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Urban Trees and Cooling: A Review of the Recent Literature (2018 to 2024)

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Abstract. Urban trees mitigate extreme heat through shading and evapotranspiration, but cooling effectiveness varies with tree traits, spatial configurations, and climate. This systematic mapping review synthesizes findings from 115 studies (2018 to 2024) using RepOrting standards for Systematic Evidence Syntheses (ROSES) protocols. Studies were categorized based on geographic location, climate zone, and heat metric (e.g., land surface temperature or air temperature), highlighting a geographic skew toward North America and Asia and underrepresentation of arid and tropical zones. Findings show that urban trees consistently outperform other vegetation types in cooling, particularly in hotter, drier climates when water is available. Dense, tall canopies provide broad-scale cooling, while mixed plantings with shrubs or grass enhance local effects. However, conflicting conclusions arise from using land surface versus air temperature, as these metrics respond differently to tree canopy. Key knowledge gaps include the role of native versus non-native species in arid climates, the effect of urban morphology on cooling, and tree performance during extreme heat. Most studies remain small-scale and limited in generalizability, emphasizing the continued need for city-specific knowledge. This review highlights urban trees as vital for heat mitigation and the importance of harmonizing research objectives and methods to inform planning and practice effectively.

Keywords. Cooling; Shading; Systematic Mapping; Transpiration; Tree Canopy; Urban Heat Island.

INTRODUCTION

By 2050, over 68% of the world's population will live in urban areas (United Nations 2019). As global temperatures rise, city residents experience higher average temperatures and more frequent extreme heat events due to relatively low urban availability of transpiring vegetation and the prevalence of heat-absorbing impervious materials (Oke 1982). Elevated surface and air temperatures pose health and thermal comfort risks, particularly for vulnerable populations (Anderson et al. 2013; Ho et al. 2016). Traditionally, the urban heat island (UHI) effect has been defined as the temperature difference between cities and surrounding rural areas. However, modern cities' fragmented, multi-nucleic growth patterns make this binary characterization insufficient (Voelkel and Shandas 2017).

Trees help to combat extreme urban heat. Cities are working to quantify intervention effectiveness with a focus on "green infrastructure" broadly and tree canopy enhancement or protection most commonly (Knight et al. 2021). It is well established that through a combination of shading and transpiration vegetation cools both urban surfaces and air (Wong et al. 2021). While this general knowledge is necessary, it forms an insufficient basis for urban heat mitigation planning given high within-city spatial and temporal heterogeneity of temperature, green space, and vulnerable populations (Aram et al. 2019; Ziter et al. 2019).

Knowledge gaps hinder optimal heat mitigation planning by planners and urban foresters (Yu Q et al. 2020; Meili et al. 2021; Paschalis et al. 2021). Specifically, the role of trees in urban cooling varies by contextual factors including background climate, the configuration of trees, location, density, leaf area index, cloud cover, and more (Rahman et al. 2020; Su et al. 2022; Locke et al. 2024). The complexity of the built environment makes it difficult to predict the future cooling effect of trees planted at candidate planting spaces (Quanz et al. 2018). How and where to best maintain and enhance tree canopy cover to optimize the vital ecosystem service of urban heat mitigation is unclear. In order to advance efficient, cooling-focused urban forest management in the face of rising temperatures, this systematic mapping review

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was conducted to scope the literature and establish current trends and knowledge gaps.

Much of the current information is collated from small-scale studies (e.g., one park) across a variety of climate zones and urban layouts, making broad synthesis challenging (Manoli et al. 2019; Knight et al. 2021). Moreover, localized and park-focused studies do not adequately align spatially with where most people, and particularly vulnerable populations, actually live or are most often found within a city (Alonzo et al. 2021). The research that does go beyond parks to study street trees or other distributed canopy often fails to account for confounding variables (e.g., wind, buildings) that also alter the local temperature (Quanz et al. 2018; Knight et al. 2021). Most estimates of this cooling are made during hot, clear days (and some nights) but this does not always represent typical summer conditions (Shi et al. 2021). Within approximately the last 5 years, high temporal and spatial resolution studies at the citywide scale are becoming available, but they have yet to be summarized (Shiflett et al. 2017; Ziter et al. 2019; Cao et al. 2021; Shi et al. 2021).

The use of multiple, fundamentally distinct temperature measurement quantities presents a further impediment to succinct knowledge transfer of canopy-cooling dynamics. Maps covering entire urban areas can now be made from either satellite-derived land surface temperature (LST) or from interpolation of spatially distributed air temperature samples (Shandas et al. 2019; Chang et al. 2021). Satellite LST data provide complete spatial coverage of any city at a relatively small time-step, which, when paired with concurrent satellite-based vegetation indices, allows for large-scale analyses of vegetation-temperature relationships (Yin et al. 2023). However, LST is not the temperature that is directly experienced by humans, and it also suffers from some measurement limitations including mixed pixels (i.e., vegetation and buildings both present in a 100 m pixel) and a fixed, morning overpass time. For example, Landsat Thematic Mapper (TM)—which is used in the vast majority of LST-based studies—passes over North America at approximately 10:30 AM local time, which is suboptimal for measuring peak-heat and canopy cooling relationships. Elevated air temperature is a more appropriate quantity to relate to human health concerns, but it is more challenging data to collect in a way that represents the many land use types found at metro scales. While both quantities add value, their differences are often not well explained or they are inappropriately lumped together (Knight et al. 2021; Wong et al. 2021). Given the urgent need to reduce extreme heat within and across cities, the large and fast-growing body of literature needs to be synthesized.

This review reports on the state of this research in several ways. First, we characterize the relevant "trees and cooling" literature by publication venue, geographic location, climate zone, scale of analysis, and year published. To understand the most common methods, papers are also grouped by heat metric employed (e.g., LST, air temperature). As the biophysical mechanisms underlying tree-derived cooling are complex and variable, we focused our review on work which directly measures temperature in relation to physical trees, as opposed to simulation studies, and review papers. Subsequently, the narrative synthesis section elevates key themes and emergent findings for discussion and seeks to provide practitioners and researchers with practical management takeaways and an understanding of where significant uncertainty still exists. This section begins with discussion of measurement and metrics then focuses on the when, where, and how of tree cooling across multiple spatial scales.

METHODS

We employed a systematic mapping review (James et al. 2016). Systematic mapping is similar to a systematic review in that it follows a rigorous, transparent process to search, screen, and code articles. However, rather than synthesizing results, systematic mapping collates and assesses available evidence in a manner that is useful for an emerging discipline and that supports informed policy decision making (James et al. 2016). This approach was used in an urban heat mitigation context by Petzold and Mose (2023) and was recommended by Knight et al. (2021) as an appropriate way to build on their full systematic review of literature up to 2018 while avoiding redundancy. To adhere to a transparent process, we followed the Reporting standards for Systematic Evidence Syntheses (ROSES) method. ROSES is adapted from the well-known Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) reporting method but tailored to the environmental sciences (Haddaway et al. 2018)(Figure 1). One relevant benefit to ROSES compared to PRISMA is a greater emphasis on context-dependence, which in canopy- cooling literature is common and limits generalizability (e.g., study site location, time of day).

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To systematize our literature search and filtering, we used the PICO scheme (James et al. 2016; Petzold and Mose 2023). Population, intervention, context, and outcome (PICO) are used to ensure that the studies ultimately included in a review clearly support the primary review goals. In our case, defining these structuring elements will only help to constrain search and filter term selection (i.e., we did not require studies to include explicitly defined key elements). In our study, the goal is to understand how trees in cities cool their surroundings, thus (Table 1):

- Population: cities worldwide;
- Intervention: tree planting, maintenance, or conservation;
- Context: urban heat and climate change; and,
- Outcome: cooling.

We developed a search string in support of these key elements using an inductive approach to determine

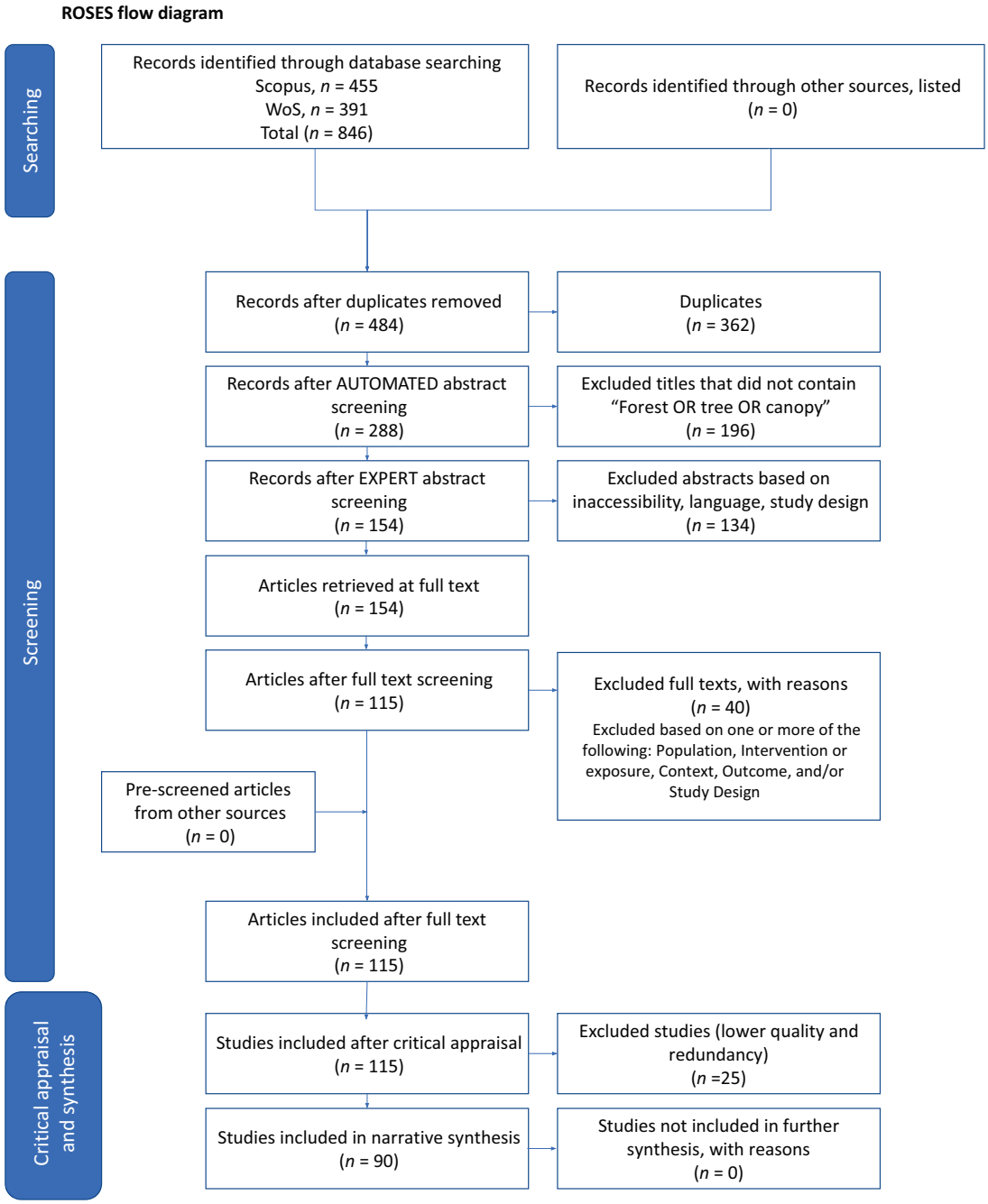

Figure 1. ROSES workflow diagram adapted from (Haddaway et al. 2018). WoS (Web of Science).

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reasonable boundaries of our search universe (Petzold and Mose 2023). The search itself—conducted in early 2024 to include articles from 2018 through 2024 April 10—used Web of Science and Scopus, as recommended for principal database searches supporting systematic reviews (Gusenbauer and Haddaway 2020). Given the focus, specifically on trees in the city, we chose to constrain our search to article titles but allowed initially for those titles to include non-tree words such as "vegetation" or "green space." As that resulted in 484 studies, we elected not to do any further snowball or word-of-mouth sampling.

Article screening was conducted using automated filtering and expert judgment to adhere to our trees and cooling review theme (Figure 1). We resolved duplicate entries. Articles with no explicit mention of *forest* OR *tree(s)* OR *canopy* in the abstract were removed. The team then reviewed abstracts to exclude articles that deviated substantially from our PICO framing (i.e., no intervention, just methods development) or our research scope (i.e., articles that were all or mostly simulation). At this stage, full texts of all accessible articles were downloaded for review. Two more stages of filtering followed, generally because we were unable to get adequate exclusion information from the abstracts. First, we excluded more articles based on scope, then we excluded a small number of articles based on subjective critical appraisal. In regard to the latter, we erred toward "include" but in some cases, we were unable to glean any useful information due to either poor study design or, more commonly, a lack of clarity in presentation of methods and findings. All retained articles at this point, in order to scope the literature in this discipline, were included in the coding and metadata extraction portion of this review. However, to avoid redundancy, only a subset of those articles were selected to represent the larger body of work in the narrative synthesis.

Table 1. Search strings for article titles operationalizing the population, intervention, context, outcome (PICO) framework.

Key element	Search string
Population	"urban" or "city" or "cities"
	AND
Intervention	"trees" or "canopy" or "forest" or "vegetation" or "greenspace" or "green space" or "green spaces"
	AND
Context	"temperature" or "temperatures"
	OR
Outcome	"cooling" or "heat"

Our analyses were chosen to support two common systematic mapping products: the coded metadata analysis and the narrative synthesis (James et al. 2016; Petzold and Mose 2023). Our choice of variables for coding was initially guided by our examination of prior literature reviews in this field (Knight et al. 2021; Wong et al. 2021)(Table 2) and then refined iteratively after the abstract review phase. These variables seek, first, to categorize and quantify the current geographic patterns in this literature. Where is this type of research being conducted and notably where is it not? As the tree-cooling relationship can be climate-dependent, which climate zones are well represented, and which require further study? Second, we sought to catalog the scales of analysis, and the heat metrics employed. Are most studies using a land surface temperature metric due to ease of access to data? Does the spatial resolution and distribution of measurements allow for generalizable results or only locally relevant findings?

Metadata analysis allows for a broad depiction of the current state of this research and points at trends relating to these questions. However, given the lack of methodological consistency of studies in this realm as well as unavoidable geographic diversity, further, qualitative analysis was required to elucidate key themes. Here, we used narrative synthesis to elevate key themes in the context of this literature search and the broader body of literature. While reading full texts, the team listed and ranked themes based on commonality in the literature but also based on a goal of translating this research for dissemination to inform industry best practices and urban climate policymaking. To facilitate readability and minimize redundancy, not every article of the $n = 90$ selected for use in the narrative synthesis was ultimately cited. Please refer to supplementary materials for the full bibliography.

RESULTS AND DISCUSSION

State of the Literature (Metadata Analysis)

We retained 115 articles for metadata analysis (Appendix) and 90 for inclusion in the narrative

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Table 2. Variables and their values used in coding.

Variable name	Values
Year	Integer values between 2018 and 2024
Continent	Africa, Asia, Europe, North America, Oceania, South America
Country	Open
Climate zone	Merged set of Koppen climate zones (n = 9) where tree growth is possible.
Heat metric	Air-distributed: distributed network of fixed sensors
	Air-few: only several sensors, precluding continuous analyses
	Air-mobile: sensor mounted on bike, moto, or car
	LST: land surface temperature
	HTC: human thermal comfort
	ET or LE: evapotranspiration or latent heat flux
Analysis scale	City-micro: individual tree to street segment
	City-sample: multiple, disconnected sampling locations
	City-full: seeks or fulfils full city coverage (frequently LST)
	City-multiple: multiple cities regionally or globally
Grid resolution (LST only)	< 30 m: high-resolution, generally aircraft or drone
	30 to 499 m, moderate resolution, most commonly Landsat
	> 500 m, coarse resolution such as MODIS

synthesis (Figure 1). The number of publications included in the analysis grew each year, from 7 in 2018, to 24 in 2023 (Figure 2). This is a conservative estimate of research productivity and growth in this space given the narrow search parameters focusing only on trees and eliminating studies with a primary method of simulation modeling.

Which Journals are Publishing this Research?

The selected articles were published in 46 unique journals, with 17 hosting at least 2 articles (Table 3). In general, these publications represented 6 main research foci including urban forestry and planning (40 articles), environmental science and climate (27 articles), forest ecology (18 articles), remote sensing (11 articles), ecological modeling (6 articles), and general multidisciplinary science (11 articles).

Space and Time (Geography and Year)

The articles included in this review represent a global distribution of research locations (Figure 2). The majority of papers originate from Asia and North America, with China (n = 33) and the United States (n = 22) publishing nearly half (48%) of all papers retained for metadata analysis. The only other nations contributing > 2 articles were Australia (n = 7), Singapore (n = 5), South Korea (n = 5), Germany (n = 4), and Chile (n = 3). Multi-country research studies are not included in this tally.

The included articles represented 8 unique, simplified Köppen climate zones covering a wide range of global conditions (Figure 3). We also included 30 articles which analyzed multiple cities, which are included in the "Mixed" category. While we found a representation of multiple climate zones in the literature, this representation does not necessarily reflect how cities are proportionally distributed by climate zone. We found some climate zones with more than half of their representation occurring in a single nation (e.g., articles from China account for 54% of research occurring in the "humid subtropical" zone). On the other hand, some nations account for a larger representation of multiple climate zones. For example, the USA provided 22 articles to this review spanning 5 different climate zones, including the only 2 from "dry arid" regions. These results both highlight how certain countries are dominant in the literature, so that their urban areas end up representing global climate, as well as how some climate zones and

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Table 3. Peer-reviewed journals with at least 2 publications retrieved for this study. Total unique journal count = 46; total articles = 115.

Publication title	Count
Urban Forestry & Urban Greening	15
Sustainable Cities and Society	10
Forests	7
Landscape and Urban Planning	7
Science of the Total Environment	7
Building and Environment	5
Urban Climate	5
Atmosphere	4
International Journal of Applied Earth Observation and Geoinformation	4
Agricultural and Forest Meteorology	3
Environmental Research Letters	3
Remote Sensing	3
Scientific Reports	3
Sustainability (Switzerland)	3
Ecological Indicators	2
ISPRS Journal of Photogrammetry and Remote Sensing	2
Remote Sensing of Environment	2

regions (such as "dry arid" studies outside the USA) are largely absent from the current literature.

Heat Metric

Of the sample studies, 55% used LST as the heat metric (Figure 4), but use of air temperature metrics are also on the rise (11 studies prior to 2021 and 26 studies after). LST data have been available globally every 16 days as part of the Landsat TM program since 1984. They offer spatially complete (i.e., "wall to wall") maps of urban temperature and, since the opening of the Landsat archive in 2008, are available for free to all (Woodcock et al. 2008). Therefore, it is not surprising that LST studies comprised 80% (20 of 25) of those conducted at the scale of an entire city and 71% (20 of 28) of multi-city studies. There were 50 of 60 LST studies conducted using Landsat's 60 to 120 m (depending on the satellite) resolution pixels, but these resolutions are frequently reported as 30 m following resampling to match the pixel sizes of other datasets such as Landsat's optical data for estimating vegetation cover.

At sub-city scales, such as neighborhood, district, or even micro (e.g., a cluster of well-instrumented trees), there is more variety in measurement techniques. At the district/neighborhood scale, 50% (6 of 12) of studies employed an air temperature metric while at micro scale, the plurality of studies were more mechanistic and used latent heat flux (LE) or sap flow measurements as a proxy for cooling (27%; 7 of 26). Micro scale studies also employed human thermal comfort metrics such as modified physiologically equivalent temperature (mPET)(Gillerot et al. 2024) or mean radiant temperature (MRT)(Zhang et al. 2020) which remain challenging to scale. When LST was used in these small study areas, it was at very high resolution in effort to explore determinants of heating and cooling in a more detailed manner (Yan et al. 2019; Speak et al. 2020).

Narrative Synthesis and Discussion

Measurement and Metrics

There is agreement that measuring air temperature (T_{air}) and direct measures of human thermal comfort (HTC) are more applicable to human health than LST (Sinha et al. 2021; Ioannou et al. 2022). However, it remains challenging to sample large geographic areas using a T_{air} or HTC metric—as they cannot yet be directly sampled remotely nor can they be easily modeled from LST (Venter et al. 2021). To achieve the gradients of both temperature and land cover determinants of temperature, there are recent efforts to distribute air temperature measurements over larger areas using mobile campaigns or crowdsourcing. For the latter, Du et al. (2024) used crowdsourced air temperature data from > 75,000 sensors in Europe to explore the tree cooling efficiency of air vs. surfaces. Volunteered temperature data present opportunities to vastly increase sampling extents and density but can come with locational biases and data gaps and may require significant statistical filtering (Venter et al. 2021; Du et al. 2024).

Mobile collection of air temperature data is becoming more common and offers flexibility with respect to study area size, sampling density, and campaign timing. At the more intensive end of the spectrum, participants with backpack temperature probes have walked transects to evaluate the cooling effects of a street greening demonstration project (Ananyeva and Emmanuel 2023). Covering more ground than

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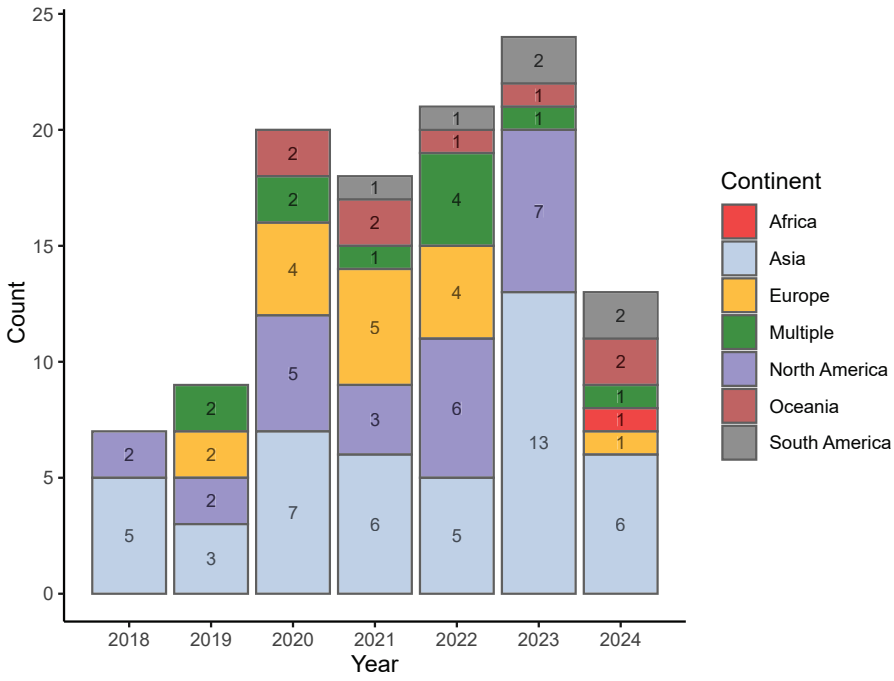

Figure 2. Study distribution by continent and year.

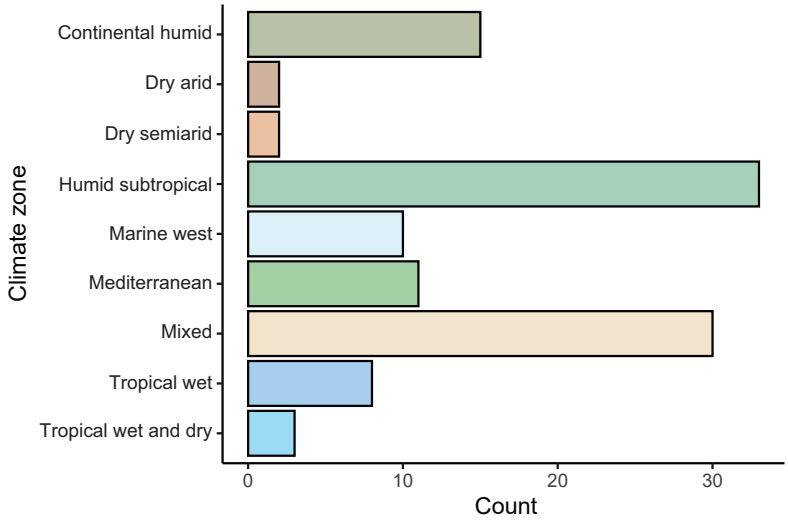

Figure 3. Distribution of publications by simplified Köppen climate zone.

walkers are bikes, mopeds, and cars (Wang et al. 2023). Compared to satellite-based surface temperatures with a fixed, mid-late morning overpass time, mobile air temperature can be collected at any time of day or multiple times in a single day (Alonzo et al. 2021). Across multiple days, bikes have been used to sample parts of cities repeatedly to assess how the relationship between tree canopy and cooling changes along with weather conditions such as heatwaves or cloud cover (Ziter et al. 2019; Locke et al. 2024). In the last 5 years there has been a rapid increase in car-collected mobile air temperature data, particularly in US cities (National Integrated Heat Health Information System 2024). In Washington, DC, and

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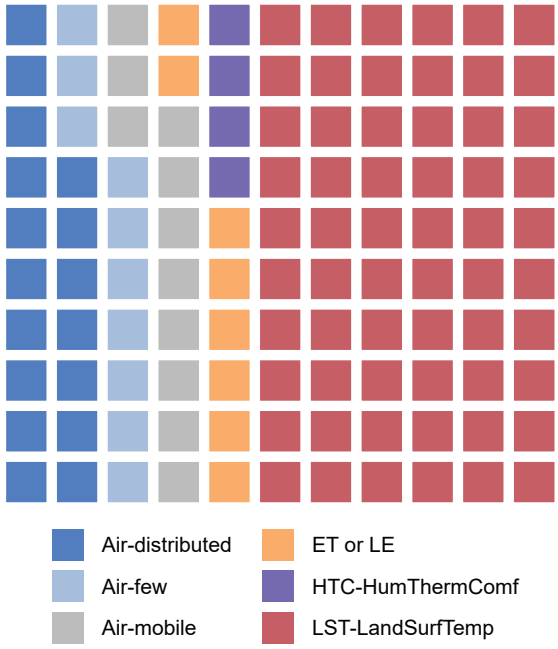

Figure 4. Primary heat metric employed in each study. Secondary heat metrics are not tallied here. See Table 2 for an explanation of heat metrics.

in Durham, NC, on hot, clear days, cars collected > 75,000 air temperatures spanning much of each city's footprint (Alonzo et al. 2021; Calhoun et al. 2024). This large sample size highlights the core value of this method: sampling is dense (1 reading per approximate 8 m in DC) and also extensive (100 to 200 km sampled per time of day) allowing for fine-scale characterization of temperature and its determinants (Alonzo et al. 2021). These "citywide" datasets have been used to derive interpolated maps of urban heat (Shandas et al. 2019). However, in their study using co-bike-mounted air and surface temperature monitors, Pena Acosta et al. (2023) note practical challenges in scaling: they report such fine scale temperature variability that they conclude that urban climate solutions will need to be implemented on a street-by-street basis.

The choice of heat metric plays an important role in the interpretation of study results and in the policy implications of those results. The surface urban heat island (SUHI) is generally more extreme than the canopy urban heat island (CUHI)(air temperature based) during the daytime when differential surface heating is driven by material albedo, thermal properties and shading. CUHI, by contrast, is maximized at night when the impervious-dominated urban fabric releases heat in the air and convective turbulence is low absent solar heating. Pena Acosta et al. (2023), using bike-based temperatures at a district scale, noted that daytime average SUHI was 4× greater than the average CUHI. This limited air temperature gradient coupled with convective mixing leads to the general finding that trees reduce air temperatures by far less than they lower surface temperatures (Du et al. 2024). Choice of a surface vs. air metric also plays a role in which tree planting locations and configurations appear to be most advantageous for cooling, as detailed below.

Attributes of Trees for Cooling (Individual)

Tree species and the manner in which species manifest distinct tree attributes—such as leaf area index (LAI), height, water use strategy—significantly influence their cooling efficacy. Numerous studies report that high-LAI species, which have a greater leaf surface area per unit of ground area, generally provide enhanced cooling capacity through both shading and evapotranspiration (ET)(Ihsan and Rosleine 2020; Rahman et al. 2020; Speak et al. 2020; Sharmin et al. 2023). Higher LAI leads to reduced temperatures in urban settings as measured by both LST and T_{air} (Ihsan and Rosleine 2020; Li et al. 2020; Ibáñez et al. 2021; Sharmin et al. 2023). In a global study (n = 596 cities), each meter increase in forest height was associated with a 0.16 °C reduction in land surface temperature (He et al. 2024). Taller trees with dense canopies offer substantial daytime cooling but may warm at night (Wujeska-Klause and Pfautsch 2020; Guo et al. 2023; Wang et al. 2023). By contrast, tall trees with high foliage height diversity both shade during the day and release heat at night (Wang et al. 2023). Species with lower, broader crowns can also be useful for cooling, especially when considering human thermal comfort. Zhang et al. (2020) showed that these shorter trees cast wider shadows and enhance cooling at ground level as measured by mean radiant temperature. Leaf structure is important for shading but also for water usage with thin-leaved species better for cooling in the short term because of their less restrictive water use strategies (Rahman et al. 2020).

How species use water under a range of climate and weather conditions determines the efficacy of their cooling and their suitability for water-limited environments. Broadleaf species, which often have

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diffuse porous xylem structures, tend to maintain higher transpiration rates than ring-porous species, facilitating effective cooling where water availability is sufficient (Rahman et al. 2020; Hwang et al. 2023). In Guangzhou, China (humid subtropical), with adequate water availability, *Schima superba* significantly outperformed *Corymbia citriodora* and *Acacia auriculiformis* in cooling (Chen et al. 2019). All of these species are broadleaf evergreen but *S. superba* is noted for higher water use efficiency and leaf mass per area, perhaps indicating suitability for drier conditions as well. In some instances, conifers, even though they have lower albedo than broadleaf trees, had cooler surface temperatures suggesting high rates of ET (Eyster and Beckage 2022; Lee et al. 2022).

A critical area of inquiry concerns which tree species will thrive and provide cooling benefits under both current and future climate conditions (Esperon-Rodriguez et al. 2022). There are necessary tradeoffs in species selection among optimization of cooling, conservation of water, and minimization of mortality. Maximizing cooling: non-native species like *Prosopis alba* and *Tipuana tipu* in Israel maintained high rates of ET even under dry conditions, making them useful for cooling in arid climates despite being introduced species (Shashua-Bar et al. 2023). Some species, instead, cool when possible and equip for survival when it's not. Seasonally dry forest species—not native to, but planted in Singapore—were shown to transpire readily when water was available but exhibit self-preservation under drought conditions by shedding leaves (Tan et al. 2020). Compared to native, aseasonal evergreen forest, these seasonal trees were also less prone to reduce transpiration under cloud cover, a useful attribute in hot, cloudy locations. On a global scale tree cooling efficiency in the coming decades is expected to be maximized in present-day mesic locations where conservative water use strategies are less common (Zhao et al. 2023). That is, as these areas get hotter and sometimes drier, atmospheric demand will increase, elevating rates of transpiration so long as soil moisture allows. By contrast, more arid areas such as the Mediterranean, with trees already adapted to low water availability, will be less equipped to provide additional cooling in these future conditions. In the longer term, it is possible that more biodiverse forests could optimize for both cooling and resilience. Some evidence points to more biodiverse urban forests relating to a lower probability of a city's temperature exceeding 32 °C in coastal California (Rendon et al. 2024).

Single and Multilayer Vegetation Configurations

Different plant functional types (PFTs)—trees, shrubs, and grass—demonstrate varied cooling capabilities, with trees consistently emerging as the most effective option (Liu et al. 2021). Trees provide significant cooling both directly within their immediate surroundings and indirectly through substantial spatial spillover effects (meaning they help cool nearby areas), reducing LST more than other PFTs (Smith et al. 2023). This was similarly true for air temperature; trees also cooled neighboring areas (from 10 to 50 m distant) while other PFTs did not (Ettinger et al. 2024). It has been shown that trees have a much stronger negative correlation with LST ($r = -0.43$) than grass (−0.16) or shrubs (−0.21), underscoring their greater cooling capacity (Yao et al. 2020). Shrubs and grass, while useful in mesic climate zones, often provide less cooling on their own; for instance, shrubs cool LST only marginally more than grass, and in the absence of supplemental water, grass may even become a warming agent in arid conditions (Smith et al. 2023). PFTs with lower leaf area, limited rooting depth, and no structural shade may offer cooling benefits at night and in the morning but are unable to maintain that cooling—while trees can—in the afternoon (Kraemer and Kabisch 2022; Gillerot et al. 2024).

Diverse planting strategies that integrate multiple PFTs can create additive or synergistic cooling effects, particularly in complex, mixed-vegetation settings. Combining trees with shrubs or grass enhances cooling compared to single-species plantings, as each PFT contributes differently to shading, ET, and air circulation (Duncan et al. 2019; Wang et al. 2023). For example, locating trees over grass results in a stronger cooling correlation ($r = -0.49$) than either trees or grass alone, highlighting the benefits of layered, biodiverse plantings (Wang et al. 2021). In more arid regions, however, natural mixed-vegetation complexes may sometimes yield less cooling than forest-only areas, potentially due to lower levels of management (e.g., irrigation)(Su et al. 2022).

There are also benefits to single-layer canopy overhanging impervious surfaces. Shading impervious surfaces like asphalt or concrete is particularly effective because these surfaces store and emit more heat than pervious ones, amplifying the cooling impact of a tree canopy (Kaluarachichi et al. 2020;

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Smith et al. 2023). For instance, Rahman (2019) found that shading pavement resulted in a 6 °C temperature reduction, compared to a 3 °C reduction when shading grass. With respect to air temperature, Alonzo et al. (2021) noted that trees overhanging impervious surface provided the most efficient cooling configuration in midday dense urban settings. While shading is likely the primary mode of cooling in impervious-dominated settings, ET may also be enhanced, compared to more forested areas. Edge exposure to sunlight and corresponding adjacency to hotter impervious surfaces can boost ET in well-watered vegetation (Wetherley et al. 2018; Teshirogi et al. 2020). However, extreme heat from impervious surfaces can also trigger stomatal closure in tree canopies, reducing ET and limiting their cooling function (Wetherley et al. 2018). Beyond this caveat, trees in heavily paved zones may even suffer from substantially reduced growth, physiological performance, and ultimately, reduced cooling (Konarska et al. 2023).

Spatial Distribution/Configuration of Trees

In urban landscapes, the spatial configuration of tree canopy and green spaces significantly impacts cooling, but rarely as much as simple tree canopy *amount* (Rakoto et al. 2021). Larger, more compact green spaces are shown to reduce temperatures more effectively within their boundaries (*direct effect*) and provide critical heat refuges (Chen et al. 2019; Yan et al. 2019). Similarly, large patches can cool to a greater distance (50 to 500 m, *indirect effect* or *spatial spillover*) than small patches or scattered trees (Lemoine-Rodríguez et al. 2022; Gallay et al. 2023; Calhoun et al. 2024; Zhou et al. 2024). High edge density from smaller patches, however, can also have an indirect cooling benefit in humid environments, as the influx of warm air from surrounding impervious surfaces increases ET at the edges (i.e., oasis effect)(Ow et al. 2020). The relative importance of canopy configuration versus canopy amount varies by climate, with configuration playing a more critical role in hotter, drier areas, while overall canopy cover remains the dominant factor in cooler or less arid climates (Wilson et al. 2024). Generally speaking, increased shape complexity of a patch can enhance the energy transfer (i.e., cooling effect) with the surrounding area (Zhou et al. 2019), which may be a positive attribute with respect to locationally matching cooling supply with cooling demand (Li et al. 2022).

Notably, there are very few examples of tree canopy configuration studies using air temperature. The results presented above only employ surface temperature data and as noted elsewhere, air and surface temperature do not respond to tree canopy the same way. Surface temperature disparities between vegetated and non-vegetated areas tend to be higher than air temperature differences. It is therefore likely that relationships between air temperature and configuration metrics vary, but further research is needed to address these hypotheses.

The literature presents differing views on whether trees cool most effectively in low or high canopy cover areas. Several LST-based studies report that incremental cooling is greatest in low-canopy cover areas, often attributing this effect to enhanced ET driven by elevated aridity in these areas (Wang et al. 2022; Lin et al. 2023; Zhao et al. 2023). This analysis has been taken further to demonstrate high tree cooling intensity in socially vulnerable communities (Zhou et al. 2021), highlighting a potential alignment between ecosystem service availability and consumer need. However, these studies are bivariate (canopy and cooling), with limited or no accounting for other influential factors like impervious surface cover. In contrast, studies employing both LST and T_{air} metrics indicate that cooling from each unit of additional canopy cover is most pronounced in medium to high canopy cover areas, with thresholds for effective cooling generally in the 35% to 50% range, depending on location and time of day (Ziter et al. 2019; Alonzo et al. 2021; Yang et al. 2023). Alonzo et al. (2021) further suggest that during periods of high convective turbulence, large contiguous canopy patches are required for substantial air cooling. Additionally, areas with very high canopy cover in urban environments are often situated in forested natural areas, which tend to have more favorable soil conditions and better water access (Zepp et al. 2023).

Background Climate

Urban trees generally cool more effectively when temperatures are hotter and drier but this is contingent on water availability (Wang et al. 2020). Background climate exerts stronger control over transpirational cooling than for shade (Rahman et al. 2020). At a given humidity, higher temperatures equate to higher atmospheric demand, and thus elevated transpiration rates (Su et al. 2020). Similarly,

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there is evidence that tree cooling intensity will be maximized in a warmer future in cities that currently have a mesic climate (Zhao et al. 2023), if they survive the harsher climates. Those trees are adapted to wetter conditions and are thus less likely to exercise strong stomatal regulation compared to trees native to drier regions. Even where trees in dry locations are observed to have high cooling intensity, such as the Sahel, it is projected that those same trees will not have the thermotolerance to continue cooling robustly under future climate conditions (Chen et al. 2022).

Further evidence of climate-driven variability in tree cooling effects comes from comparing studies in different regions. In an intensive study comparing local tree ET in temperate Munich, Germany, and hot, arid Beer Sheva, Israel, Israel's desert-adapted trees were limited in their capacity for transpirational cooling by substantially higher hydraulic resistance (Shashua-Bar et al. 2023). The authors thus suggest that tree species selection criteria for planting in dry regions should favor shading over ET. However, Du et al. (2024), using crowd-sourced air temperature data throughout Europe, found that increased tree canopy was only effective at cooling the air in hotter, drier southern Europe. Perhaps helping to explain these contradictory results, Yu et al. (2018) found that, while a mesic, temperate climate, such as in Munich, may allow for unconstrained water use, higher humidity there can depress transpiration. In a more extreme, tropical wet case, increased tree canopy may have negligible impact on cooling either the air or surfaces (Best et al. 2023) though more studies are needed in this climate zone. Most of the aforementioned studies employ LST as their heat metric. It is clear that ET cooling will be maximized where aridity is high, and water is available, but it is unclear whether tree planting for ET maximization is sensible in current or projected water limited environments.

CONSISTENT FINDINGS AND PERSISTENT UNCERTAINTIES

A review of the recent "urban trees and cooling" literature provides increased confidence in certain practical findings but also illustrates the ongoing challenge of arriving at globally useful recommendations for how to plant for heat mitigation (Figure 5).

Consistent Findings

Urban trees consistently cool more than other vegetation types, both locally and at larger scales (Liu et al. 2021; Smith et al. 2023; Ettinger et al. 2024), making them a critical component of urban heat mitigation strategies. Their cooling efficacy is driven by shading and ET, with tree characteristics such as high LAI and canopy height playing a pivotal role (Ihsan and Rosleine 2020; Rahman et al. 2020; Speak et al. 2020; Sharmin et al. 2023). Dense, tall canopies are particularly effective for broad scale daytime cooling, though they may warm microclimates at night,

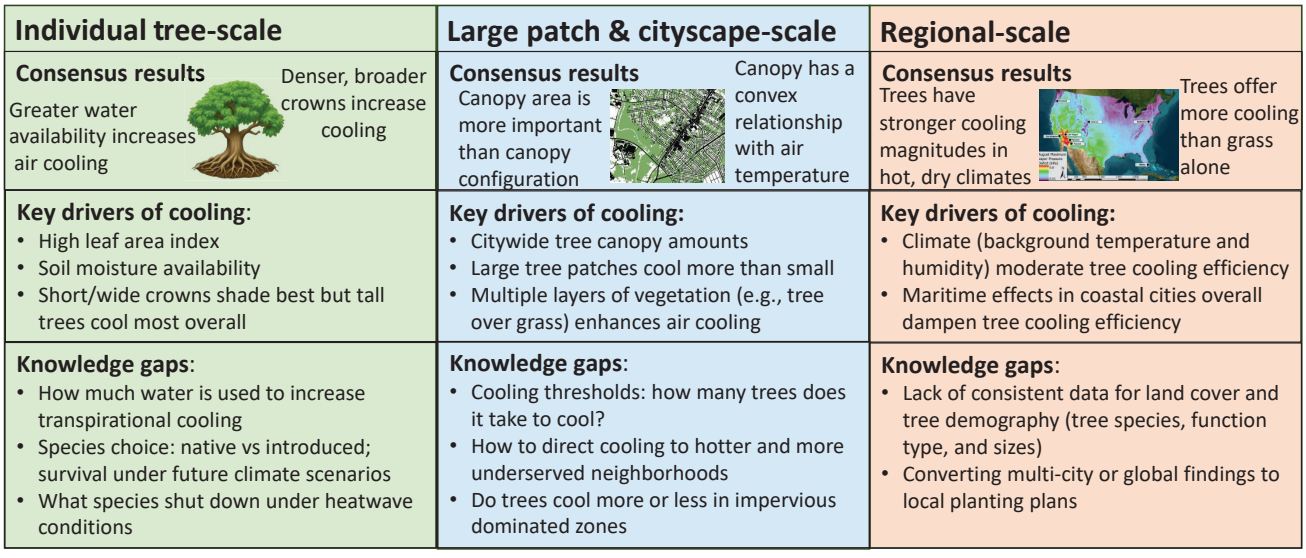

Figure 5. Key takeaways from this study across scales in terms of agreed upon drivers of cooling and knowledge gaps.

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suggesting a need for planting trees with vertically well-distributed leaves (He et al. 2024; Wang et al. 2023). More locally, lower stature, wide-crowned species optimally shade people and surfaces (Zhang et al. 2020), but practical or regulatory considerations may preclude widespread implementation of this strategy in dense urban settings, making this cooling strategy moot in those cases.

Vegetation configuration also matters both vertically and horizontally. Vertically, multi-layered assemblages combining trees, shrubs, and grass consistently provided enhanced cooling compared to single-species plantings (Duncan et al. 2019; Wang et al. 2023). Horizontally, larger, contiguous green spaces outperform smaller or fragmented patches in reducing temperatures locally and at a distance, particularly when considering T_{air} reduction (Lemoine-Rodríguez et al. 2022; Gallay et al. 2023; Calhoun et al. 2024; Zhou et al. 2024). In an LST context, shading impervious surfaces such as asphalt and concrete is an effective cooling strategy as it undercuts their high heat storage capacity (Kaluarachichi et al. 2020; Park et al. 2023; Smith et al. 2023). Planting for shading in these densely built areas more generally may be a primary component of a planting plan to prioritize heat mitigation, but it is unlikely that air cooling will be substantially lowered in these zones (Alonzo et al. 2021; Park et al. 2023; Shashua-Bar et al. 2023). At regional to global scales, tree cooling is amplified in hotter and drier climates but only when water availability is sufficient (Su et al. 2020; Wang et al. 2020; Zhao et al. 2023). It is thus important to consider (1) whether the conditions in a city are amenable to cooling through shading only or shading and ET, and (2) whether trees that cool well now will be optimal (or even viable) under near-future climate conditions and water availability scenarios.

Remaining Uncertainties

A number of uncertainties persist, necessitating additional research to achieve transferable insights. First, the cooling ability of tree species, particularly the role of native versus non-native species in different climatic contexts, remains unclear (Chen et al. 2019; Eyster and Beckage 2022; Lee et al. 2022). This is especially pertinent in arid regions, where introduced species may cool more robustly than native ones, requiring deeper investigation into species-specific cooling dynamics and species adaptability to changing water availability (Shashua-Bar et al. 2023; Zhao et al. 2023). Second, the influence of urban morphology, including wind patterns, topography, and building density, on the cooling efficacy of different tree configurations is still not well-understood (Wetherley et al. 2018; He et al. 2024; Locke et al. 2024). This is an area of recent improvement though, with the growing availability of both large LST and T_{air} datasets, as well as more high-resolution land cover and LiDAR data for urban areas, enabling more complex, multivariate analyses (Ziter et al. 2019; Alonzo et al. 2021). Third, while trees generally cool more effectively on hotter days, their sometimes-reduced cooling intensity during extreme heat events (likely relating to species-specific responses) merits further review (Wetherley et al. 2018; Chen et al. 2022).

Although there is substantial literature dedicated to determining where trees offer the most cooling benefit, communities still are challenged to arrive at operational conclusions. A key finding in this review is just how much care is required in interpreting results depending on the heat metric employed. For example, there is a set of studies suggesting that canopy marginal utility for cooling is highest in areas of low cover (Zhou et al. 2021; Wang et al. 2022; Lin et al. 2023; Zhao et al. 2023). On the contrary, there are others presenting data that more trees are best at cooling in areas with already substantial canopy cover (Ziter et al. 2019; Alonzo et al. 2021; Yang et al. 2023). The former studies always use surface temperature while the latter set is more often T_{air}, with T_{air} results most dramatically demonstrating this convex threshold effect. The issue of heat metric choice is also germane in the debate over optimal canopy configurations. Is it optimal to *directly* cool maximally or is it instead preferred to maximize energy exchange *between trees and people* (Zhou et al. 2019; Ow et al. 2020; Li et al. 2022). The former prioritizes large patches while the latter leads to high edge density (serpentine) planting patterns. While there are many "tree configuration" studies, few use a metric other than LST. It is thus not clear yet whether spatially distributed canopy can effectively cool a parcel of air at all times of day (Alonzo et al. 2021).

Aligning Our Findings with Other Relevant Reviews

These findings reinforce well-established patterns in the literature and highlight ongoing uncertainties.

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The consistent cooling effect of trees, particularly through shading and ET, aligns with prior reviews (Bowler et al. 2010; Knight et al. 2021), which found that urban forests and tree-covered areas (as defined by study authors) reliably reduced air temperatures by 1.6 and 0.8 °C on average respectively. This cooling was maximized under high insolation, hot conditions where tree transpiration and shade density are both maximized (Knight et al. 2021). In 2010, there were not enough data for Bowler et al. (2010) to draw conclusions with respect to effect modifiers on cooling such as canopy location or configuration. In the subsequent decade, however, it became possible to more robustly conclude that some tree locations cool air better than others: air cooling is minimized under street trees, perhaps due to anthropogenic heat in those areas, or the overlapping cooling from collocated building shade (Knight et al. 2021; Wong et al. 2021). We also conclude that isolated trees overhanging pavement will be challenged to cool air, albeit while reducing urban surface temperatures substantially.

Our results further support the importance of canopy structure, with high LAI and multi-layered plantings providing enhanced cooling (Yu Z et al. 2020). There remains a need, as noted in Knight et al. (2021) to balance shading during the day with heat dissipation at night. While they recommend a mix of open grassy areas and forest, we show preliminary evidence that trees with high foliage height diversity might be suitable at both times of day. While we see a convergence of evidence regarding vertical vegetation configuration, the utility of horizontal canopy configuration remains unconfirmed (Bowler et al. 2010; Yu Z et al. 2020). We posit that part of the challenge here is lack of clarity and consistency concerning study objectives and heat metrics: First, what is the anticipated cooling outcome? Is it to minimize temperature within the green space or the temperature of the surrounding neighborhood? Second, is LST or air temperature the response variable? Moderate resolution LST pixels will cool linearly with the addition of tree canopy, but we have shown that air temperature will be largely unaffected until a threshold of canopy cover (e.g., 40% is achieved). Therefore, with LST, it would appear that serpentine planting configurations are effective neighborhood coolers, but with air temperature, less so. Nevertheless, at a certain green space size (e.g., the threshold value of efficiency)(Yu Z et al. 2020), air will be cooled and perhaps advected to neighboring, inhabited areas. Our findings are consistent with the literature indicating that this sort of spatial spillover is more likely in treed rather than grass covered locations (Yu Z et al. 2020).

CONCLUSIONS

In this study, we provide a concise summary of the recent literature on the effectiveness of tree canopy on cooling in cities. While some relationships are consistently observed, others varied across climates, methods, geographic scales, or vegetation type. A key challenge remains scaling localized findings to citywide or regional applications, as urban heat dynamics are influenced by myriad site-specific factors. However, as high-resolution, citywide datasets become more widely available, researchers are better equipped to bridge this gap and identify generalizable relationships and trends. This review contributes to that effort by synthesizing emerging findings, highlighting robust patterns, and identifying key uncertainties that remain. Importantly, while broad-scale analyses offer valuable insights, urban foresters and practitioners bring essential local expertise that cannot be replaced by generalized models alone. Each city is unique in its biophysical, social, and political context, and the most effective cooling strategies will integrate both city-specific experience and data-driven analysis to optimize urban tree planning and management.

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Appendix.

Below is the full list of articles that were included in our review (n = 115). The "Use" column indicates whether an article was used in only the metadata analysis or in both the metadata analysis and the narrative synthesis. Note that not all articles selected for narrative synthesis were cited in the main text. This choice was simply made to maintain readability and minimize redundancy.

Citation	Use
Alonzo M, Baker ME, Gao Y, Shandas V. 2021. Spatial configuration and time of day impact the magnitude of urban tree canopy cooling. *Environmental Research Letters*. 16(8):084028. http://doi.org/10.1088/1748-9326/ac12f2	both
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An H, Cai H, Xu X, et al. (2022). Impacts of urban green space on land surface temperature from urban block perspectives. *Remote Sensing*. 14(18):4580. http://doi.org/10.3390/rs14184580	both
Ananyeva O, Emmanuel R. 2023. Street trees and urban heat island in Glasgow: Mitigation through the 'Avenues Programme.' *Urban Forestry & Urban Greening*. 86:128041. http://doi.org/10.1016/j.ufug.2023.128041	both
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