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A Systematic Review of the Cooling Effects of Urban Forests

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Abstract. Urban forests have been widely recognized as a nature-based solution to address urban environmental changes like urban heat islands. Although previous studies have explored the cooling effects of urban forests, the extent of this effect and related influencing factors remain unclear and have not been comprehensively synthesized yet. To fill this research gap, we conducted a systematic literature review using the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) method with 20 keywords and their combinations in Web of Science to address 3 main research questions: (1) what is the cooling range of urban forests; (2) what are the factors that may affect the cooling effects; and (3) how can we better manage urban forests to optimize cooling effects? We systematically reviewed 73 peer-reviewed articles selected from an initial pool of 4,072 search results following the PRISMA method. We found that urban greenspaces generally have cooling effects, but it is challenging to draw a clear conclusion on the cooling range due to variation in study design, measurement approaches, spatial scales, and local climate contexts. Moreover, the main influencing factors include land cover compositions, tree cover and canopy structures, leaf area index, forest types and tree species, and spatial arrangements of urban vegetation. Additionally, the cooling benefits of urban forests might be affected by local background climate and weather conditions, as well as distances from water bodies. These findings can help guide urban greening efforts (e.g., land cover types, tree species selection, and spatial arrangements) to achieve a greener and cooler future.

Keywords. Air Temperature; Land Surface Temperature; Nature-Based Solutions; Urban Greenspaces; Urban Heat Islands.

INTRODUCTION

The global population reached 8.2 billion in 2024 (United Nations 2024), with over half living in urban areas; and the urban population is projected to increase to approximately 68% by 2050 (UN-Habitat 2022). On one hand, urbanization brings economic growth and higher-quality public services, especially in developing nations (Liang and Yang 2019; Jiang et al. 2022). On the other hand, urban development magnified the risk of environmental hazards, such as air pollution, poor water quality, the 'Urban Heat Island' (UHI), 'Urban Dry Islands' (UDI)(Hao et al. 2018; Huang et al. 2022; Hao et al. 2023), stormwater runoff (Boggs and Sun 2011) and flash flooding (Hao et al. 2015), ecosystem degradation (Chen et al. 2024), and public health issues (Ventriglio et al. 2021; Yao et al. 2021; Pata et al. 2023; Wang et al. 2024).

Global warming is another driver of urban environmental threats. According to the World Meteorological Organization (WMO 2025), as of January 2025, the global average surface temperature was 1.55 ± 0.13 °C warmer than it was in the 1850 to 1900 period, and the last decade (2015 to 2024) was the 10 warmest years on record. The United Nations Environment Programme (UNEP) also reported that 2024 was globally the warmest year ever recorded. According to the National Oceanic and Atmospheric Administration (National Weather Service 2025), heat kills more people (i.e., 194 per year, 1994 to 2023) than any other natural disaster (e.g., flooding, tornadoes, and hurricanes) in the United States. The UHI effect exacerbates heat-related impacts, threatening the sustainability of urban development. In this regard, there is a pressing need for advancement in urban planning and management to improve the quality of the environment and make cities more sustainable and livable under global warming (Bush and Doyon 2019). Finding an effective solution to mitigate the UHI effect is one of the most important research issues for urban ecosystems (Hayes et al. 2022).

One promising strategy is the integration of urban forests, which have been increasingly recognized as a nature-based solution (NbS) to combat urban heat. Urban forests refer to "all woodlands, groups of trees, and individual trees located in urban and peri-urban areas, which includes forests, street trees, trees in parks and gardens, and trees in derelict corners" (Salbitano et al. 2016). Urban forests provide a wide range of ecosystem services, including removing air pollutants (Zhang et al. 2020), cooling the environment (Gillerot et al. 2024), mitigating stormwater runoff (Selbig et al. 2022), and supporting habitats for migratory birds (Buron et al. 2022). In particular, urban forests and other greenspaces provide cooling for residents, reducing the UHI effect on hot summer days (Kabisch et al. 2017). For example, increasing tree cover by 10% could significantly reduce the heat-related mortality in several cities (e.g., Phoenix, New York City) of the United States (Sinha et al. 2022). Among these services, cooling is especially important for improving the urban microclimate and mitigating the UHI effect. Several studies have shown that urban design and greenspaces can effectively alleviate the UHI effect and increase thermal comfort (Brown 2011; Jaganmohan et al. 2016; Elmes et al. 2017; Yang et al. 2017; Aram et al. 2019; Imran et al. 2019). Although some studies have confirmed that urban green areas were generally cooler than non-green areas, the cooling range of urban forests is still uncertain. Moreover, some studies have explored the potential factors that affect cooling effects. Yet, the influencing factors are usually examined in isolation (Qin et al. 2014; Liu et al. 2016; Martini et al. 2017; Chen et al. 2020a; Ma et al. 2021), which limits holistic consideration of all the influencing factors.

To address these research gaps, in this study, we systematically reviewed relevant literature to better understand the cooling effects of urban forests that serve as a NbS for solving urban environmental issues. Specifically, our research questions include: (1) what is the cooling range of urban forests; (2) what are the factors that may affect the cooling effects; and (3) how can we better manage urban forests to optimize cooling effects?

MATERIALS AND METHODS

This systematic review used the Web of Science databases to search literature about urban forests and cooling effects. We searched 20 keywords and their combinations (e.g., "urban + forest + cooling", "urban + forest + heat")(Table 1) in the topic and limited our search to peer-reviewed papers published in English before 2023 September 20. Initially, a total of 17,575 articles were found. Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) is a standardized guideline that improves transparent, consistent, and reproducible reporting of systematic reviews, including literature selection (Knobloch et

Table 1. Keywords and their combinations used in the Web of Science database before 2023 September 20.

Keywords and combinations	
1. Urban + forest + cooling	11. Urban park + cooling
2. Urban + forest + heat	12. Urban park + temperature
3. Street tree + cooling	13. Urban park + heat
4. Urban + forest + air temperature	14. Industrial trees + cooling
5. Trees + cities + cooling + temperature	15. Industrial trees + temperature
6. Urban green space + cooling	16. Industrial trees + heat
7. Urban green space + heat	17. Residential trees + cooling
8. Urban green space + temperature	18. Residential trees + temperature
9. School trees + heat	19. Residential trees + heat
10. School trees + temperature	20. School trees + cooling

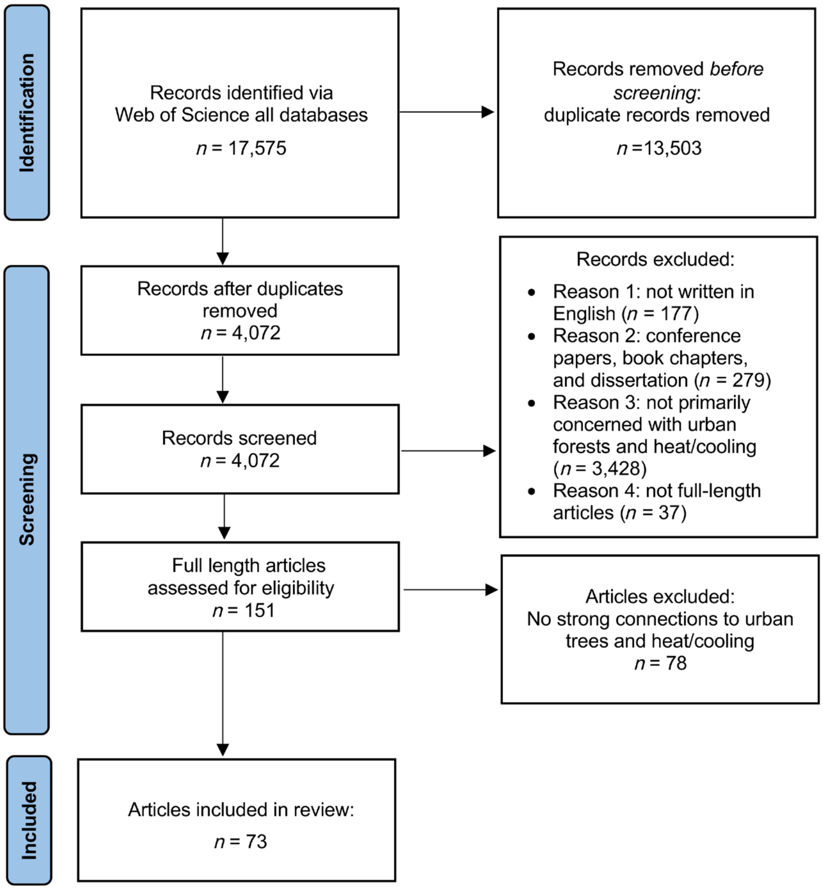

Figure 1. PRISMA (Preferred Reporting Items for Systematic Review and Meta-Analyses) diagram outlining selection and screening criteria for the systematic literature review process.

al. 2011). Following the PRISMA guidelines (Figure 1), we removed 13,503 duplicates from the total count of collected literature, leaving 4,072 articles for screening. We then excluded non-English literature, conference papers, book chapters, and dissertations. We reviewed the abstracts of these articles to determine the suitability of each publication for our objectives and excluded those articles that are not primarily concerned with urban forests and heat/cooling, also removing articles that were not full length. This left 151 full-length articles for eligibility. Among these, 78 articles were excluded due to lacking strong connections to urban trees and heat/cooling. Finally, a total of 73 peer-reviewed articles were included in the systematic review for further analysis.

RESULTS

In general, at the global level, the existing research on the cooling effects of urban forests is not evenly distributed geographically (Figure 2). The majority of the 73 articles covering a total of 90 study areas at the regional level were conducted in Asia (43 in total; 47.8%), followed by North America (17 in total; 18.9%) and Europe (14 in total; 15.6%), while Africa and Oceania were less studied (6 in total; 6.7%; each). South America was the least studied region (4 in total; 4.4%). This distribution underscores a concentration of research efforts in Asia, North America, and Europe, with other regions, particularly South America, Africa, and Oceania, receiving comparatively less focus. In addition, the total number of articles published has also changed over time (Figure 3). Overall, the selected 73 articles were published from 2007 to 2023, and the total number of publications has increased over time, with a significant increase since 2019. The comparatively lower number of publications in 2023 is likely due to the search cutoff date of 2023 September 20.

Cooling Range of Urban Forests

Based on the studies identified in our systematic review, we summarized the documented cooling effects of urban forests, drawing from studies that use air temperature (AT) and land surface temperature (LST) as key variables. These two variables capture different dimensions of urban thermal environments. AT reflects the conditions experienced directly by people and is crucial for assessing human thermal comfort, but it is often limited to localized measurements. LST enables largescale assessments through remote sensing, but it may not fully capture human-experienced heat. Both are commonly reported in the literature under the term "cooling", and their inclusion could provide a more comprehensive overview of urban forest cooling effects across multiple scales.

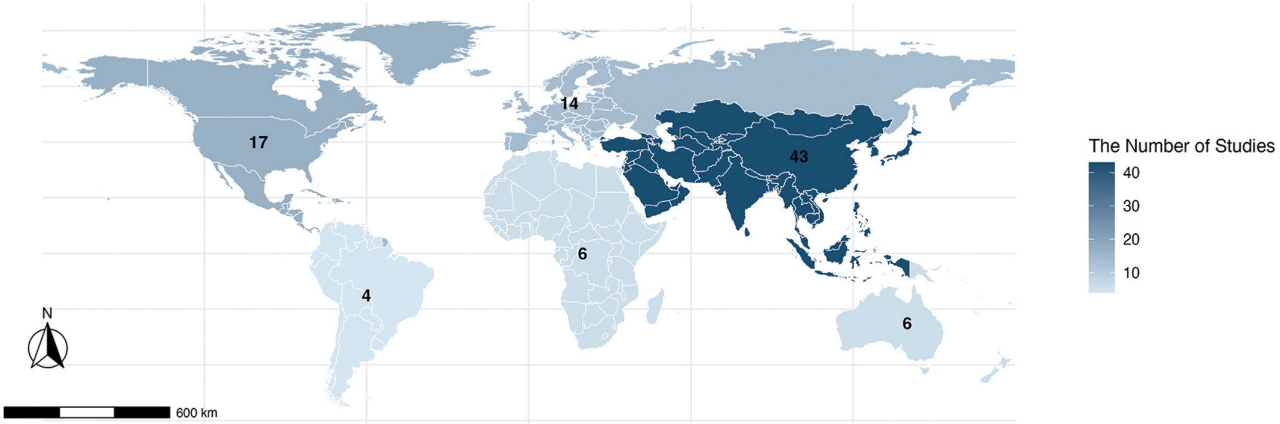

Figure 2. Distribution of study locations by regions around the world (*N* = 90). Note: one study covered two regions; two studies covered four regions; and two studies were global scale, covering all regions.

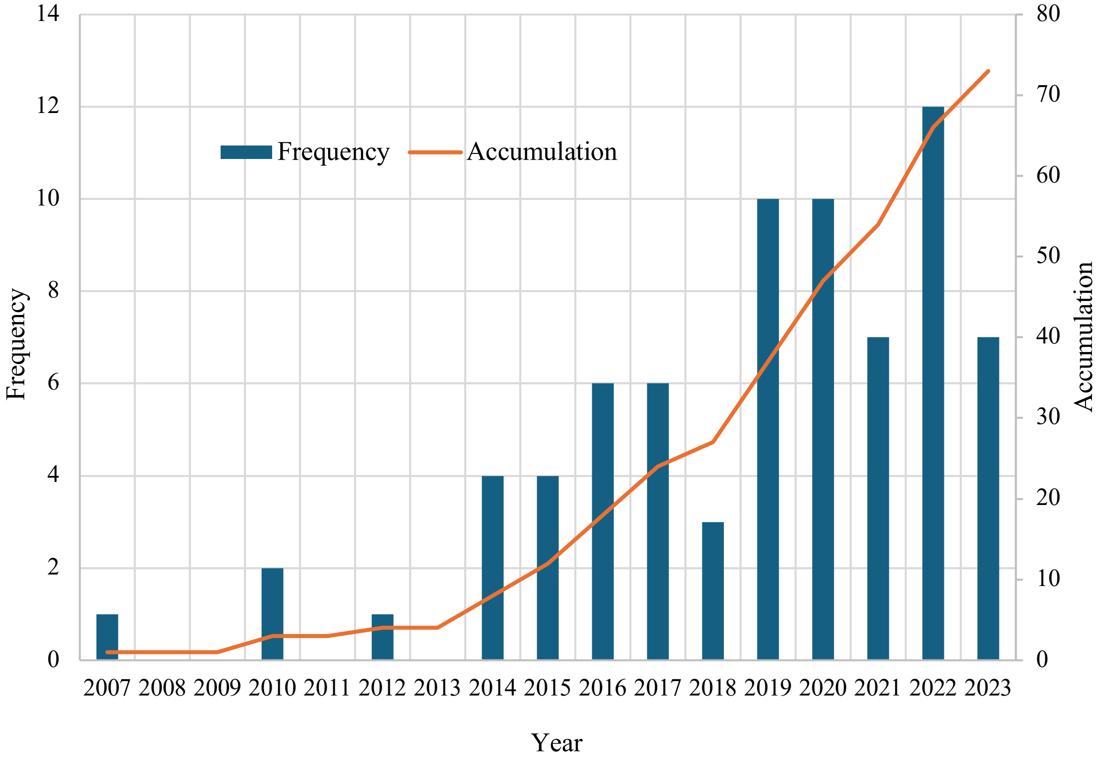

Figure 3. The total number of articles published on urban forests' cooling effects from 2007 to 2023. Note: blue bars indicate the total number of publications each year; the orange line indicates the accumulated total number of publications by year.

However, the wide variabilities in study contexts, methods, and climate conditions make it difficult to generalize the exact cooling range. In general, the cooling effects have a large variability due to several factors and processes involved. Although it is challenging to draw general conclusions, here we present some specific examples on the cooling benefits of urban forests across the globe.

Air Temperature (AT)

In general, the cooling effect on AT ranged from 0.2 °C to 2.2 °C at different study scales (Tsiros 2010; Coutts et al. 2016; Knight et al. 2021). At the park or garden scale, the cooling effect of urban forests was 0.8 °C on average, with trees playing a significant role in influencing this effect during daytime (Knight et al. 2021). At the street tree scale, the average daytime cooling was by about 0.2 °C to 0.6 °C, and the maximum cooling of street trees could reach 1.5 °C in Melbourne, Australia (Coutts et al. 2016). Cooling effects also fluctuated throughout the day. For example, Tsiros (2010) found that, at the street tree scale, the mean of cooling range was 0.5 °C to 1.6 °C at 14:00 hr and 0.4 °C to 2.2 °C at 17:00 hr; the maximum cooling was 2.2 °C in Athens, Greece.

Land Surface Temperature (LST)

The cooling effect on LST ranged from 0.02 °C to 0.68 °C at different study scales, and these studies usually used remote-sensing data from Landsat (Amani-Beni et al. 2019; Wang et al. 2020a; Wang et al. 2022; Cao et al. 2023). LST was shown to decrease with increasing urban tree canopy (Elmes et al. 2017). At the city scale, a 1% increase in urban tree canopy could lead to a 0.02 °C to 0.34 °C reduction in LST in Baltimore City, MD, United States (Wang et al. 2022). Wang et al. (2020a) evaluated urban trees' cooling efficiency across 118 cities in the United States and found considerable variation among cities, with an average value of 0.168 °C and a range of 0.040 °C to 0.574 °C. Similarly, Cao et al. (2023) found that when vegetation coverage in the Tongzhou District, Beijing, China, increased by 10%, temperatures decreased by 0.58 °C to 0.68°C. At the forest park scale, for every 10% increase in greenspace ratio, the LST decreases by 0.4 °C (Amani-Beni et al. 2019).

Some studies considered AT and LST at the same time and developed some models to estimate the cooling effects of urban vegetation (Marando et al. 2022; Iungman et al. 2023). For example, Marando et al. (2022) developed a model and found that urban green infrastructure (UGI) reduces urban temperatures in European cities by an average of 1.07 °C, with cooling effects reaching up to 2.9 °C; however, achieving a temperature reduction of 1 °C requires a minimum tree cover of 16%. In addition, Iungman et al. (2023) estimated that increasing tree coverage to 30% would reduce urban temperatures by an average of 0.4 °C in 93 European cities.

Environmental Factors and Urban Forest Cooling Effects

We found that there are several factors that affect cooling effects, including land cover types, tree canopy cover and canopy structures, leaf area index (LAI), forest types and tree species, and spatial arrangements of urban vegetation (Figure 4). In addition, the tree cooling effects are affected by background climate and weather conditions, seasonal variability, and distances from water bodies.

Land Cover Types

Land cover types have an impact on both air and land surface temperatures (Rhee et al. 2014). Strategically arranged vegetations in urban areas have been shown to be effective in mitigating the UHI effects by enhancing heat transport efficiency, thereby improving human thermal comfort (Ueyama and Ando 2020). Large areas with dense tree cover or forested land cover can provide more cooling, while impervious-dominated land cover (e.g., parking lots, concrete, asphalt) can significantly increase surface temperatures (Rhee et al. 2014; Pace et al. 2022). Different land covers show different degrees of cooling effects. For example, Wang et al. (2020b) found that forests and croplands contributed to cooling the city with varying cooling effects in Nanjing, China. Jaganmohan et al. (2016) compared the cooling effects of urban parks and forests in Leipzig, Germany, and found that the cooling effects were more pronounced in urban forests compared to parks. In terms of green roofs, a study from Changsha, China, showed that more trees and greater albedo are more effective than green roofs in reducing potential summer temperatures at the street level (Chen et al. 2020b). In addition, woodlands provided higher cooling for cities than grasslands (Zhou et al. 2019), and an increase in tree and shrub cover had a greater cooling effect than grass coverage within a location (Duncan et al. 2019).

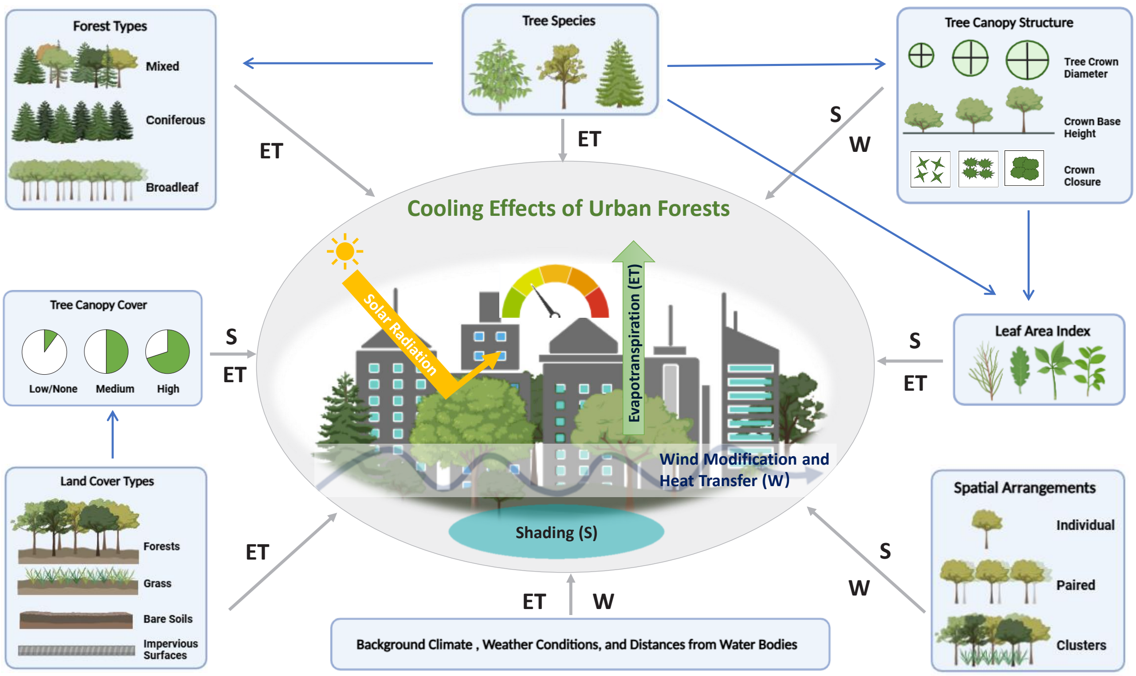

Figure 4. Illustration of main factors (based on the 73 reviewed articles) and processes affecting the cooling effects of urban forests. Urban forests contribute to cooling through 3 main mechanisms: shading (S), evapotranspiration (ET), and wind flow modification (W). Main factors include land cover types, forest types, tree species, tree canopy cover and canopy structures, leaf area index (LAI), and spatial arrangements of vegetation, background climate, weather conditions, and distances from water bodies. The blue arrows indicate the interactions among these main factors. The grey arrows indicate how these factors affect cooling effects through different processes.

In general, woodlands and water bodies both have obvious cooling effects (Fan et al. 2021a; Ma et al. 2021). The water area has the most cooling effect on LSTs compared to forests and grasslands, primarily due to their high heat capacity and heat absorption associated with evaporation, which reduces temperatures more effectively (Fan et al. 2021a). It is worth noting that water areas, water depths, and other factors can also influence the cooling effect of water bodies, which needs to be further investigated. However, woodlands provide a longer cooling effective distance than water bodies. For example, Ma et al. (2021) found that the cooling effective distance of woodlands was 330 m, while it was 180 m for water bodies.

Different land cover changes may also contribute to UHI effects. Increasing the area of greenspaces and water bodies, or decreasing the area of impervious surfaces, can reduce the LST (Naeem et al. 2018). For example, Khan et al. (2020) observed that transforming forestlands, grass/agricultural lands, and water bodies into impervious surfaces increased the LST by 1.52 °C from 1993 to 2018 in the city of Islamabad, Pakistan. This finding highlights that impervious surfaces have low heat transfer efficiency and tend to trap more solar energy. Moreover, Zhang and Liang (2018) found that land cover changes from croplands to urban lands increased LST by 0.18 °C during daytime and by 0.01 °C at night. In Indonesia, LSTs are rising due to the expansion of oil palm and other cash crops (Sabajo et al. 2017). In China, the estimated intensity of UHI has risen by 0.11 °C each decade in the spring due to land use change from 1991 to 2000 (He et al. 2007). Liu et al. (2016) found that there is a positive correlation between the size and number of land cover patches and heat contribution. Conversely, vegetation patches could provide a critical ecosystem benefit by offsetting UHI effects at a local scale (Melaas et al. 2016). An experiment conducted by Sato et al. (2016) investigated the effects of land use changes on future maximum surface AT in the Kanto region, Japan, and found that afforestation might reduce maximum near-surface air temperature.

Tree Canopy Cover and Canopy Structures

Tree cover is the core factor affecting temperature, and the cooling effect of urban trees/vegetation gradually increased with increasing tree/vegetation coverage (Zhou et al. 2014; Aalto et al. 2022; Zhang and Dai 2022). In other words, areas with a higher proportion of urban forests/vegetation tend to experience more pronounced cooling effects (Kong et al. 2014; Duncan et al. 2019; Masutomi et al. 2019; Wu et al. 2019). For example, Chen et al. (2020b) found that a 30% increase in tree cover can reduce incoming solar radiation and lower the average AT by 0.10 °C to 0.30 °C, while increasing tree cover by 60% can result in a drop of approximately 0.10 °C to 0.60 °C during the day. An assessment in a residential neighborhood in Phoenix, AZ, United States, showed that a linear relationship exists between percent canopy cover and AT reduction, with an average cooling of 0.14 °C per percent increase in tree cover (Middel et al. 2015). However, Ziter et al. (2019) observed a nonlinear decrease in temperature with increasing canopy cover, with the greatest cooling occurring when canopy cover exceeded 40%. Besides, McDonald et al. (2020) estimated that urban tree cover provides $5.3 billion to $12.1 billion (USD) worth of heat-reducing services (e.g., lower electricity consumption and heat-related health risks) annually in the United States.

In addition to tree canopy coverage, tree canopy structure plays a role in the cooling effects. Wang et al. (2023a) selected 167 trees across multiple species (e.g., *Koelreuteria paniculata*, *Osmanthus fragrans*, and *Elaeocarpus decipiens* Hemsl) in Hangzhou, China, and they found that under the same coverage, trees with a tree crown diameter (TCD) of 3 m have the strongest cooling capacity, followed by trees with a TCD of 7 m, and trees with a TCD of 5 m have the weakest cooling capacity. Tree canopy structure affects the AT by changing the penetration of solar radiation (Zheng et al. 2022). Canopy density also has a great effect on cooling and humidification, especially from 08:00 hr to 13:00 hr (Qin et al. 2014). Wang et al. (2023b) found that canopy structural characteristics (e.g., canopy density and vertical and horizontal canopy structures) had a strong relationship with the reduction of AT, and “high canopy coverage and unevenly distributed canopy in high layers” usually have stronger cooling effects during summer. Besides, crown closure, the height of the crown base, and trunk circumference influence cooling primarily by altering shading and transpiration capacity (Ren et al. 2018; Helletsgruber et al. 2020).

Leaf Area Index

Generally, LAI relates the leaf quantity, canopy size, and its density. An urban forest with a larger leaf area offers greater cooling potential (Moss et al. 2019); but in cold temperate and boreal regions, increasing LAI usually led to surface warming due to the reduction of surface albedo (Forzieri et al. 2017). For example, Zhang et al. (2022) identified LAI as a key factor positively correlated with park cooling intensities, finding that an increase of one unit in LAI could help increase park cooling intensities by 0.31 °C, with significant microclimatic regulation observed particularly during late evening hours. Guo et al. (2022) indicated that if the increase of one unit of LAI, the AT will decrease 2.5 °C. Su et al. (2022) estimated the cooling effects of urban vegetation in different climate zones and found that the LAI of different vegetation types has diverse correlations with cooling effects. In temperate rainforest cities, LAI, leaf boundary layer resistance, and dry mass per leaf area are the 3 primary tree traits that drive urban cooling (Eyster and Beckage 2023). Leaf thickness and leaf texture also affect the cooling effects of trees, and thick and rough leaves usually provide better cooling effects (Lin and Lin 2010).

Forest Types and Tree Species

Different forest types provide different cooling effects. The number and density of trees are the components of urban forest typologies which affect the cooling effect and microclimate (Martini et al. 2017). A study (Wang et al. 2020a) conducted with 118 cities in different biomes in the continental United States showed that cities in the biome dominated by broadleaf forests had significantly higher cooling effects compared to other biomes dominated by coniferous or sparse trees. Similarly, mixed and broadleaved forests showed better temperature reduction effect than coniferous forests in Seoul, Korea (Hwang et al. 2023). However, other studies had different results. For example, coniferous trees were found to be more effective than broadleaf trees in reducing temperature, and thermal comfort levels were most improved when coniferous trees were planted in paired settings (Choi et al. 2021). In temperate rainforest cities, coniferous species provide greater cooling than broadleaf species (Eyster and Beckage 2023). Moreover, Zheng et al. (2022) found in a subtropical island park that evergreen coniferous clusters had the highest cooling effect, followed by deciduous broad-leaved clusters, then evergreen broad leafed clusters, and palm dominated clusters (e.g., *Washingtonia filifera*) had the lowest cooling effect. This difference in results may be due to a combination of several factors, such as the height, canopy size, and shape of the trees (de Abreu-Harbich et al. 2015).

The mixed community of trees, shrubs, and grasses exhibited the most significant cooling effect (Fan et al. 2021b). Imran et al. (2019) evaluated the cooling effect of urban vegetation patches, including mixed forest (MF), a combination of mixed forest and grasslands (MFAG), and a combination of mixed shrublands and grasslands (MSAG); the results showed that MF and MFAG demonstrated greater cooling effect compared to MSAG.

In addition, tree species is an important factor that affects the cooling effects of urban forests. For example, Chen et al. (2019) investigated the cooling effects of 3 common urban tree species (*Schima superba*, *Eucalyptus citriodora,* and *Acacia auriculaeformis*) in a subtropical city (Guangzhou, China). They found that the strongest cooling effect of these 3 species was observed in the summer, and *S. superba* had the highest canopy transpiration cooling effect among the 3 species. In addition, Rahman et al. (2015) tested 5 tree species in Manchester, United Kingdom, and the results showed that *Pyrus calleryana* and *Crataegus laevigata* provided the greatest cooling, while *Malus* 'Rudolph' had low cooling ability, and *Prunus* 'Umineko' and *Sorbus arnoldiana* showed moderate cooling effects. However, it is noted that these trees were 10 years to 11 years old, and the cooling patterns may change as they mature. Gillerot et al. (2022) also indicated that tree ages may have an impact on cooling effects. In a tropical climate (Bangkok, Thailand), *Melaleuca quinquenervia* (Cav.) S.T. Blake, *Albizia saman* (Jacq.) Merr., and *Chukrasia tabularis* A. Juss. were found to substantially reduce temperatures, while other species like *Hopea odorata* Roxb. and *Millingtonia hortensis* L.f. provided limited cooling (Yarnvudhi et al. 2022). Finally, strong shade casting, small leafed evergreen species can enhance cooling effects according to the study of 131 forest plots across 4 European countries (Gillerot et al. 2022). Furthermore, higher tree species diversity shows an important role for mitigating UHI effects and cooling cities (Wang et al. 2021).

Spatial Arrangements of Urban Vegetation

The spatial arrangement of urban vegetation was found to be a factor in affecting the cooling effect (de Abreu-Harbich et al. 2015; Fan et al. 2015; Choi et al. 2021). For instance, trees in clusters can provide more cooling compared with individual trees, and clustering trees in 2 lines and 5 to 10 trees in each line provides more thermal comfort than other designs (de Abreu-Harbich et al. 2015). The greatest improvement in thermal comfort was seen when coniferous trees were planted in a paired arrangement (Choi et al. 2021). Clustered or less fragmented patterns of green vegetation are more effective in reducing surface temperatures than dispersed patterns (Fan et al. 2015). With a fixed amount of vegetation cover, an aggregated distribution has been shown to produce a better cooling effect compared to a fragmented distribution, and increasing the overall shape complexity of woodlands was found to enhance the cooling effects (Zhou et al. 2019). In addition, Gao et al. (2023) found that the medium sized (6 ha to 8 ha) park with greater than 5 ha to 6 ha internal greenspaces had higher cooling efficiency in Zhengzhou, China. Lu et al. (2012) also found that urban parks with more rounded shapes tend to provide greater cooling effects in Chongqing, China.

Background Climate and Weather Conditions, Seasonal Variability, and Locality

The cooling effect of urban vegetation highly depends on the background climate of urban areas (Su et al. 2020). The cooling effects of trees exhibit seasonal and diurnal variations and are influenced by prevailing weather conditions (Lindén et al. 2016). Meteorological variables, such as wind speed (Lu et al. 2017), have complex impacts on the cooling effects of urban forests. This means that increasing the urban tree cover to mitigate heat stress is not necessarily suitable for cities with different climates. For example, in arid African cities, urban trees' cooling efficiency (i.e., the negative ratio of the LST change to the tree cover percentage change) increased with AT up to 34 °C but decreased beyond this threshold due to heat induced limits on transpiration (Cheng et al. 2022). Therefore, in African cities, especially those with arid climates, it may be inadvisable to rely solely on increasing tree cover to mitigate urban heat stress in a warming future (Cheng et al. 2022).

Additionally, urban vegetation shows different cooling effects in different seasons, and the stronger cooling is generally in warm seasons, daytime periods, and at low latitude zones (Su et al. 2020). Similarly, Fung and Jim (2019) also found that woodland cooling was strongest during summer and on sunny days while less pronounced in winter and on cloudy days. Yang et al. (2017) indicated that urban greenspaces exhibited significant cooling effects across all seasons except winter. Even on the same day, urban forests showed different cooling effects. For example, the influence of the tree canopy on the LST was stronger during the day than at night (Chen et al. 2020a), and one study (Yu et al. 2020) found that tree shade at 07:30 has the most important cooling effects on LST in both Tampa, FL, and New York City, NY, in the United States.

Furthermore, the cooling effects might be affected by the distance from the sea or water bodies (Vo and Hu 2021; Zhang et al. 2022). For example, Zhang et al. (2022) observed that parks with more trees and those located closer to the sea tended to be cooler, probably due to the high heat capacity of water moderating temperatures and driving continuous air exchange, enhancing cooling near water body areas. An experiment conducted by Sato et al. (2016) revealed that the effect of reforestation was primarily determined by the total distance that the prevailing air masses passed above the afforested areas, which suggests that afforestation along the coast of Kanagawa could help reduce high urban temperatures in the inland areas of Saitama and Tokyo, Japan. Besides, Aalto et al. (2022) found that the elevation affected cooling effects on LST: when the altitude rises above 1,000 m, the cooling effect was reduced by about 50% compared to lowlands, probably because lower temperatures at high elevations limit plant evapotranspiration, thereby reducing evapotranspiration cooling, while the effect of canopy albedo may not change dramatically (Zeng et al. 2021).

DISCUSSION

The Environmental Factors and Related Mechanisms of the Cooling Effects of Urban Forests

Although this review did not directly measure or quantify the mechanisms of the cooling effects of urban forests, several studies included in this analysis (Khan et al. 2020; Zheng et al. 2022) provided interpretive insights into the mechanisms based on observed temperature patterns and contextual environmental factors. Urban forests contribute to the cooling mainly through 3 mechanisms: shading, evapotranspiration, and wind flow modification (Figure 4). First of all, trees can reduce the amount of solar radiation that reaches and heats the ground surface by providing shade. Shading provided by trees can significantly affect human thermal comfort (de Abreu-Harbich et al. 2015). Secondly, urban vegetation could increase the rate of evapotranspiration more than the impervious surfaces (Hao et al. 2023). The process of evapotranspiration, turning water into vapor, could provide moisture and reduce the AT. During hot summer days, trees usually absorb more water via roots and transpire to the atmosphere, which increases the humidity (Khan et al. 2020). Lastly, urban forests can affect the moisture and heat balance between trees and surroundings through reducing wind speed, enhancing airflow turbulence, changing outdoor flow field characteristics, and wind field distribution (Zheng et al. 2023). However, in dense urban contexts, the impact of trees on wind speed is minimal (Kong et al. 2017). In summary, tree canopy structure affected the temperature by changing the amount of solar radiation that penetrated it; additionally, the transpiration of leaves produced water vapor, which could increase the relative humidity and cool the air (Zheng et al. 2022). The results of these 3 main mechanisms are the microclimates regulation, which makes urban forest areas cooler than their surroundings.

This study helps to understand the cooling process by identifying and categorizing the key factors influencing AT and LST identified in existing studies. By systematically analyzing these influencing factors, this study also helps bridge the gap between empirical observations and the mechanistic understanding of urban forests' cooling effects. For example, in general, shading mainly depends on tree canopy, tree form and placement, LAI, and daily and seasonal variabilities (Berry et al. 2013; Hwang et al. 2015); evapotranspiration could be affected by land use and land cover changes, forest cover, forest types and tree species, and LAI (Sun et al. 2011; Li et al. 2017; Litvak et al. 2017; Ning et al. 2020); and wind flow modification could be influenced by spatial arrangements of trees and tree canopy structure (Gromke et al. 2008; Hsieh et al. 2016; Jian et al. 2018).

Implications to Urban Forestry for Optimizing Cooling

Urban forests are considered a key strategy in mitigating UHI effects. Current research indicates that increasing tree cover in cities may be the best solution for improving local thermal comfort during peak daytime heat (Gillerot et al. 2024). It is important to protect existing urban forests and increase tree canopy cover (e.g., by planting street trees) to enhance urban resilience to climate change (Ettinger et al. 2024).

To effectively mitigate UHI effects, it is important to not only increase tree canopy area and optimize its spatial configuration but also to consider the vertical canopy structure (Chen et al. 2020a). For example, trees with dense and big canopies (Helletsgruber et al. 2020), large crowns, short trunks, and dense canopies (Kong et al. 2017) could be considered for providing more cooling. Furthermore, due to global warming and UHI effects on urban tree growth, it would be better to select the heat tolerant urban tree species. For instance, Freeman maple (*Acer × freemanii*), Ginkgo (*Ginkgo biloba*), and Honey locust (*Gleditsia triacanthos*) are more heat resistant (Percival 2023). In addition, urban greening managers could also consider native tree species, which could preserve local species and reduce the costs of tree care.

Furthermore, the location and planting methods of trees need to be carefully considered. Within the city, we could consider the size and shape of urban parks. For example, considering the medium sized (6 ha to 8 ha) park with more than 5 ha to 6 ha internal greenspace (Gao et al. 2023) and more rounded shapes (Lu et al. 2012). In addition, the spatial arrangement of urban trees also needs to be considered. For instance, planting coniferous trees in a paired arrangement (Choi et al. 2021) and clustering trees or other vegetation to provide more thermal comfort than a dispersed design (de Abreu-Harbich et al. 2015; Fan et al. 2015). At the same time, afforestation in coastal areas might be a valid option for reducing inland city temperatures (Sato et al. 2016). Besides, the distance between urban greenspaces and water areas needs to be considered (Vo and Hu 2021), and we can plant more trees around a lake to achieve effective cooling effects (Zhou et al. 2022). In terms of the land cover, since impervious surfaces, such as parking lots, buildings, or roads, can significantly increase the surface temperature, it is recommended to divide large parking lots into smaller ones (Rhee et al. 2014).

Research Gaps, Limitations, and Future Directions

Although many researchers have explored the extent to which urban forests have more cooling effects at different study scales, it is still challenging to give a specific value to answer the question of how much the air or land surface temperatures can be reduced by urban forests. The cooling effects of urban forests are affected by many variables, such as tree canopy cover, tree species, canopy structure, and background climate. These factors also vary in different cities, which makes it hard to estimate the cooling value in a certain city based on previous studies. Therefore, for a specific city, it is necessary to collect field observational data to evaluate its urban forests' cooling effects locally. Moreover, further research is needed to assess the cooling effect of urban forests using field measurements of both LST and AT to obtain more accurate and representative data, rather than solely relying on remote sensing data. In addition, based on the literature that was researched in this review, only about 36 tree species have been studied. Therefore, data on more tree species are needed to explore whether they could provide cooling and to what extent. We also need broader geographic research coverage, particularly in the regions of Africa and South America. We also found that most studies were conducted in temperate climates (41 in total; 61.2%), followed by continental climates (15 in total; 22.4%) and arid climates (7 in total; 10.4%), while few studies were conducted in tropical climates (4 in total; 6.0%) and no study was conducted in polar climates (N = 67)(Note: 12 studies were global in scale or whole countries that did not distinguish climate zones; 3 studies covered two cities each, and 1 study covered 4 cities). As a result, tropical and polar climate zones remain understudied and require further studies to provide more climate specific evidence to better inform practical decisions across different climate zones. Additionally, we need to learn more about real world urban forest best management practices (e.g., a review of municipal technical standards and urban forest management plans, interviews with practitioners), which may not be captured in the scientific literature alone. The limitations of this review include: (1) some relevant studies published in other databases outside of the Web of Science and/or in non-English languages may not be searched and/or included; (2) 20 keywords and their combinations used in this review could neglect some relevant studies; and (3) limited data exist at the tree species level and for variations in climate, measurement methods, and study scales.

CONCLUSIONS

The current literature strongly supports the notion that urban areas with greenspaces including urban forests were cooler than areas without them. The primary cooling mechanisms for urban forests affecting energy balances include direct shading of ground surfaces, heat loss through evaporation, and heat dissipation through altering wind profiles. The cooling effects vary by a suite of factors related to LAI, dominance of land cover types, forest types, tree species, tree canopy cover and canopy structure, spatial arrangements of urban vegetation, background climate and weather conditions, seasonal variability, and distances from water bodies. The findings of this review offer insights into the cooling processes and energy balance response to forest cover change at multiple scales. Also, information can help guide future urban planning and urban forest management by informing tree species selection, landscape design, and site specific urban greening strategies that consider local climate and contexts, helping to maximize the cooling benefits of urban forests with limited spaces in cities.

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Résumé. Les forêts urbaines sont largement reconnues comme une solution naturelle pour lutter contre les changements environnementaux urbains tels que les îlots de chaleur urbains. Bien que des recherches antérieures aient étudié les effets rafraîchissants des forêts urbaines, l'ampleur de cet impact et les facteurs qui l'influencent restent flous et n'ont pas encore fait l'objet d'une synthèse exhaustive. Pour combler cette lacune de recherche, nous avons procédé à une revue systématique de la littérature à l'aide de la méthode PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis soit Norme de réalisation de revue systématique de méta-analyses en français) en utilisant 20 mots-clés et leurs diverses combinaisons sur la plateforme Web of Science afin de répondre aux trois principales questions de la recherche: (1) quelle est la marge de rafraîchissement des forêts urbaines; (2) quels sont les facteurs susceptibles d'influencer les effets de rafraîchissement; et (3) comment mieux gérer les forêts urbaines afin d'optimiser les effets de rafraîchissement? Nous avons systématiquement examiné 73 articles révisés par des pairs, sélectionnés parmi un bassin initial de 4 072 résultats de recherche, en suivant la méthode PRISMA. Nous avons constaté que les espaces verts urbains ont généralement des effets rafraîchissants, mais qu'il est difficile de tirer une conclusion nette sur l'ampleur de cet impact en raison des variations dans la conception des études, les méthodes de mesure, les échelles spatiales et les contextes climatiques locaux. De plus, les principaux facteurs d'influence sont les occupations variées du sol, la couverture arborée et la structure de la canopée, l'indice de surface foliaire, les types de forêts et les espèces d'arbres, ainsi que la disposition spatiale de la végétation urbaine. En outre, les avantages des forêts urbaines en matière de rafraîchissement pourraient être influencés par le climat et les conditions météorologiques locales, ainsi qu'en fonction de l'éloignement par rapport aux plans d'eau. Ces constats peuvent aider à orienter les efforts de verdissement urbain (par exemple, les types d'occupation du sol, le choix des espèces d'arbres et l'aménagement des espaces) afin de garantir un futur plus verdoyant et plus frais.

Zusammenfassung. Stadtwälder sind weithin als naturbasierte Lösung für städtische Umweltveränderungen wie städtische Wärmeinseln anerkannt. Obwohl frühere Studien die kühlenden Effekte von Stadtwäldern untersucht haben, sind das Ausmaß dieses Effekts und die damit verbundenen Einflussfaktoren nach wie vor unklar und wurden noch nicht umfassend zusammengefasst. Um diese Forschungslücke zu schließen, haben wir eine systematische Literaturauswertung unter Verwendung der PRISMA-Methode (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) mit 20 Schlüsselwörtern und deren Kombinationen in Web of Science durchgeführt, um drei zentrale Forschungsfragen zu beantworten: (1) Wie groß ist der Kühlungsbereich von Stadtwäldern? (2) Welche Faktoren können die Kühlwirkung beeinflussen? (3) Wie können Stadtwälder besser bewirtschaftet werden, um die Kühlwirkung zu optimieren? Wir haben 73 begutachtete Artikel, die aus einer anfänglichen Auswahl von 4.072 Suchergebnissen ausgewählt wurden, systematisch nach der PRISMA-Methode überprüft. Wir haben festgestellt, dass städtische Grünflächen im Allgemeinen kühlende Effekte haben, aber es ist schwierig, eine klare Schlussfolgerung zum Kühlungsbereich zu ziehen, da es Unterschiede im Studiendesign, den Messansätzen, den räumlichen Maßstäben und den lokalen Klimakontexten gibt. Zu den wichtigsten Einflussfaktoren zählen außerdem die Zusammensetzung der Bodenbedeckung, die Baumbedeckung und die Kronenstrukturen, der Blattflächenindex, die Waldtypen und Baumarten sowie die räumliche Anordnung der städtischen Vegetation. Darüber hinaus können die kühlenden Vorteile von Stadtwäldern durch das lokale Grundklima und die Wetterbedingungen sowie durch die Entfernung zu Gewässern beeinflusst werden. Diese Erkenntnisse können als Leitfaden für städtische Begrünungsmaßnahmen (z. B. Bodenbedeckungstypen, Auswahl der Baumarten und räumliche Anordnung) dienen, um eine grünere und kühlere Zukunft zu erreichen.

Resumen. Los bosques urbanos han sido ampliamente reconocidos como una solución natural para abordar los cambios ambientales urbanos, como las islas de calor. Si bien estudios previos han explorado los efectos de enfriamiento de los bosques urbanos, el alcance de este efecto y los factores de influencia relacionados siguen siendo inciertos y aún no se han sintetizado exhaustivamente. Para subsanar esta deficiencia en la investigación, realizamos una revisión sistemática de la literatura utilizando el método de Elementos de Referencia para Publicar Revisiones Sistemáticas y Metaanálisis (PRISMA, *por sus siglas en inglés*) con 20 palabras clave y sus combinaciones en Web of Science para abordar tres preguntas principales de investigación: (1) ¿cuál es el rango de enfriamiento de los bosques urbanos?; (2) ¿cuáles son los factores que pueden afectar los efectos de enfriamiento?; y (3) ¿cómo podemos gestionar mejor los bosques urbanos para optimizar los efectos de enfriamiento? Revisamos sistemáticamente 73 artículos revisados por pares, seleccionados de un conjunto inicial de 4072 resultados de búsqueda siguiendo el método PRISMA. Descubrimos que los espacios verdes urbanos generalmente tienen efectos de enfriamiento, pero resulta difícil extraer una conclusión clara sobre el rango de enfriamiento debido a la variación en el diseño de los estudios, los enfoques de medición, las escalas espaciales y los contextos climáticos locales. Además, los principales factores influyentes incluyen la composición de la cobertura terrestre, la cobertura arbórea y la estructura del dosel, el índice de área foliar, los tipos de bosque y las especies arbóreas, y la distribución espacial de la vegetación urbana. Asimismo, los beneficios de refrigeración de los bosques urbanos podrían verse afectados por las condiciones climáticas y meteorológicas locales, así como por la distancia a los cuerpos de agua. Estos hallazgos pueden ayudar a orientar las iniciativas de reverdecimiento urbano (p. ej., tipos de cobertura terrestre, selección de especies arbóreas y distribución espacial) para lograr un futuro más verde y fresco.