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Perspective Article

More than a canopy cover metric: Influence of canopy quality, water-use strategies and site climate on urban forest cooling potential

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HIGHLIGHTS

- Urban tree canopy cover is a promising solution for mitigating heat island.
- Data-driven guidance on tree selection and planting locations is still limited.
- Four research priorities are proposed, requiring a collaborative research effort.
- Cross-climate morphological and physiological characteristics are desired.
- Integration with atmospheric boundary layer models is suggested.

1. Introduction

The summers of 2022 and 2023 in the northern hemisphere have demonstrated that extreme heat events are an urgent, real problem that cities must address (NOAA, 2023). Among the many aspects of urban planning that relate to human thermal comfort, a significant aspect that can contribute to the solution is maintaining and increasing urban tree canopy cover (Rahman et al., 2022). Konijnendijk (2023) suggested as a global target the 3–30-300 rule, whereby residents in urban areas should be able to see at least 3 trees from home; there should be 30 % tree canopy cover in each neighbourhood, and 300 m should be the maximum distance to the nearest high-quality public green space. Similarly, the forthcoming nature restoration law by the European Union requests a minimum tree cover of 10 % and no net loss of urban tree cover by 2030 (European-Commission, 2022). These recent tree-planting targets and aspirations are preceded by other tree-planting programmes in cities such as New York City and Philadelphia (Roman et al., 2021) and Los Angeles (Pincetl, 2010). Other recent efforts include the One Million Tree programme in Singapore (Singapore Green Plan, 2030) and the Five Million Trees grant programme in Greater Sydney (NSW Government Planning and Environment, 2019). A common goal of such programmes is to increase urban forest canopy cover to mitigate urban temperatures, among many other benefits. However, until today, there is a big knowledge gap regarding data-driven evidence on tree species selection, planting locations, and long-term maintenance across different climatic conditions (Ko et al., 2015; Miller et al., 2015; Pena Acosta et al., 2021) to answer the key uncertainties regarding the extent of urban forest canopy cover.

Urban tree crowns and the urban forest canopy overall can mitigate urban temperatures through two principal mechanisms (Rahman et al., 2020a). First, by creating shade, trees reduce shortwave radiation load on walls, windows and ground surfaces through the reflection and absorption of solar radiation. Crowns that are denser will absorb a larger fraction of incoming shortwave radiation. However, differential

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phenological responses to the growing season for deciduous tree species, crown pruning, herbivory or leaf drop during droughts can reduce tree crown density. Second, trees cool themselves and the air around them through the latent energy absorbed in the phase change of water to water vapour within their leaves. This water vapour then transpires (is released) into the urban atmosphere through open leaf stomata. These stomata open during the daytime to enable the fixation of carbon dioxide through photosynthesis but can close in response to soil water stress or high evaporative demand from the atmosphere, thereby preventing or reducing transpiration cooling.

In mitigating urban temperatures, trees improve thermal comfort and may also reduce temperature extremes and premature death from heat stress (Iungman et al., 2023). The perception of thermal comfort in the urban domain is directly related to several scalars that describe climate and interact with urban structures, e.g., temperature, solar and terrestrial radiation, wind speed and humidity. All of these, in the vicinity of a person in the domain, are influenced by urban vegetation, and several models exist to integrate climate scalars into scalars that quantify human thermal comfort. For quantification of thermal stress, over 60 heat stress indices have been proposed (Rahman et al., 2022). Still, two that have achieved predominance in studies of urban greenspace are the physiologically equivalent temperature, PET and universal thermal climate index, UTCI. PET represents the equivalent air temperature at which the human body would experience the same heat stress as in the actual environment being assessed and calculated based on heat balance equations considering air temperature, humidity, wind speed, and radiation. In comparison, UTCI is a more advanced index that considers additional factors such as metabolic heat generation (from activity level) and skin wetness (due to sweating).

The potential for trees to mitigate urban heat (i.e., to cool) is thus intuitive to most through our experience of cooler temperatures under a street tree on a warm, sunny summer day. The scientific evidence for the magnitude of cooling benefit is sparse and highly variable (Rahman et al., 2020b). Using the simulation model ENVI-met (Bruse and Fleer, 1998), a modelling study for the city of Phoenix, Arizona, showed that a 10 % increase in urban tree canopy cover (e.g., from 18 % to 28 %) could reduce summer air temperatures by 1.4 °C (Middel et al., 2015). Other studies suggest that the same 10 % increase in urban tree canopy cover may only reduce summer air temperatures by 0.5 °C (Shashua-Bar et al., 2010) in Athens, Greece, by using the simulation model CTTC (Shashua-Bar and Hoffman, 2002) or as little as 0.25 °C (McDonald et al., 2020) in 97 US cities by using a remote sensing approach. Moreover, the amount of greenspaces may also exert a non-linear effect on the extent of cooling provided. For example, a study in the upper Midwest, US, showed that temperature decreased nonlinearly with increasing canopy cover, with the most significant cooling achieved when the canopy cover exceeded 40 % (Ziter et al., 2019).

A number of studies and reviews have included large numbers of species and locations and tabulated indexes of tree cooling potential (Kroeger et al., 2018; Morakinyo et al., 2018; Rahman et al., 2017b; Wang et al., 2023b), shade factors (McPherson et al., 2018), and economic benefits of cooling (McDonald et al., 2016). Currently, these tables are probably the best option for city planners and urban landscape architects to inform decisions on which species to plant. Aram et al. (2019) classified studies based on sample evaluation methods into three groups: remote sensing & satellite data that examine large urban areas (an entire city or specific regions), field observations that focus on specific parks with identifiable locations, and simulations that model different green space layouts within urban areas. However, experimental studies are needed to better understand the mechanisms involved. Scientific evidence measured at the individual tree level is greater and is provided by studies around the world. Generally, these studies indicate that the maximum air temperature cooling benefit of individual tree crowns in summer is typically <2.0 °C and in hotter and more humid cities, the expected cooling benefit may be <1.0 °C (Supplementary Table 1). On the other hand, the maximum influence on PET as a measure for human thermal comfort that integrates all relevant climatic energy flows, especially of shade, can be in the order of 10 °C (Lee and Mayer, 2018; Potchter et al., 2011). The high variability in the modelled or measured cooling benefit from urban tree crowns or urban forest canopy cover is due to many factors, such as the climate of the city, the urban landscape context surrounding the trees, and the traits of the trees measured or modelled. Larger green spaces generally provide greater cooling, but tree canopy layout and its interaction with surrounding buildings also significantly impact cooling effectiveness (Aram et al., 2019; Wang et al., 2023a). In this instances, studies with bikes or cars (Wang et al., 2023b; Ziter et al., 2019) offer broad geographic coverage, but their results require cautious interpretation for generalisability. The dynamic nature of urban environments, with numerous interacting variables, means these methodologies lack the 'all else remaining equal' conditions necessary for unequivocally discerning the impact of trees.

We conducted a systematic literature review to identify research gaps and outline future research directions pertaining to the concept of urban tree's cooling potential across the globe, especially considering the key drivers of environmental changes in cities: urbanisation and climate change. We used Scopus search between 2010–2023 (keywords: urban AND trees AND cooling AND climate AND zones, yielded 65 documents; urban AND trees AND cooling AND review, yielded 47 documents; urban AND tree AND cooling AND model, yielded 337 papers). After the initial screening, 46 relevant studies were selected for in-depth analysis. These studies encompassed (i) field investigations to elucidate the physical characteristics of trees and their cooling effects under various environmental conditions and (ii) the application of tree growth models or micro-scale models incorporating green infrastructure components (leveraging both ground-based and satellite-derived vegetation data). Despite extensive research on the cooling effect of urban green spaces across various scales and climates, the number and distribution of studies in this field should adequately reflect its significance. Much research has been concentrated in Eastern Asia, and many of them have measured the land surface temperature (LST), limiting generalizability to other regions (Aram et al., 2019). Even though, research on individual trees is growing (Rahman et al., 2020b), a comprehensive understanding on how these individual responses translate to the stand level as a whole remains elusive. Therefore, there are still significant knowledge gaps in understanding generalised relationships and empirical data for specific locations. Numerous urban regions in both the Global North and Global South are still expanding and densifying, and in the process, displacing remnant patches of urban forests or reducing available space for urban tree planting. Urban trees are not only a way to mitigate the effects of climate change; heat waves and unpredictable rainfall patterns may also have unforeseen consequences on the physiological stresses that trees experience and their ability to cool the environment. In this article, we propose four research priorities related to the ability of urban trees to improve human thermal comfort that require collective global research attention from the urban forest and urban climate research communities based on the systematic literature review (Supplementary Table 2). We need:

1. Studies that characterise canopy quality instead of only quantifying canopy cover.
2. Measurements of different heat and drought stress response strategies and their impact on cooling benefits.
3. Coordinated studies of urban tree cooling benefits across major climate zones.
4. An improved understanding of the cooling benefits provided at the urban stand level.

Addressing these four research priorities will help us more accurately predict the cooling benefit that urban tree crowns and a collective urban forest canopy can provide in different cities around the world when either healthy or when experiencing and responding to heat or drought stress. This knowledge will help tree managers at different levels (city, state or nationwide) to make sound decisions about their future urban forests from a solid scientific evidence base and using ROI ('return-on-investment') criteria. This knowledge will help people living in cities to better understand how much cooling benefit their urban trees can really provide and why various tree species may be selected and managed differently in the future.

2. Priority 1: Studies that characterise canopy quality instead of only quantifying canopy cover

Tree crown size, which determines the horizontal area of shade, is considered a key variable for addressing cooling effects by urban trees, as crown size is directly linked to both the shading and the transpiration effect. Crown dimensions are affected by species characteristics, tree development stage, inter-tree interactions and management, as well as by environmental conditions (Franceschi et al., 2022; Pretzsch et al., 2015). Thus, an integrated analysis of the crown dimensions and key metrics is needed to promote management that will provide adequate ecosystem services.

The radiation levels in the shade, which are essential for thermal comfort calculations, are quantified as fractions compared to those above the canopy (i.e. transmittance) and in energy units such as Watt m^{-2}. For comparison with cooling expressed as temperature, cooling a leaf by 1 °C reduces its thermal radiation by about 6 Watt m^{-2} (Campbell and Norman, 2000). Canopy structure parameters such as leaf area index (LAI), i.e. leaf area per unit of ground area and leaf angle distribution function (LADF) significantly impact radiation penetration in plant canopies (Fig. 1), as does canopy clumpiness, the tendency of leaves to be clustered around branches (Cohen et al., 1995), or sparsely spaced trees (Chen and Cihlar, 1995). Drought and disease can reduce LAI and cause leaves to droop or invert and thus transmit more radiation. If the radiation at mid-day is close to 1000 Watt m^{-2}, a difference of one LAI can change transmittance by more than 100 Watt m^{-2}, greatly exceeding the cooling influence of several degrees in leaf and air temperatures. The additional influence of clumping is that in a clumped canopy the effective LAI is reduced since radiation passes freely between the clumps as opposed to an even canopy; so for the same LAI transmittance is increased. Urban canopy quality assessment traditionally uses probabilistic models, but research on their inferential potential in urban contexts is lacking.

Beyond the possible influence of tree traits and vigour on tree leaf area, there are important variations between functional species traits. Fig. 2 shows considerable interspecific differences in the allometric relationship between leaf and crown projection areas for six well-analysed tree species. This evaluation was based on the leaf-area functions by Forrester et al. (2017) and the crown size functions by Pretzsch et al. (2015). Those functions were based on trees in forest and urban areas, as the database for urban trees exclusively is still rather poor. By transformation of both the allometric relationship between leaf area and stem diameter and the relationship between crown projection area and stem diameter, we arrive at the relationship between leaf area and crown projection area visualised in Fig. 2.

The figure conveys that for trees with a given crown projection area, the leaf area, all else being equal, can vary considerably depending on the tree species (Ellenberg and Leuschner, 2010; Körner, 2002; Larcher, 2003). Even the same species can have significantly different canopy quality based on the growth conditions (Rahman et al., 2011). This indicates the relevance of crown quality and shape in addition to crown quantity and size to more comprehensively assess the ecological functions and services of tree crowns in urban environments (Rötzer et al. 2021a). Future research may improve the database on crown quality in terms of leaf area density, vitality, etc., to better assess the contribution of crown to urban climate.

Based on the traditional field survey, we are limited to acquiring information on canopy quality (Hu et al., 2018). Canopy analysers, such as the LAI-2200 which use fisheye geometry sensors to quantify canopy density by assessing the extent of radiation attenuation caused by the canopy. However, this approach is time-consuming and limited in its applicability to individual or plot scales. Simultaneously, the vertical structure of the canopy (i.e., vertical foliage distribution) is challenging to obtain from conventional measurement methods (Kong et al., 2016). In this instance, LiDAR scanning could evaluate multidimensional canopy quality, facilitating the scaling from individual to regional levels (Alonzo et al., 2016). Moreover, LiDAR can also facilitate the study of a temporal series of crown characteristics related to tree health/vigour and weather conditions. Thus, there is a great need and potential for 3D modelling of tree canopies, encompassing diverse functional traits and site conditions. Analysing not only the external 3D geometry of the canopy through Terrestrial Laser Scanning (TLS) but also the internal crown structure, encompassing branch architecture, foliage distribution, and potential crown stratification, yields an even more comprehensive understanding of tree function. This precision is crucial for accurately modelling shade area and density and estimating cooling benefits.

3. Priority 2: Measurements of different stress response strategies to provide optimum cooling benefits

Increasing global temperature and reduced rainfall further stress urban trees in already challenging urban environments. This would potentially jeopardise the viability of planting certain species in some cities (McBride and Laćan, 2018). However, different tree species will respond differently to changes in climate and water availability, depending on their morphological and physiological traits, which determine their drought resistance strategy (Choat et al., 2018). Fig. 3 shows a framework of drought resistance strategies modified from Levitt

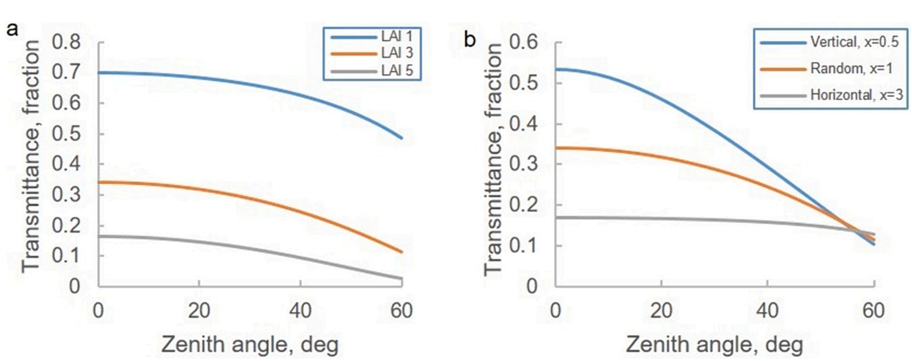

Fig. 1. Model transmittance of solar radiation in a plant canopy as a function of solar zenith angle for (a) three values of LAI and (b) three common leaf angle distribution functions (LADF), based on Campbell and Norman (2000). The parameter x is the ratio of the leaf projected areas on horizontal and vertical surfaces, and the values 0.5, 1 and 3 are equivalent to mean leaf angles of 73, 60 and 34°. Fig. 1(a) was computed using a random leaf angle distribution, x = 1 and figure (b) is for LAI = 3.

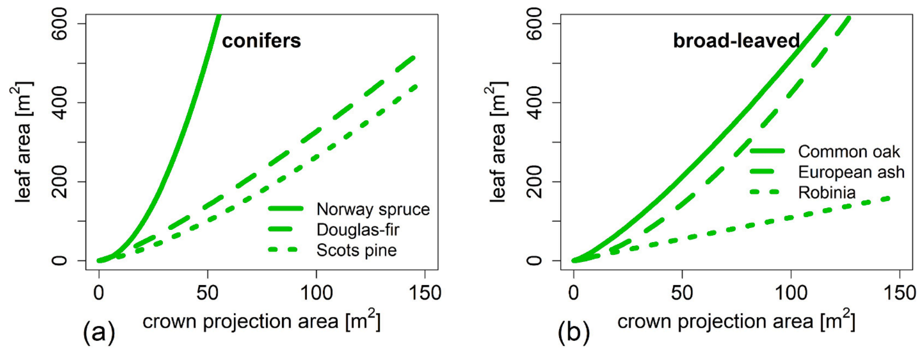

Fig. 2. Allometric relationship between leaf area and crown projection area shown for selected (a) conifers and (b) broad-leaved species. Crown quantity in terms of crown projection area can come along with very different species-specific crown quality in terms of leaf area (data from Forrester et al., 2017; Pretzsch et al., 2015). Norway spruce (Picea abies), Douglas-fir (Pseudotsuga menziesii), Scots pine (Pinus sylvestris), common oak (Quercus robur), European ash (Fraxinus excelsior), Robinia (Robinia pseudoacacia).

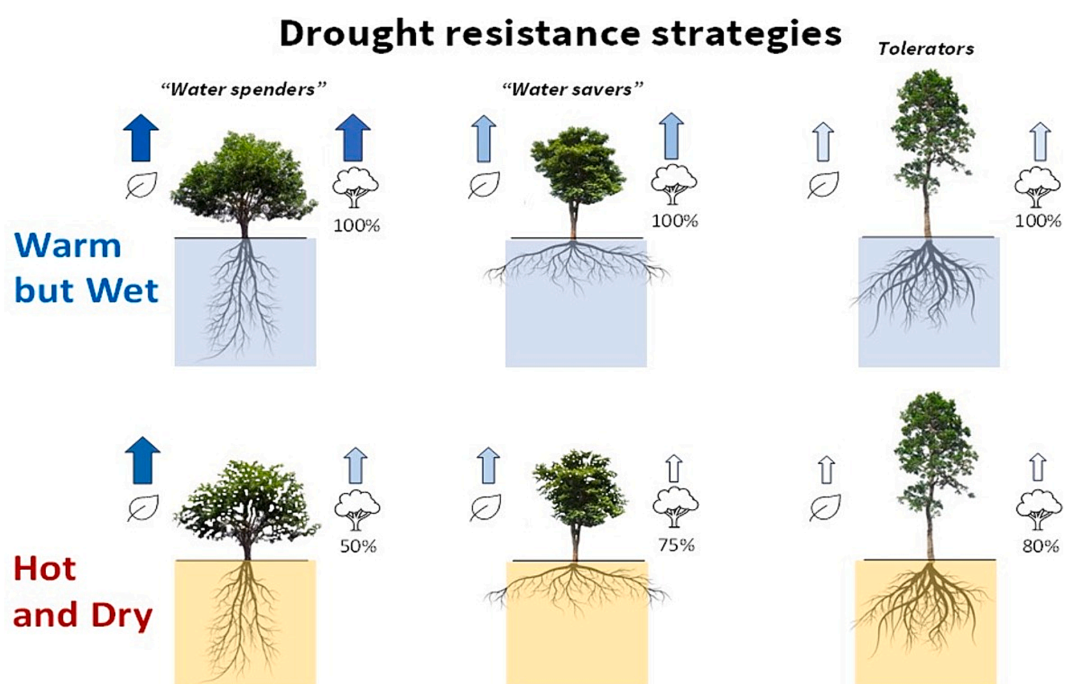

Fig. 3. Three types of tree drought resistance strategy and their impact on transpiration at the leaf level ( ), as well as canopy leaf area and, therefore, transpiration at the canopy level ( ) under warm, wet conditions (upper) and hot, dry conditions (lower). Numbers and arrow sizes are rough estimates of the influence of the two contrasting climatic conditions.

(1980). Although all tree species sit on a continuum of resistance to drought, we can consider three broad drought response strategies: water spenders, water savers (both drought avoiders) and drought tolerators.

Water spenders are phreatophytes – species that access groundwater via a deep root system. A classic example is *Eucalyptus camaldulensis*, which, even in arid riparian environments, maintains high leaf transpiration rates despite little to no stomatal regulation (Nolan et al., 2018). However, in an urban context, a deep root system will likely be constrained by the built environment (Day et al., 2010), potentially reducing transpiration-related cooling under hotter and drier conditions (Fig. 3). Water spenders may experience heavy leaf drop and thinning of canopy density in an attempt to survive periods of drought and heat in an urban environment (Sanusi and Livesley, 2020). Without active or passive irrigation using runoff from impervious surfaces (Thom et al., 2020), water spenders may not maintain good canopy quality through an entire summer and, as a result, may cool less than expected through both transpiration and shade.

Water savers avoid drought by closing their stomata or dropping leaves to reduce transpiration and maintain a higher leaf water status. These tree species have classically been described as *isohydric* (Berger-Landefeldt, 1936). The ability to better control stomata in response to stress (Klein, 2014) means that isohydric-behaving species can maintain higher water status during drought and recover rapidly when water availability improves (Hanley et al., 2023; Preisler et al., 2021). One common example would be *Robinia pseudoacacia*. Although described as water savers, some isohydric species can transpire large volumes of water when soil moisture is available (Thom et al., 2022). But, when we want transpiration cooling most (hot-dry summer days), these trees are likely to close their stomata during the middle of the day, restricting benefits to shade-related cooling. While, isohydric species have been observed to open stomata when exposed to a heatwave during periods of drought, potentially to avoid damaging leaf temperatures (Marchin et al., 2022).

Drought tolerators, classically described as *anisohydric* (Berger-

Landefeldt, 1936), typically have narrow xylem vessels with thick cell walls that can withstand high tension and, as such, rely less on stomatal control survive periods of low soil water availability (Tardieu and Simonneau, 1998). One example of a commonly planted urban tree is *Platanus* × *hispanica*. However, drought tolerance often comes at the expense of reduced hydraulic efficiency (water use) and, therefore, lower leaf transpiration rates (Pfautsch et al., 2016). Tree species that tolerate drought may also possess other traits such as i) tight stomatal control, ii) osmotic adjustment of turgor and iii) leaf drop to minimise water loss (Pritzkow et al., 2020). Which traits respond and to what extent is hard to predict and will likely also be influenced by the climate that species originated in. In addition, it is important to emphasise that stem elongation and leaf growth in all cases are sensitive to water limitation and stress, but quantification of the extent of this response awaits further research.

Based on five leaf-level traits (leaf mass per area, leaf thickness, unit leaf area, leaf dry matter content and leaf water potential at turgor loss point), Tabassum et al. (2021) distinguished between three groups of drought strategies: dehydration avoiders, dehydration tolerators and intermediate. In relation to our proposal, dehydration avoiders can be compared with water spenders, dehydration tolerators with drought tolerators and intermediate with water savers. However, Klein (2014) argued that tree species exist somewhere along a continuum between isohydric and anisohydric and currently, the degree of stomatal control is considered to be related to the vulnerability (or safety) of the hydraulic xylem system (Brodribb et al., 2020). Species from more humid environments are likely to be less drought tolerant and have larger xylem vessels with high hydraulic efficiency and, therefore, higher transpiration rates (Pfautsch et al., 2016) but may drop leaves in a survival response to dry conditions. As such, less drought-tolerant trees can provide good transpiration and shade cooling when unstressed but, under drought, can often greatly reduce both transpiration and shade cooling benefits. In contrast, species from arid environments are likely to be more drought tolerant and have smaller xylem vessels less prone to failure but also a low leaf area (canopy density) such that their cooling benefits under wet soil conditions are small and will decrease further under dry soil conditions. Highly drought-tolerant tree species (anisohydric) tend to be more conservative with water, exhibit slower growth rates, lower leaf area, thicker, smaller leaves, and invest more in root biomass for water capture or storage (Oliveira et al., 2021). And yet, some drought-tolerant anisohydric tree species can also support high transpiration rates under well-watered conditions (Thom et al., 2022). In addition, within the humid tropics, transpiration rates of trees can also differ, for instance, among species from seasonally dry forests and aseasonal evergreen forests (Tan et al., 2020). This reflects the complexity of transpiration regulation under the influence of genetically determined plant traits and environment.

It is important to consider a range of factors when assessing or predicting the transpiration and shade cooling of trees planted into urban landscapes. The amount of transpiration will depend partly on their climate of origin and partly on their suite of functional traits and drought response strategies. The amount of water transpired will also always depend on the ability of that tree to support and maintain leaf area. The total canopy leaf area can and will change over time, either seasonally or between wet versus hot-dry years. Abscission of leaves is a very effective way for trees to reduce their water requirements quickly. Consequently, more experimental or field-based studies are needed to describe the transpiration of trees in the urban environment in longitudinal studies to predict and model their cooling effectiveness. A coordinated study across cities in contrasting climate zones with trees of contrasting morphological and water use strategies within matched field sites and locally adapted Local Climate Zones (LCZ) is absolutely necessary (Stewart and Oke, 2012). This method can capture the variation in microclimates by typifying neighbourhoods ($\geq$1 km^2) in cities and thus can overcome spatial coverage limitations typical for single-city assessments. While in a cross-city study, it is essential to carefully address potential confounding variables, including environmental factors (climate, topography, and land cover), socio-economic factors (population density and demographics, urban infrastructure), and study design factors (data collection method, timing of data collection).

4. Priority 3: Coordinated studies of urban tree cooling benefits across major climate zones

Cooling from urban trees in terms of surface temperature reduction (e.g. review paper Rahman et al. (2020b)) or air temperature reduction (e.g. review paper Bowler et al. (2010)) as well as in terms of human thermal comfort (e.g. review paper by Jameia et al. (2016)) has been studied in urban settings in different climatic conditions. However, the cooling effects of trees are difficult to disentangle in terms of contributions from shading and transpiration. Even in a temperate climate (i.e. Munich, Germany) during hot summer days, the contribution of transpiration is insignificant (<20 %) compared to shading due to the excess energy increase (Rahman et al., 2018). Whereas in tropical Singapore, Tan et al. (2018) showed the transpiration contribution is ~ 29 % in air temperature reduction compared to the shading.

These differences are of practical importance for the optimum use of tree characteristics under different climatic conditions and future climate situations. So far, many researchers have shown plant responses to high temperature (Hughes, 2000; Lindner et al., 2010; Way and Oren, 2010) or reduced precipitation (Allen et al., 2010; Breda et al., 2006; Knapp et al., 2017; Rötzer et al., 2021b). However, there is still a big knowledge gap in terms of the independent physiological effects of high vapour pressure deficit (VPD) on tree transpiration (Preisler et al., 2023). Many studies have modelled stomatal conductance to decreasing soil water content and increasing VPD (Cochard et al., 2021; Nadal-Sala et al., 2021). In any case, there is evidence that suggests stomatal conductance declines under high VPD; nonetheless, transpiration increases in most species up until a given VPD threshold (Grossiord et al., 2020).

In a recent study, Shashua-Bar et al. (2023) compared summertime sap flow, canopy resistance (the reciprocal of conductance) and energy budgets of urban trees in cool and temperate Munich, Germany, with those in hot, arid Beer Sheva, Israel. For similar values of VPD, canopy resistance in Beer Sheva was usually more than two times that in Munich, even though trees in Beer Sheva were well irrigated. In addition, since the trees in Beer Sheva had wider crowns, the latent heat flux per unit ground area in Beer Sheva was lower. Thus, the relative contribution of trees to cooling due to transpiration was much less in Beer Sheva. Since species in arid climates have higher WUE (Medlyn et al., 2011) due to lower leaf conductance, and wide canopies are more common in arid climates (Dai et al., 2020), it is likely that this finding applies to other arid conditions if local tree species are used. Even so, in hot climates, the contribution of reduced canopy temperatures to improved thermal comfort in canopy shade is significant. The above also demonstrates the importance of conducting experimental studies to understand and mitigate climate change in urban settings in different climates.

We collected available data on air temperature reduction across the globe between 1983 and 2023 using Scopus search (keywords: 'air' AND 'temperature' AND 'urban' AND 'tree'). In addition to the air temperature under the tree and control site, we collected data on the city, climate, annual air temperature, annual rainfall, time of measurements, LAI, and arrangement of trees. From the initial screening of 200 studies, we selected 39 studies that fulfilled all the criteria of the dataset and estimated the De Martonne aridity index for each selected city (Supplementary Table 1). In combination with shading and transpiration, the air temperature reductions (ΔAT) under tree shade (as individual, clustered or in linear stand overbuilt or natural surfaces) compared to open control sites were variously reported between 0 to 4.3 °C across the globe (Fig. 4a). On average; the highest ΔAT was reported from trees in humid continental climates (Dwa), e.g. in cities such as Beijing, with

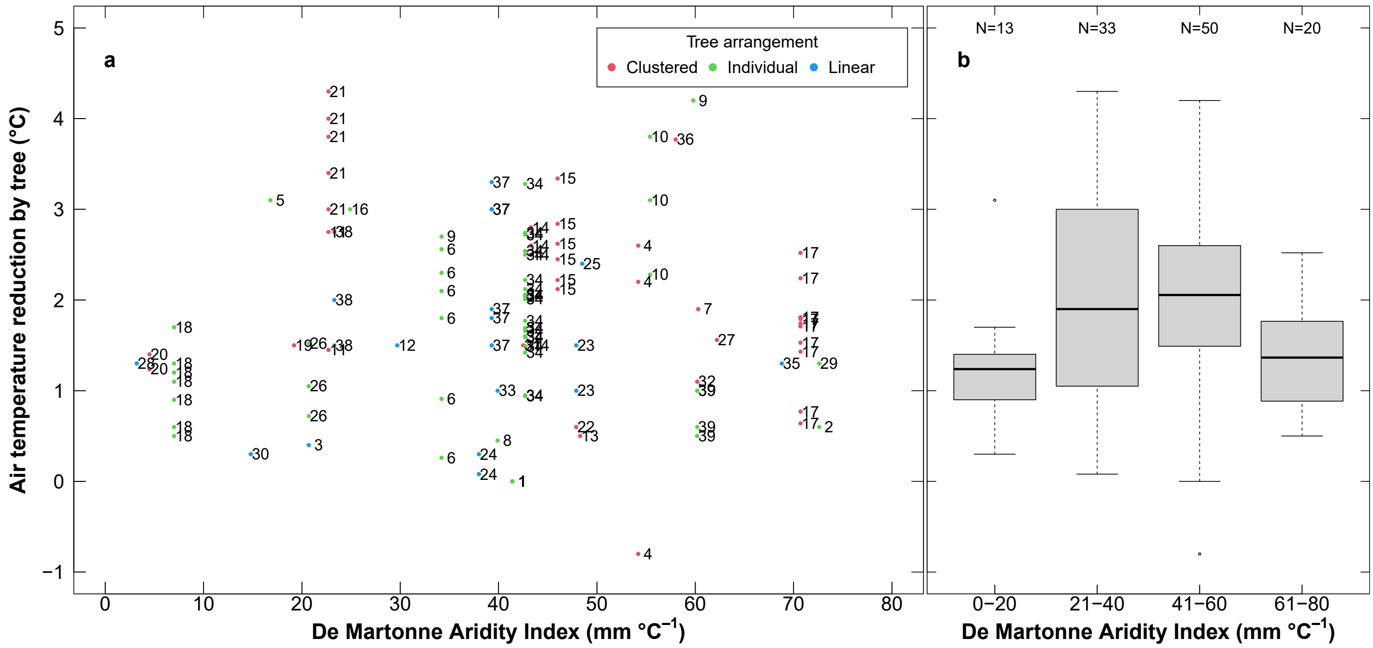

Fig. 4. Air temperature differences under the tree shade compared to open surfaces across climate zones following the De Martonne Aridity index. a. the numbers indicate the specific study according to Supplementary Table 1, and different colours refer to the tree arrangement. b. box plot showing the air temperature differences due to tree shade according to the range of aridity index.

ΔAT up to 4.3 °C followed by temperate oceanic climates (Cfb), cities such as Salzburg with ΔAT up to 4.2 °C. With higher background temperatures or under heat wave events, the influence of solar radiation will most likely dictate the surface energy balance. Therefore, with the hot air masses, shade benefits and reduced transpiration might have a decreasing slope of benefit compared to lower VPD conditions. Across the aridity gradient, ΔAT followed a bell-shaped trend with the lowest in highly arid areas (aridity index range between 0–20). With the lowest aridity index, cities such as Tempe, Negev Highlands, Athens, Tel-Aviv and Melbourne showed an average ΔAT of 1.15 °C (range 0.3 – 3.1 °C). The highest ΔAT was found within the aridity index range between 20 and 60. Cities such as Beijing, Dresden, Sydney, Manchester, Bangkok, Nanjing, Shanghai, Munich, and Nagoya showed an average ΔAT of 1.93 °C (range 0 – 4.3 °C). This was followed by an aridity index range between 60 and 80. Cities such as Kuala Lumpur, Taipei, and Hong Kong showed an average ΔAT of 1.50 °C (range 0.6 – 2.5 °C) (Fig. 4b). This leads to the hypothesis that with higher background temperature and high VPD, the cooling potentials diminish proportionally. Meanwhile, with higher temperatures and lower VPD, the trends are also somewhat low with reduced transpiration.

However, air temperature is only one of the several factors important for improving thermal comfort in cities. Mean radiant temperature (T_{mrt}), which sums the shortwave and longwave radiation fluxes to which the human body is exposed, is the most important metric for thermal comfort (Taleghani et al., 2016). Similar to the air temperature reduction potentials of tree shade, human thermal comfort measurements are also highly variable. Analysing the tree cooling benefit on human thermal comfort from temperate climate (Würzburg and Freiburg, Germany – (Mayer et al., 2009; Rahman et al., 2020a); humid Mediterranean (Florence, Italy – (Speak and Salbitano, 2022); subtropical (Campinas, Brazil – (De Abreu-Harbicha et al., 2015), Birmingham city of Alabama – (Sabrin et al., 2023), Guangzhou, China – (Yang et al., 2023; Zheng et al., 2018), Hong Kong, China – (Cheung et al., 2020; Jia and Wang, 2021; Morakinyo and Lam, 2016); tropical (Singapore – (Meili et al., 2021); hot and humid (Wuhan, China – (Huang et al., 2020); continental subarctic climate (Lhasa city, China – (Zhang et al., 2023), it appears that, similar to Fig. 4 results, higher background hot air masses (hot and dry climates) correlate with a decrease in the magnitude of ΔPET and ΔUTCI. However, this is very uncertain mainly due to the lack of standardised study protocols, especially without comparable control conditions (e.g. T_{mrt} largely varies with surrounding surface conditions).

A climatic transect is an integral component in the study of cooling potential of trees in urban environments due to the role of local climate in variations of the urban heat island. Studies have shown that the cooling efficiency (CE, defined as the land surface temperature, LST reduction for a 1 % tree cover increase) of urban tree canopy varies among cities and climate zones (Wang et al., 2019; Wang et al., 2020; Zhou et al., 2017). For example, trees' CE was higher in Baltimore than in hotter and drier Sacramento (Zhou et al., 2017). In their global studies, Yang et al. (2022) investigated 510 cities and showed that daytime LST decreases significantly with the increase in relative humidity, such as in tropical cities. There were differences also in effect of spatial configuration of trees on LST. More recently, Wang et al. (2022) examined the spatial variation of CE within and among four cities: Shenzhen and Beijing, China, and Sacramento and Baltimore, United States. This comparison brought to light the strong effect of a city's background climate on CE. However, local studies are difficult to combine into a *meta*-analysis due to a lack of standardization in data and methods and thus are inadequate for characterizing CE across a single city landscape (Wang et al., 2020). To address this concern, multi-city analysis of CE have been conducted over larger scales, although specifically in US cities (11 metropolitan cities by Wang et al. (2019); 118 cities by Wang et al. (2020). Additionally, an eight US city study across an aridity gradient provided evidence that the magnitude of vegetative cooling increased with aridity, and the cooling effect increased during heat waves (Ibsen et al., 2021). However, this study only reported on nighttime temperatures when solar irradiation is missing and only reradiation matters and considered urban vegetation overall, not specifically trees. Collecting standardized data to populate datasets on the cooling potential of multiple tree species in urban areas across several cities will allow us to recognize global patterns. Global studies using remote sensing approaches, and incorporating many climate regimes and cities of varying tree cover levels have helped to quantify tree CE as well as determine the factors that regulate it, such as leaf area index, climate variables, and city albedo (Zhao et al., 2023). However, large parts of the world have been ignored, particularly Africa, South America, and the Middle East (Yang et al., 2022).

Significant knowledge gaps also exist regarding the growth conditions of individual trees, particularly concerning ground surface types like asphalt and grass (Rahman et al., 2019) since grass itself is an evapotranspiring surface (Rahman et al., 2021). Depending on urban topography (Gulyás et al., 2006), a single tree versus a cluster of trees (Streiling and Matzarakis, 2003) or street canyon type (Rahman et al., 2017a), tree cooling effect may differ by a factor of five (Rahman et al., 2015; Rahman et al., 2011). Therefore, a coordinated effort to quantitatively assess the cooling effects from shading and transpiration using standardised protocols and stratified urban context is important. With the advent of modern and comparatively cheaper technologies, it is possible to measure both sensible and latent heat fluxes along with biometeorological variables across major climate zones.

5. Priority 4: An improved understanding of the cooling benefits provided at the urban stand level

In addition to a large number of tree-specific parameters, the species vulnerability to climate change (mortality and growth) and other biotic and abiotic stress factors should be considered (Allen et al., 2015) for optimum cooling benefits at stand level. However, cooling by a stock of trees cannot be quantified by simply summing up the cooling capacities of the individual trees. Above all, other factors play an important role: the competition among tree individuals for resources such as light, water and nutrients. These patterns of competition (Pothier, 2017), which have been studied in detail in forests (Castagneri et al., 2022; Forrester, 2019), can also be found in tree stocks in urban environments. Also in terms of spatial configuration of urban tree stock, such as canopy layout and its interactions with surrounding buildings, can impact not only the light but also water availability as a key driver of growth and cooling effectiveness at a stand level (Aram et al., 2019; Wang et al., 2023a).

Remote sensing data can help to determine the spatial parameters and tree characteristics (tree canopy) of a neighbourhood or an entire city. Combining such information (e.g. geographical positions of neighbouring objects such as houses or trees) and tree dimensions with growth models that also include a simulation of the water balance and other regulating ecosystem services based on resources such as light and water, the carbon sequestration and cooling potential for a neighbourhood or an entire city can be estimated (Rötzer et al. 2021a). Spatially relevant impact factors such as the Sky View Factor (SVF), which is the ratio of the visible sky area of a point in space to the total sky area or the soil sealing under the tree, can help to improve the simulations of the cooling potential. For instance, the CityTree model (Rötzer et al., 2019) includes the soil sealing under trees as well as the SVF of the surrounding objects and the competition between the trees (Fig. 5). Secondly, integration of process-based tree growth model output into urban climate model is important to consider the influence of species specific structure, growth and dimensions of individual trees as well as their development in the course of the year on the local climate. In the meantime, modelling tools have become available that can simulate the urban climate, including the cooling effect of city trees under variable past and future atmospheric boundary conditions, varying urban topography, and green and blue infrastructure. For instance, the urban climate model PALM-4U can reach a scale of a few meters based on a large-eddy approach and can map street canyons and city quarters (Hellsten et al., 2020). The atmospheric boundary conditions under different emission scenarios and (extreme) weather types can be provided by a convection-permitting version of the regional climate model REMO that can also account for different land cover and land use patterns around the cities (Paeth et al., 2009). Afterwards, the tree growth model can be integrated into the REMO-PALM4U environment to link cooling effects and other ecosystem services of cities directly to climate change and urbanisation scenarios in a scale-interacting approach from the microscale within city quarters to the landscape scale around cities.

Thus, implementing these variables in modelling tools such as CityTree and using remotely sensed data may provide a realistic determination of the cooling potentials of the tree population of a neighbourhood or an entire city. This way, information on the performance and growth of urban trees at the city or neighbourhood level could contribute significantly to an adapted management of the existing urban tree stock and thus to urban climate adaptation. Hereby, it is important to include the interactions of all stress factors, tree traits, canopy quality – as well as the small-scale environmental conditions (competition, soil sealing) (Fig. 6).

6. Conclusion

This paper has proposed research priorities aimed at formulating evidence-based strategies for urban forestry that are effective in developing climate-resilient cities. We have argued that collective global research attention needs to be directed towards studies that develop a mechanistic understanding of the growth of urban trees in urban environments and how structural and functional properties of urban trees relate to their cooling capacity at single tree and urban stand levels. A long-term perspective needs to be adopted in such studies. Moreover, coordinated and strategic collaborations along global climate gradients are advocated for recognised functional tree types to account for canopy quality and stress response strategies.

Such globally coordinated studies can test allometric growth relations in different climate zones, contributing to the fundamental knowledge of tree physiology. At the same time, the application of cutting-edge technology such as LiDAR analysis will enable more precise data on the cooling effects of urban forests to provide a dynamic understanding of city spaces and climate. The energy balance analysis of

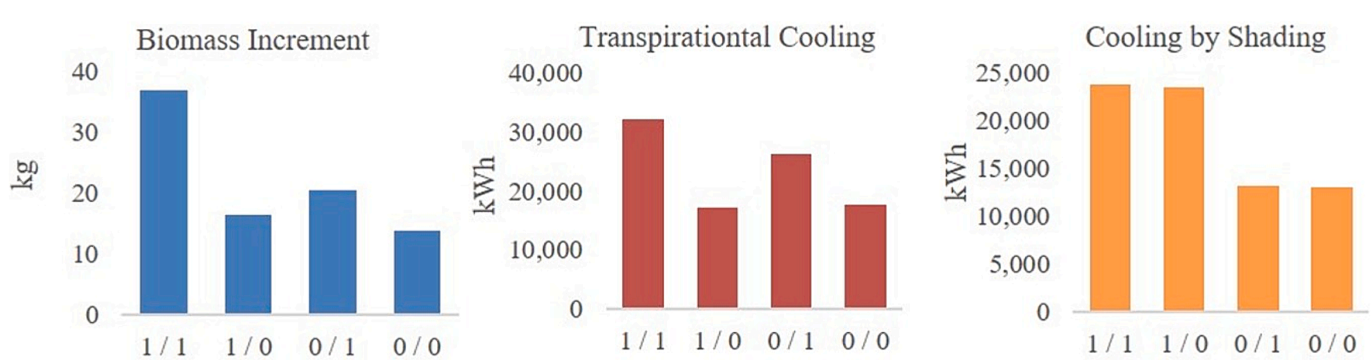

Fig. 5. Biomass Increment, Transpirational Cooling and Cooling by Shading for a 50-year-old *Tilia cordata* tree in Munich under current climate conditions with different site conditions. Here, 1/1 stands for highest SVF and no soil sealing, 1/0 for highest SVF, 70% soil sealing, 0/1 for lowest SVF and no soil sealing, and 0/0 for lowest SVF and 70% sealing.

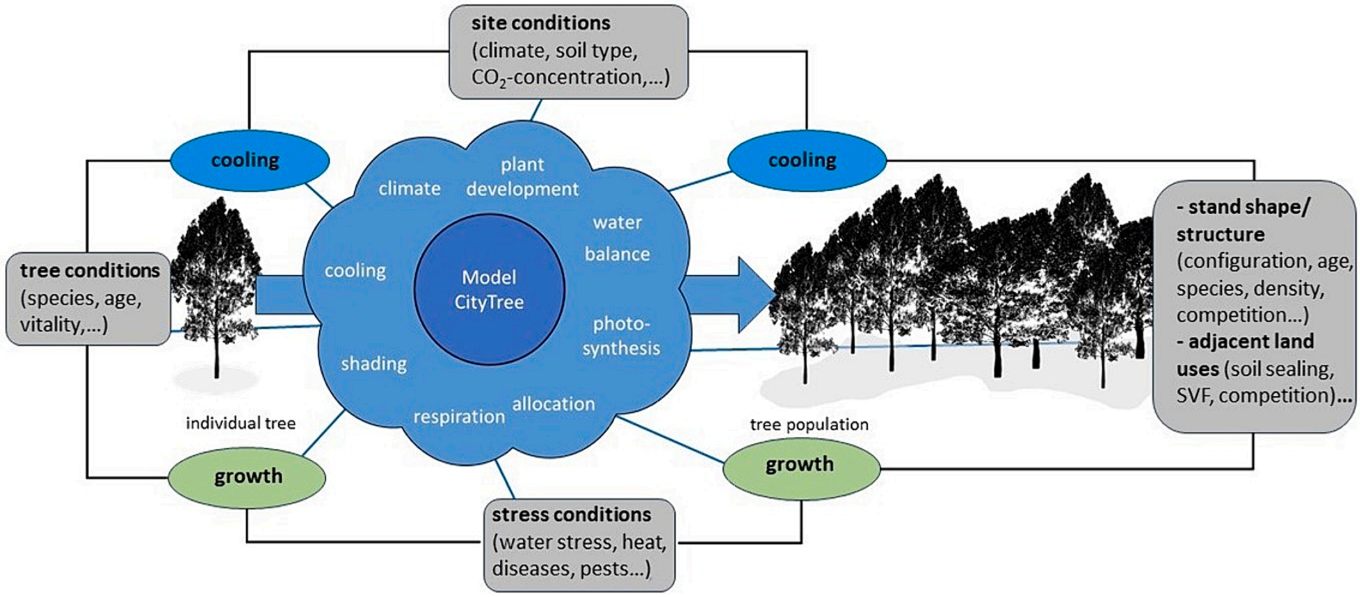

Fig. 6. A proposed schematic diagram of upscaling a process-based tree growth model CityTree (Rötzer et al., 2019) to the plot level.

the microclimate under individual trees will also allow the integration of process-based tree growth models and atmospheric boundary layer macro-scale models, advancing the field of simulation and modelling in urban climate communities. Overall, the research findings will guide the selection of suitable tree species, inform optimised planting strategies and establish best practices for urban tree management. Finally, such global studies can inform urban planning and policy decisions related to climate adaptation, offering evidence-based recommendations for sustainable city development as well as refining existing planting and policy guidelines such as general 3–30-300 rules. Although conducting immediate large-scale global studies may not be feasible, utilising existing systematic reviews (Aram et al., 2019; Bowler et al., 2010; de Quadros and Mizgier, 2023; Hami et al., 2019; Priya and Senthil, 2021; Rahman et al., 2020b; Wheeler et al., 2019; Zou and Zhang, 2021) can serve as a basis for understanding state of the art. By developing standardised study protocols and utilising established initiatives such as The Urban Climate Change Research Network (UCCRN) or The International Urban Forestry Forum (IUFF), international collaboration can be promoted to secure resources for collaborative studies, effectively addressing existing knowledge gaps comprehensively.

CRediT authorship contribution statement

Mohammad A. Rahman: Writing the first draft, review & editing, Visualization, Supervision, Resources, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Stefan Arndt:** Writing – review & editing, Investigation, Formal analysis. **Felipe Bravo:** Writing – review & editing, Resources. **Pui K. Cheung:** Formal analysis, Data curation. **Natalie van Doorn:** Writing – review & editing, Visualization. **Eleonora Franceschi:** Writing – review & editing, Visualization, Formal analysis, Data curation. **Miren del Río:** Writing – review & editing, Resources. **Stephen J. Livesley:** Writing – review & editing, Visualization, Supervision, Resources, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Astrid Moser-Reischl:** Writing – review & editing, Visualization, Formal analysis, Data curation. **Nayanesh Pattnaik:** Writing – review & editing, Visualization, Formal analysis, Data curation. **Thomas Rötzer:** Writing – review & editing, Supervision, Resources, Funding acquisition, Formal analysis, Conceptualization. **Heiko Paeth:** Writing – review & editing, Visualization, Resources. **Stephan Pauleit:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Yakir Preisler:** Writing – review & editing, Investigation, Formal analysis. **Hans Pretzsch:** Writing – review & editing, Resources, Methodology, Formal analysis, Conceptualization. **Puay Yok Tan:** Writing – review & editing, Methodology, Conceptualization. **Shabtai Cohen:** Writing – review & editing, Visualization, Methodology, Formal analysis, Conceptualization. **Chris Szota:** Writing – review & editing, Investigation, Formal analysis. **Patricia R. Torquato:** Formal analysis, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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