged for compact (LCZ 1-3) and open (LCZ 4-6) urban forms, and in tropical, arid, temperate and continental climate groups

Tropical		$\Delta T_{air, max}$ (°C)	$\Delta T_{air, min}$ (°C)	$\Delta T_{air, mean}$ (°C)
LCZ 1-3	Compact	−1.28	−0.42	−1.18
LCZ 4-6	Open	−4.36	−0.21	−2.57
Arid		$\Delta T_{air, max}$ (°C)	$\Delta T_{air, min}$ (°C)	$\Delta T_{air, mean}$ (°C)
LCZ 1-3	Compact	−2.92	−0.25	−1.72
LCZ 4-6	Open	−2.83	−0.52	−2.14
Temperate		$\Delta T_{air, max}$ (°C)	$\Delta T_{air, min}$ (°C)	$\Delta T_{air, mean}$ (°C)
LCZ 1-3	Compact	−1.42	0.05	−1.03
LCZ 4-6	Open	−2.07	−0.04	−1.33
Continental		$\Delta T_{air, max}$ (°C)	$\Delta T_{air, min}$ (°C)	$\Delta T_{air, mean}$ (°C)
LCZ 1-3	Compact	−1.97	−0.20	−1.31
LCZ 4-6	Open	−2.91	0.14	−1.55

$\Delta T_{air,max}$, $\Delta T_{air,min}$, and $\Delta T_{air,mean}$ represent temporal maximum, minimum, and mean reductions in pedestrian air temperature by trees on summer days or typical hot days.

potential than other climate types. 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 notable and, meanwhile, highly sensitive to environmental humidity levels.

Given current global warming and increasing precipitation, it is becoming increasingly imperative to reform urban planning policies to embed climate-specific strategies and adapt to future warming. Heatwaves can strain trees by increasing their water demand while simultaneously reducing water availability due to higher evapotranspiration rates. Exceptionally high temperatures and extremely high vapor pressure deficits at the hottest hours can cause stomatal closure, which reduces transpirational cooling[34,53,123], particularly in tropical and arid climates. Studies have quantified that during heatwaves, the cooling benefits of urban trees could decrease by up to 30% due to stress-induced stomatal closure and water scarcity[38,124]. Additionally, prolonged heat stress can lead to tree mortality, further diminishing urban canopy cover and exacerbating the heat island effect. This phenomenon highly depends on tree species. Urban planners should plan for future warmer climates by choosing resilient species, such as anisohydric species, that can thrive in changing climate conditions[125].

On the other hand, trees may take decades to fully mature and deliver the full magnitude of their expected shading benefits[95,126]. Young trees with smaller crowns and root systems may not provide expected shading and may even struggle to survive during hot summers[28]. Given the urgency of global warming and its consequences, waiting for trees to mature over a long period may not be practical. Other complementary shading and evaporation solutions, such as solar shading and reflective materials, are essential in combating future detrimental urban overheating in the short term.

Several international and national tree-planting initiatives have focused on the strategic selection and placement of trees. Most of the initiatives are designed to enrich biodiversity and climate resilience. In Hong Kong, the government's Plantation Enrichment Programme has been instrumental in introducing both exotic and native tree species to improve ecological health upstream and minimize the tree risks downstream[127,128]. Projects like the European Union's 3 Billion Trees initiative encourage the creation of green corridors and urban forests[129]. Cities like Singapore have integrated tree planting into their urban planning policies, emphasizing the creation of green roofs and vertical gardens in addition to traditional tree planting. Cities in Australia have promoted local species like the Australian eucalyptus and various native trees, which are known for their ability to withstand high temperatures[130].

Limitations and future perspectives

A substantial proportion of these studies originate from Eastern Asia, Western Europe, and Northern America – regions known for their high levels of urbanization, research funding and institutional support (Fig. 2). 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 diverse climates.

It is also essential to underscore that our meta-analysis, based primarily on pedestrian-level air temperature changes, might not fully encapsulate the complexities of thermal comfort conditions. Studies also use many other quantitative indicators, such as surface temperature T_{sur}[25], sensible and latent heat fluxes, and radiative fluxes[131]. Despite this potential limitation, ΔT_{air} remains the most frequently employed and well-documented climate indicator, featuring in over 70% of the studies assessed in this meta-analysis. Furthermore, ΔT_{air} has also been used to calculate vegetation cooling effectiveness (*VCE*), serving as an adequate means to quantify the cooling effectiveness of trees[39].

Apart from cooling benefits, urban trees offer other environmental advantages that support sustainable, resilient, and livable cities. Urban trees reduce energy consumption, decreasing the need for air conditioning in adjacent buildings[132]. In tropical and arid climates, evergreen trees provide continuous cooling, reducing energy demand year-round[132,133]. In temperate and continental climates, deciduous trees are favourable for reducing energy demand because they shed leaves in winter, thus minimizing summer cooling demand and allowing for necessary winter solar access. Additionally, urban trees can enhance air quality by filtering pollutants, which reduces the urban heat accumulation from air pollution[99,134]. Future research should leverage multi-variable analysis. Urban climates are influenced by a multitude of factors, including temperature, humidity, wind speed, solar radiation, and pollution levels[48,135], which are closely linked to heat-related health issues[135–137].

Meanwhile, future research should also enhance modelling with multiscale studies, which allows for comprehensive understanding from micro- and local scale to mesoscale numerical modelling. Recently, more studies have been conducted at the meso-scale (Supplementary Note 2). Krayenhoff et al. revealed large discrepancies in the results of mitigation strategies between micro-scale models and meso-scale models[138]. A few innovative studies have integrated methodologies combining simulations across different scales[55,57,103,139,140]. Remote sensing technology provides data on a large scale[141]. Nevertheless, it is 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 or pedestrian level.

Conclusion

This meta-analysis focus on the cooling effects of urban trees, drawing from studies that span 110 cities or regions across 17 climate types based on 182 studies. Understanding the mechanisms by which trees provide shade, enhance evapotranspiration, and influence aerodynamic resistance throughout the day reveals how interconnected tree traits, urban surroundings, and the local climate work together to create cooling effects. Rising background temperatures can lead to a non-linear amplification of the cooling effects of trees. Studies with a higher diversity of plant use are often linked to mixed use of evergreen and deciduous trees, yielding higher cooling benefits for most climate types. The meta-analysis indicates that urban trees generally provide more considerable daytime cooling ($\Delta T_{air,max}$) in open areas (LCZ 4-6) and in hot and dry climates.

Our study also notes the occurrence of reduced cooling or even warming effects due to stomatal closure, longwave radiation trapping, and aerodynamic resistance. These effects remind us of the inherent limitations and natural constraints to the cooling benefits that trees offer, the magnitude of which is contingent on the background temperature and humidity of the area.

We provide evidence-based guidelines that account for variations across different climates and various local climate zones (LCZ) to maximize trees' cooling benefits. An integrated approach requires selecting tree species that complement local climate suitability, available ground spaces, and future climate conditions. Balancing the urgency of combating urban overheating with the extended timeline for tree maturity is crucial, as trees require time to reach optimal sizes for adequate cooling. We also developed an interactive database and map, documenting hundreds of case studies worldwide on tree-based urban cooling solutions. Our database enables users to estimate the cooling efficacy of strategies based on data from cities with similar climates and urban structures. In addition, this work supports broader sustainability goals, benefiting local governments and communities committed to achieving SDGs, particularly good health and well-being (SDG 3), sustainable cities (SDG 11), climate action (SDG 13), and life on land (SDG 15).

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

Methods

Scope and methodology of the systematic meta-analysis

In this study, we conducted 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[142], 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 other integrations with buildings, residential areas, campuses, and urban parks[42]. In this study, to quantitatively assess their cooling effectiveness, we exclude research that solely focuses on trees planted in urban parks or integrated at rooftops, as in such locations, the impact of tree shading and evapotranspiration on pedestrian level is trivial or difficult to isolate. Instead, we focus on trees integrated into urban settings such as streets, building perimeters, and residential areas, where the cooling of trees in the urban outdoor environment is examined. On the other hand, although urban trees have been extensively studied for their environmental, social, aesthetic, and economic benefits, our study only covers studies on the outdoor cooling effects of urban trees. We specifically focus on their heat mitigation and modification of air and surface temperatures and outdoor thermal comfort levels.

PRISMA 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 this study involves identifying relevant scientific papers published between 2010 and May 2023 in the Web of Science Core Collection and Scopus. One reason for this time frame is the dramatic increase in studies in this research field since 2010. Previous review studies in this area have typically examined fewer than 50 research articles from the year 2010 or 2015[25,38,40,43,45,48]. Additionally, given the rapid urbanization over the past decades, urban morphology and climate have altered largely, which includes a 1.2 °C increase in air temperature compared to the baseline period of 1951-1980[143]. This timeframe ensures a comparable context for the studies.

To achieve this, we used a combination of search terms, urban or similar words, combined with tree or similar words, and further combined with cooling or similar words to identify relevant studies on the cooling effects of urban trees in outdoor environments. The detailed search words and steps in selecting literature following PRISMA guidelines on identification, screening, eligibility, and inclusion are shown in Supplementary Note 3. This study includes 182 high-quality journal studies, with 126 case studies reporting quantitative changes in pedestrian-level air temperature due to urban trees. Detailed documentation is listed in Supplementary Note 5, where we describe the author (year), method, spatial scale, climate type, city or region, country, topic, and quantitative climate indicator.

Classification and climate indicators of meta-analysis

The climate classification is based on the Köppen climate classification (Supplementary Note 4), determined by the background temperature and precipitation of the local sites[144]. Tropical climate is identified with an annual average temperature of 18 °C or higher, with substantial precipitation. 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. Continental climate has at least one month with an average temperature below 0 °C.

Tree traits, by definition, refer to the characteristics of trees, such as their crown shapes, leaves, and roots. From the analyzed studies, factors that influence the cooling effects of trees include tree species (TS), tree morphology (TM), LAI and LAD (LD), leaf morphology (LM), and leaf stomatal characteristics (LS). Tree species, to a large extent, define most tree traits and are commonly reported in the analyzed studies. More than 120 plant species are reported in 57% of the analyzed studies, while over 40% do not specify the species. For classification, we employ leaf retention type as an important tree trait parameter for quantitative analysis. Leaf retention type generally reflects leaf and crown shape, leaf texture, and seasonal leaf density. Deciduous trees have broad, flat, thin, and flexible leaves that are up to 30 cm in length. Their crowns are usually rounded and spreading, with leaf density dramatically changing with the seasons. Evergreen trees have needle-like or scale-like leaves with a thick and waxy coating, usually small and narrow in size. Their crowns are typically conical (conifer), columnar, or irregular, with no seasonal changes in leaf density.

Urban morphology is the form, structure, and layout of urban areas, including the spatial patterns and physical configuration of buildings, streets, green and blue infrastructures, and open spaces. When it comes to urban tree cooling studies, topics mainly discussed include tree location and arrangement (TL), tree density (TD), tree implementation (TI), building morphology (BM), road orientation (RO), and sky view factor (SVF). To classify the urban morphological factors in the analyzed studies, we record LCZ for each case study based on the sky view factor, canyon aspect ratio, mean building height and building surface fraction parameters[145]. About 29% of studies are located in LCZ 1-3 compact areas and 38% in LCZ 4-6 open areas.

Our meta-analysis statistically combines the results of multiple grouped studies to provide a reliable estimation of the climatic effects during the daytime and nighttime. Climate indicators are used to compare thermal conditions or thermo-physiological comfort indexes to quantify the cooling effects of urban trees. Specifically, thermo-physiological comfort indices, such as the Universal Thermal Climate Index (*UTCI*), Physiological Equivalent Temperature (*PET*), Predicted Mean Vote (*PMV*)[146], Standard Effective Temperature (*SET*)[59,147] and thermal Sensation Vote (*TSV*)[148], along with quantitative climate indicators, including air temperature at 2 m height (T_{air}), surface temperature (T_{sur}), and mean radiant temperature (T_{mrt}) are employed in the analyzed studies. T_{air} is the most frequently used indicator. It is also known as near-surface air temperature at a height of 1.5-2 m, which corresponds to the level at which people engage in walking, resting, or other physical activities in urban areas[149,150]. ΔT_{air} is usually reported in the analyzed 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[58,151].

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The detailed information on the analyzed studies is recorded on an interactive map (https://www.sustainabledesign.arct.cam.ac.uk/projects/urban-green-health/trees-heat-stress). The base map for our interactive map is from the open-source dataset of Natural Earth.

Code availability

The code of meta-analysis in this study is available at GitHub repository of Cambridge Sustainable Design Group (https://github.com/sdgresearch/CoolingOfTrees).

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Author contributions

H.L. and R.B. jointly initiated the study and analyzed the data, prepared figures, and developed the manuscript. Z.Y., W.C., Ü.V.D. and C.J. provided input into preliminary discussions, editing and contributed to the study completion. All authors contributed to subsequent manuscript drafts and documents and gave final approval for publication.

Competing interests

The authors declare no competing interests.

Additional information

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