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CHAPTER SIX

Understanding and measuring the cooling performance of trees

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6.1 Introduction

Trees and the urban forest are essential cooling devices for adapting cities to urban heat. This chapter explores the potential of these solutions to adapt to climate change while addressing essential considerations and challenges within the urban design domain. Thermal mechanisms through which trees contribute to cooling urban environments are presented, ranging from shade provision and evapotranspiration at the scale of the tree to the scale of a tree ensemble, area, and urban forest network. Principles for careful green space planning and strategically placing trees are introduced with a specific focus on the spatial factors that optimize their cooling effects and maximize their benefits. Additionally, this chapter highlights the value of onsite measurements in assessing the magnitude of trees' cooling potential. Data collection methods are introduced to evaluate the impact of trees and other nature-based interventions on temperature, humidity, and wind patterns. Finally, this chapter discusses the complex nature of urban environments, related limitations and opportunities for enlarging, maintaining and integrating green areas into densely built areas.

Adapting to Urban Heat:
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6.2 The role of urban forests as cooling devices for adapting to urban heat

The effects of heat in cities represent a rising concern as more frequent heatwaves and higher magnitudes of urban heat islands converge to create more challenging urban thermal environments (Wilby, 2007). The symbiotic influence generates warm thermal conditions that are projected to have increasingly harmful effects on human health, air quality, energy infrastructures, and water availability (Zhao et al., 2018). As temperature increases in cities, so does the urgency to develop strategies to mitigate heat in the transition to adaptive urban areas. Many factors that impact atmospheric and surface thermal conditions in cities are within the control of urban designers and planners, including the morphological configuration of urban tissue (building height, height-to-width ratio of streets), the selection of building and pavement materials and the design of unbuilt spaces. Together, they influence thermal mechanisms such as absorption and reflection of longwave and shortwave radiation, as well as aerodynamic roughness and, thus, airflow movement and velocity.

Increasing city vegetation cover is among the major strategies urban planners and designers have explored to mitigate heat stress (Jacobs et al., 2018). Urban vegetation and the broader concept of urban green infrastructure (UGI) are widely credited for their potential to cool urban spaces (Ramyar et al., 2021). During the last decade, understanding nature as an "infrastructure" with ecosystem services values has started to drive policies for climate adaptation at various administrative levels. However, the elaboration and actualization of green infrastructure have continued to be challenged by urban development drivers that pressure green areas, boosting their fragmentation and limiting the space available for increasing green cover (Chatzimentor et al., 2020). Only in recent years have the higher frequency of heat waves and the heightened awareness about the land cover influence on urban heat islands mainstreamed the debate on the climate-control benefits of vegetation. Conceptualized as a planning approach, UGI is seen today as a promising solution for heat stress adaptation and a provider of multiple benefits such as enhanced biodiversity, improved quality of life, human health, and (social) well-being.

However, implementing thermal-effective UGI continues to pose challenges for planners and designers. Despite scientific evidence supporting the positive impact of vegetation on temperature reduction and thermal comfort (Marando et al., 2022), there is a need for better elaboration of the various vegetation types and their possible impacts on cooling for effective climate adaptation. Variations in the composition and configuration of vegetation can also impact cooling performance in different ways, according to the specific microclimatic characteristics and growth conditions of each location in the city. Moreover, analysis reveals a need for more standardization in protocols and classification systems for green infrastructure, to allow accurate reporting and comparison of data (Bartesaghi Koc et al., 2018). On the positive side, there is a growing body of knowledge on foundational components of UGI, such as urban trees and their contribution to city thermal conditions in cities. As such, of the various components that are considered in the concept of UGI, we will focus on trees as a foundational and critical contributor to cooling in cities.

Trees are the largest and most elementary component of urban vegetation and thus represent an evident first step in elaborating the amelioration of urban heat by vegetation. Urban trees occur in an array of configurations and scales, from individual specimens to a variety of groups, linear configurations, and wooded complexes, which together give rise to the overarching term "urban forest" (de Wit & van der Velde, 2024). This term encompasses not only the woodland mosaic at its different scales but also presents a frame to focus on trees as the mainframe of urban greenspace, to manage tree inventories and develop integrated and strategically planned networks of greenery within the urban fabric. As such, the urban forest and its disciplinary specialization urban forestry, offers a holistic framework to not only cool cities down but also to provide other regulating services such as air quality improvement, flood control, and carbon sequestration.

This chapter outlines the foundational factors enabling vegetation to cool cities. To do this, it expands on the base conditions that determine heat amelioration by the urban forest. Recognizing that variables such as scale and situation may have significantly different impacts on the urban forest's cooling potential, this chapter focuses first on the fundamental cooling mechanisms of individual trees and their effect on different meteorological indices such as air temperature (AT), surface temperature (ST), and mean radiant temperature (MRT). It expands on differences in cooling performances arising from variations in species' physiognomic, physiologic, and allometric traits. It provides insights into instruments, methods, and protocols to measure various meteorological values. It extends on these findings by discussing variables at the single-tree scale, such as the impact on performances through differences in urban morphology, building-space configurations, and (tree)growth conditions. It expands on further areas of inquiry, such as the cooling potential of tree groups, lines, complexes, systems, and combinations of trees with other vegetation types. Through this exploration, this chapter hopes to provide a foundational understanding of how trees and the urban forest can help cities adapt to thermal extremes brought about by UHI and climate change.

6.3 Cooling mechanisms of tree

A common understanding of how trees impact city thermal conditions includes shading and lesser-known phenomena such as evaporative cooling and altering air movement (see Fig. 6.1). To understand how these processes work and their specific influence on urban thermal conditions, we elaborate on their mechanisms. Additionally, Box 6.1 gives more information about the Climate Arboretum Research Project, in which an extensive Tree Architecture Typology was developed and a large sample of trees pertaining to the different types was analyzed on their cooling potential.

6.3.1 Shading and radiation

Shading refers to the characteristics of trees that impact reflection, absorption, and transmission of solar radiation through the tree canopy, and ensuing radiant energy reaching objects and surfaces beneath them (Oke, 1989). At the scale of the leaf, up to 30% of visible and infrared radiation can be reflected and up to 50% absorbed for processes such as photosynthesis. A single layer of leaves in a tree crown can thus

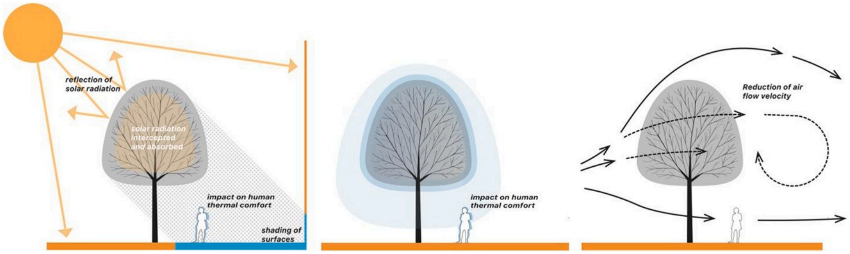

Figure 6.1 Cooling mechanisms of trees: shading and radiation, evaporative cooling, and influencing air flows.

hypothetically prohibit up to 80% of radiation from reaching people, objects, and surfaces beneath it. However, significant variations in these percentages occur through differences in leaf attributes such as size, shape, color, thickness, texture, and orientation. Research on leaf traits and their impact on shade cooling results in two overall trait categories: foliage texture and foliage luminance (Van der VELDE et al., 2023). Foliage texture combines attributes such as leaf size, leaf shape, and leaf orientation, while foliage luminance combines the attributes of leaf color and leaf thickness. Using combinations of these two categories, trees can be classified into one of six foliage categories: (1) coarse–light, (2) fine–light, (3) coarse–medium, (4) fine–medium, (5) coarse–dark, and (6) fine–dark. Fine-dark classes of foliage will have the highest shadow density, while coarse-light classes the lowest.

These performances can vary given that trees consist of multiple layers of leaves, a phenomenon often expressed as leaf area index (LAI). LAI is defined as half the total (all-sided) leaf area per unit projection area on the ground [m^2 m^{-2}] (Chen & Black, 1992). Some trees can have an LAI of around 10, a leaf area more than 20 times the crown projection area; in other words, 10 layers of foliage for radiation to pass through. LAI is tempered by the presence of gaps between leaves through which radiation can freely pass caused by the spacing of individual leaves, by leaf orientation, and by foliage distribution, specifically clumping.

Foliage clumping results from the patterns of branching particular to each species. An even and concentric zoning of branches and twigs will result in a more continuous foliage structure with a higher reflection and radiation interception. At the same time, less even, more random branching will lead to concentrated and less concentrated patches of foliage, which let radiation through. Within the Urban Climate Arboreta project, Van der Velde, de Wit, and Pouderoijen (2023) developed a twofold classification for trees: those having an Even Wood Zoning (regular distribution of branches) and those with an Uneven Wood Zoning (irregular distribution of branches). The grain and density of branches also impact foliage distribution, resulting in three possible classes: (1) coarse grain–low density, (2) average grain–medium density, and (3) fine grain–high density.

Finally, at the whole tree scale, the proportional ratio of crown width (measured at the point of maximum horizontal dimension of the crown) and crown height (measured at the point of maximum vertical dimension of the crown) also has an impact on reflection, absorption, and transmission of solar radiation. Of the sample trees analyzed, five proportion groups

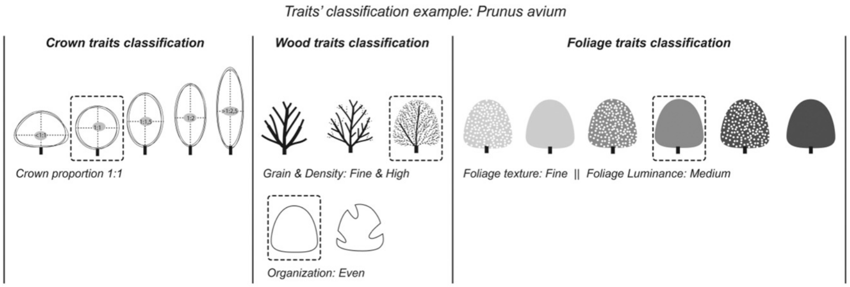

Figure 6.2 Trait classifications for Cool Tree Architecture Typology.

were identified: < 1:1; 1:1; 1:1.5; 1:2; and > 1:2.5. Using these attribute classes, any tree may be classified into a particular architectural type, from its specific category of canopy proportion, wood grain, wood density, wood zoning, and foliage. Such a typology allows for a large number of tree species to be reduced to a reduced number of tree architecture types, each with a specific impact on the reflection, absorption, and transmission of solar radiation (Fig. 6.2). These impacts are threefold: on MRT, on ST and on-AT. Values of MRT reduction beneath certain tree canopies can reach 30°C. ATs can also be brought down up to 2°C by the reflective capacity of the canopy, its albedo (the degree of reflection of light, measured on a scale from 0 to 1.0), and evapotranspiration processes.

6.3.2 Evaporative cooling

A second mechanism, evaporative cooling, impacts city thermal conditions, precisely ATs. Moisture released from tiny pores on the underside of the leaf (stomata) during photosynthesis evaporates and causes a drop in AT. Evaporation requires energy, which is extracted from the air as heat. For every liter of water evaporated, an average of 700 W of heat is absorbed from the atmosphere. Individual trees can produce tens of liters of water per day, with some mature trees reaching many hundreds of liters per day (Wullschleger et al., 1998). The evaporation of 100 L of water produces a cooling capacity of 70 kWh, equivalent to two average-sized air conditioners. Cool air produced in the canopy is heavier than warm air and consequently drops down to the area beneath the canopy, further impacting thermal comfort.

6.3.3 Air flows

Trees also influence the movement of air, which can have a positive but also a negative effect on thermal comfort, as convective heat transfer is limited in areas with low wind speeds. Furthermore, lower wind speeds and decreased mixing of air lead to a reduction in replacing air saturated by evapotranspiration by drier air. The wind pattern around the tree and the decrease in wind speed in the wake area behind the tree are highly influenced by the porosity of the crown. The denser the crown, the more the flow pattern resembles that of a solid object like a building; most air is deflected around the tree, little air penetrates through the vegetation and wind speed reduction is high. The more porous the crown, the more air that goes through the vegetation and the less deflected air, leading to a smaller reduction in wind speed.

BOX 6.1 Measuring the cooling effect of trees.

Urban Climate Arboreta (UCA)

Developing accurate insights into how a tree's physical form and characteristics affect its cooling capacity is the focus of the Urban Climate Arboreta research project run by the research group urban forestry at the Faculty of Architecture and the Built Environment, TU Delft. The project's core is the studying and measuring of living trees in controlled (outdoor) laboratories. The 68 trees in this arboretum form part of a set of outdoor laboratories in different locations around the Netherlands. The trees chosen are species commonly planted in Dutch cities, but also include less common species that show potential for cooling and resistance to extreme heat and drought. The cooling effect of specimens of each tree architecture type in the UCA is measured. Various instruments measure air temperature, mean radiant temperature, and humidity (see Figs. 6.3 and 6.4) on hot days with clear skies and temperatures above 20°C.

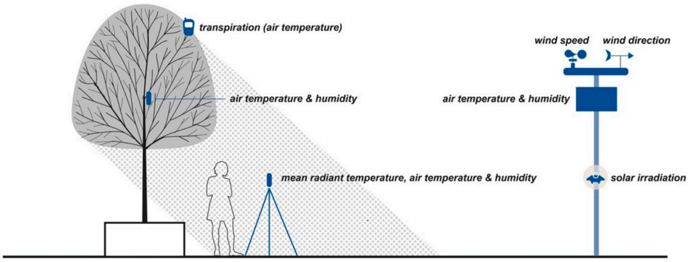

Figure 6.3 Setting for measuring the cooling effect of trees in the Climate Arboretum Project.

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BOX 6.1 Measuring the cooling effect of trees. (Continued)

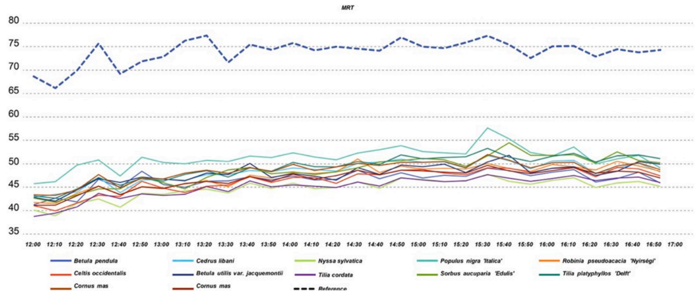

Figure 6.4 Data sample of Mean Radiant Temperature values during a measurement campaign.

Results show that single trees contribute to lower mean radiant temperatures up to 33°C and air temperatures up to 2.2°C locally. The reduction in mean radiant temperatures under the tree canopy underscores the impact of trees, particularly in mitigating radiant heat and thereby enhancing thermal comfort compared to sun-exposed locations. Cooling differences among species are less visible in extreme weather conditions, with air temperatures at the reference weather station above 30°C.

6.4 Key cooling factors of urban forests

Despite the recognized cooling mechanisms of vegetation, quantifying the overall cooling effect in urban environments remains a significant challenge. This difficulty in isolating the cooling intensity and extension of vegetation arises from the thermal interplay of multiple factors, including (1) the variety of green types and their composition and configuration, (2) the morphological characteristics of urban environments and their thermal mechanisms, and (3) the geographical and climate context of the region or city.

As such, although research has advanced considerably in terms of techniques and approaches to quantifying the cooling effect of vegetation at an elemental level, studies' results often cannot be aligned due to the methodological differences and variations in vegetation characteristics, morphology, context, and abiotic growing conditions. As a result, designers and policymakers remain challenged in defining guidelines for implementing urban greenspaces with a heat-adaptive perspective. Instead of solely focusing on quantifying atmospheric and ST reductions, understanding what key characteristics boost the cooling performance of green spaces has the best potential to drive comprehensive design thinking in the application of the urban forest and its thermal regulatory services.

The first critical consensus exists in the literature about the negative correlation between green coverage and urban temperatures. Green coverage refers to the ratio or percentage of urban surface occupied by vegetation. A high green coverage is generally associated with lower atmospheric and ST due to shading and evapotranspiration processes, and thus UHI magnitude. Increasing up to 40% of green coverage can bring AT reductions above 1°C (Morakinyo et al., 2018). However, the magnitude of temperature reduction depends greatly on the vegetation types and composition of green patches since the impact of evapotranspiration and shadow depends on plant species and their physical characteristics. For example, the shading contribution of trees is structurally higher than that of shrubs and grass. The variation in cooling potential is significant, with shrub-covered areas still 0.5°C to 1.0°C (AT) warmer than tree-covered areas (Giridharan et al., 2008). As a result, a larger share of tree canopy in green areas has more cooling potential than shrubs or grass.

Furthermore, trees' configuration and spatial distribution in scattered, linear, or concentrated patterns (see Figs. 6.5 and 6.6) influence the extent and intensity of shade and evaporative cooling. For trees, the closeness of canopies created by varying plant distances increases cooling benefits. For example, in avenues, a large planting distance has hardly more effect than a sum of scattered trees, while reducing that distance and creating a completely closed canopy can provide a continuous shadow area with a much lower average radiant temperature under the canopy. However, from an aerodynamic perspective, the proximity of tree crowns also creates a significant barrier to air flows, reducing wind speed and potentially stopping cool breezes (e.g., coming from rivers or large water bodies).

The extent and the intensity of cooling by vegetation also differ according to the size of green areas. The Cool Island Effect is an important phenomenon attributed to wooded parks and other wooded spaces. These areas are usually cooler than their urban surroundings by between 1.5°C and 9.5°C (AT) (Hiemstra et al., 2017). Heat exchanges and air convection

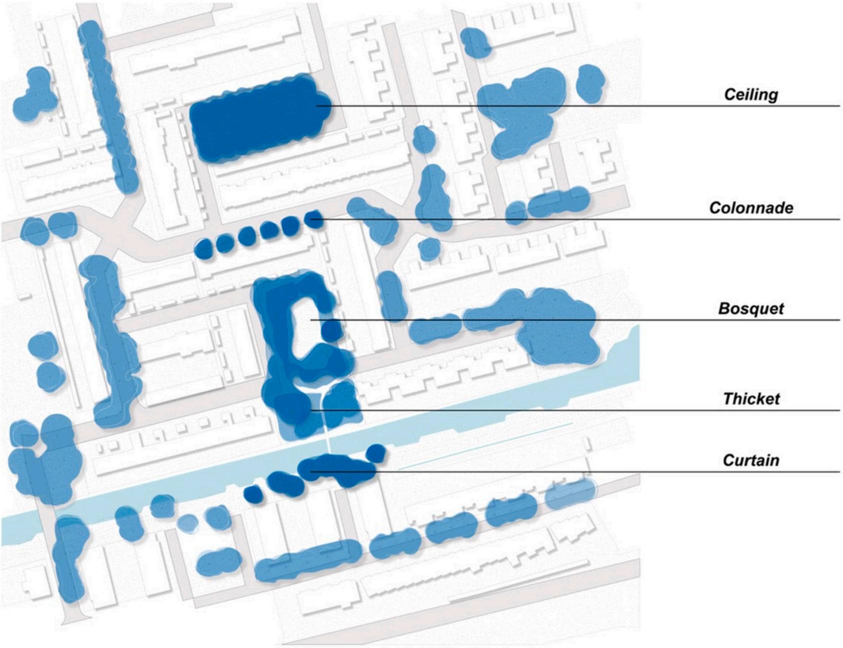

Figure 6.5 Exemplary configurations of green patches (by Kokkona, Viola, and de Wit, 2022).

Figure 6.6 Exemplary patch configurations with different closeness and spatial distribution of plants: thicket - A, ceiling -B, and colonnade -C (by de Wit, 2022).

can also spread the cooling effect up to a certain distance. Fan et al. (2019) found the positive correlation between size and cooling magnitude to be logarithmic. Depending on the morphological and geographical conditions, this effect can reach up to 1.5 km from park boundaries (Yan et al., 2018). Parks with a surface area larger than 10 ha can decrease temperatures up to 300 m from park borders. In contrast, temperature changes and the extension of their influence on "pocket parks" (green spaces smaller than one hectare) are still under debate. Empirical studies suggest that pocket parks' cooling potential largely depends on their urban surrounding and climate zone and can go from a negligible effect up to 7°C of AT difference (Aram et al., 2019).

From a cooling perspective, coverage, composition, and configuration are as important as green areas' morphological and geographical context. The morphological context and the configuration of street canyons/urban fabric set the microclimatic surroundings of green areas and define the UHI magnitude level. The compactness, density, and roughness level of the built environment (see Chapter 5) are among the major determinants of surface and atmospheric temperature, and wind velocity in the area where the vegetation performs. The higher the compactness, density, and roughness are, the higher the challenge for cooling through vegetation (both in terms of space available and starting temperatures to lower). Finally, the climatic context, that is, geographical contexts and related local background climate, needs some consideration. Despite the physical characteristics of green areas, climate zones play a major role because they determine the total incident radiation, ambient AT, and humidity levels (Yu et al., 2018). Previous research has identified the cooling intensity of vegetation to range between 0.5°C and 2.0°C in continental climates,reaching 4.5°C in hot desert climates, and 0.5°C and 2.5°C in oceanic climates.

6.5 Methods and protocols to measure tree/nature-based solutions cooling performance

As vegetation cools through various mechanisms (described in Section 6.2) and has various thermal effects (Section 6.2), different methods exist to study its cooling performance. These methods can be classified under two approaches: (1) observational and (2) modeling (see Fig. 6.7). Observational analyses use sensors to measure different physical phenomena such as (visible and near-infrared) radiation, ST, AT, wind speed and direction, and humidity. Modeling approaches use numerical simulation to compute these same physical phenomena. The two approaches are often applied in combination; observational data are needed to validate the simulations, and observations usually need computational postprocessing. Koc et al. (Bartesaghi Koc et al., 2018) distinguish a third approach, called "experimental methods." This approach entails the controlled manipulation of green

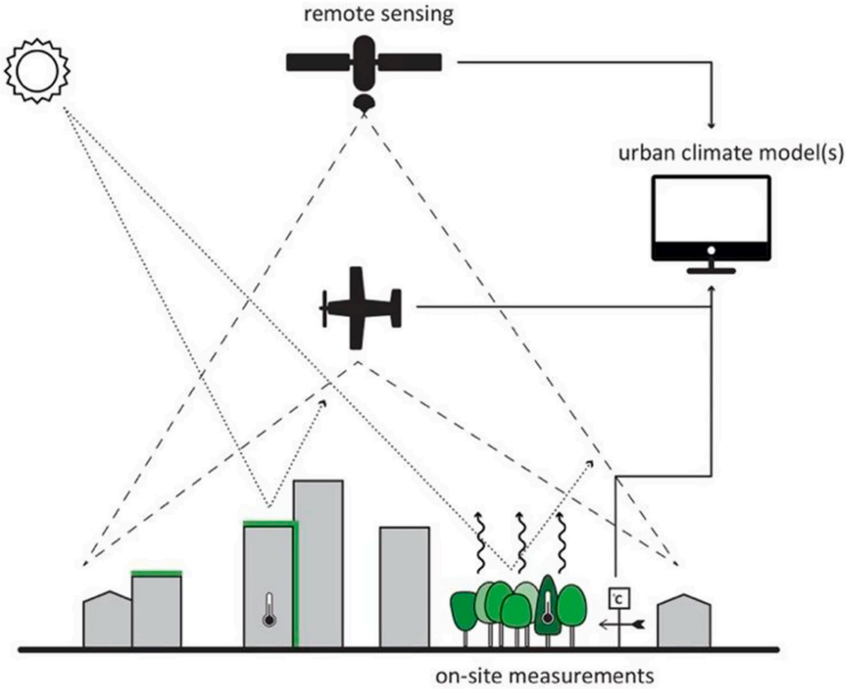

Figure 6.7 Scheme of methods to measure the cooling performance of vegetation (by van Esch 2023).

features by researchers to be able to measure the effects of different parameters in (relative) isolation—rather than measuring the status quo.

Observational methods include remote sensing, both spaceborne (with satellites) and airborne (with aircraft), as well as on-site measurements. Remote sensing is commonly employed to estimate STs, often correlating vegetation indices of vegetation cover. It is also used to analyze the spatial variability of the surface urban heat island effect. The main difference between spaceborne and airborne remote sensing is the height at which data are collected. Satellites have the advantage of having an extensive spatial coverage but with a relatively coarse resolution, making it very difficult to capture microclimatic processes. Airborne imagery has a finer resolution and can obtain information from vertical surfaces, but it is more expensive and has limitations due to (possible) flight restrictions above urban areas.

In situ observations of vegetation cooling performance include AT and humidity measurements, usually inside or near single tree canopies, parks, or other urban green spaces. Wind speed and MRT are also measured when human thermal comfort is of interest. The sensors are either fixed in place for a more extended period, or sometimes mounted to vehicles such as (cargo) bikes or backpacks. In situ measurements can capture small-scale climate phenomena at high temporal resolution but need many instruments to provide sufficient spatial coverage. Combining remote sensing with in situ measurements helps overcome most of the challenges of the singular approaches.

High spatiotemporal resolution can also be achieved by modeling. Meso-scale atmospheric models can predict the cooling performance of green infrastructure on the scale of a whole city (or larger). In contrast, urban canopy models and computational fluid dynamics approaches allow for predicting local to microscale phenomena related to a single tree, building or other object. Modeling has the advantage that it can be used to assess the impact of nature-based solutions as it allows for the comparison of "before and after" situations under the exact same climate conditions, something that is nearly impossible in real-life situations. Because the physical processes involved are highly complex (and sometimes not even fully understood), models always contain simplifications to a higher or lower extent, and results are, therefore, always an approximation of ground truth. However, modeling results can build a well-supporting base for designers, helping them to select solutions and understand their performance. Box 6.2 shows an example of a fully integrated decision-making process supported by modeling techniques.

BOX 6.2 Use of climate modeling and an alternative design process for heat adaptation.

The Van Leeuwenhoekpark (Delft, the Netherlands)

Vegetation can provide shade and evapotranspiration, lowering outdoor temperatures. However, vegetation can also hamper ventilation and emit long-wave radiation. Therefore a careful design of urban green spaces is crucial. To achieve this, not only designers need to be well informed, but decision-makers as well, as they have a key role in the tendering process of urban designs and projects and their eventual use and maintenance (Fig. 6.8).

(*Continued*)

BOX 6.2 Use of climate modeling and an alternative design process for heat adaptation. (Continued)

Figure 6.8 Van Leeuwenhoekpark design by Baljon Landscape Architects. Baljon landschapsarchitecten. (n.d.). Impressie Schetsontwerp Van Leeuwenhoekpark.

During the tendering and design process of the Van Leeuwenhoek Park in Delft, the Netherlands, policymakers, designers, and researchers worked together to create a thermally comfortable environment. The statement of requirements included the demand for climate adaptation in general and the minimization of heat stress in particular. During the design process, several meetings were held in which heat stress-mitigating measures were explicitly discussed. Furthermore, TU Delft researchers carried out a microclimate simulation to predict thermal comfort in the park during a heatwave. The simulation results proved to be instrumental to the process of increasing understanding and interest in the topic of microclimate among the project team, further aiding the decision-making process. This ultimately led to design alterations for potentially heat-stress-prone areas in the park.

After realization, dedicated observation campaigns will be held in the park, serving multiple purposes: measuring the park's performance, providing data for the validation of climate simulations, and providing feedback for possible alterations and maintenance of the park.

6.6 Conclusions

As urban landscapes continue to evolve and expand, the role of green spaces in mitigating rising temperatures becomes increasingly crucial. As the elementary unit of the urban forest, trees temper thermal extremes in urban microclimates by shading, evapotranspiration, and altering air movement. However, optimal cooling performance through urban forests involves a nuanced understanding of various factors in the urban built environment. The cooling efficacy of the urban forest is contingent on a range of design elements and measures, each playing a vital role in shaping the overall impact.

First and foremost, vegetation coverage and types, together with their spatial composition and configuration within an urban setting, significantly influence the cooling magnitude of green areas. Carefully considering tree species, their height, and canopy coverage is essential to maximize shade provision and enhance cooling effects. Additionally, understanding the morphological context, and optimizing the design of green areas to promote shading, and evaporative cooling—while not forgetting airflow—is an integral component of effective urban forest design. Also, considering the potential of vegetation as a cooling medium in relation to the specific geographical and climate context can help to understand the cooling intensity that can be achieved and select the set of heat adaptive solutions more suitable for the specific climate zone. Finally, ensuring the most optimum growing conditions for plants concerning surface and subsurface conditions, moisture, and aeration within the confines of the situation will allow vegetation to perform at its best.

Despite the growing recognition of the importance of the urban forest in heat mitigation, formulating comprehensive design guidelines remains a formidable challenge since the dynamic and diverse nature of urban environments makes it difficult to propose one-size-fits-all solutions. The heterogeneity of cities asks for a flexible approach that can adapt to the unique conditions each urban setting presents. A pressing need emerges for a deeper understanding of local and microclimate conditions for formulating heat mitigation measures. Research efforts should focus on gathering comprehensive data about the intricacies of each locus, including prevailing microclimate patterns, surface and subsurface characteristics, and heterogeneous morphological conditions. This localized knowledge is indispensable for developing context-sensitive strategies that can effectively address the challenges posed by different urban environments.

From a design perspective, approaches should involve analyses of local conditions complemented by microclimate simulations and continuous monitoring. Harnessing technology to simulate how vegetation interacts with its surroundings enables designers to anticipate and optimize cooling effects. Real-time monitoring can further provide valuable insights into the performance of green spaces, allowing for adaptive management strategies that respond to changing urban dynamics and climatic conditions. Monitoring also appears fundamental to better understand the behavior of vegetation under conditions of stress. For example, temperature, drought, and other stressors strongly influence BVOC emissions from trees. Emissions typically rise with heat and can be further stimulated under water shortage or oxidative stress, sometimes continuing even when photosynthesis is reduced (Calfapietra et al., 2013). In urban settings, where heat islands, ozone episodes, and multiple stressors interact, emissions can increase markedly and contribute to ozone formation (Biagi et al., 2025; Fitzky et al., 2019). The extent of this response is species-specific and depends on tree physiological status, meaning that stress conditions not only increase emission magnitudes but may also alter the chemical profiles released (Fitzky et al., 2019). Additionally, under heat stress, evapotranspiration patterns may also become weaker than in mild weather conditions, leading to a reduction in cooling performance (Gao, Feng & Santamouris, 2024). The duration and the magnitude of this response vary according to species, soil water content, and threshold temperatures. However, the determinants of this coping mechanism of trees, aimed at preserving available moisture in hot conditions, are still largely understudied.

The resilience of the urban forest is, moreover, a critical dimension that demands further attention. Ensuring adequate space for trees to mature into more performative stages is imperative from a long-term perspective. Designers must prioritize creating environments that foster healthy tree growth, considering soil quality, irrigation, and good maintenance practices. Additionally, establishing green spaces that can withstand the challenges posed by climate change, including more frequent and severe drought seasons, is paramount. Research initiatives should delve into innovative approaches to enhance the adaptability and robustness of the urban forest in the face of evolving climatic conditions.

In conclusion, the future of urban forestry lies in a holistic and context-aware approach that integrates research insights and innovative design practices. While acknowledging the undeniable role of green spaces in cooling cities, the journey toward effective heat mitigation requires a comprehensive understanding of local nuances, continual monitoring, and a commitment to maintaining a resilient urban forest. Only through a concerted effort to bridge the gap between research and design in this realm, can we hope to create heat-adaptive urban environments that embrace the challenges of a changing climate.

References

Aram, F., Higueras García, E., Solgi, E., & Mansournia, S. (2019). Urban green space cooling effect in cities. *Heliyon, 5*(4), e01339. https://doi.org/10.1016/j.heliyon.2019.e01339.

Bartesaghi Koc, C., Osmond, P., & Peters, A. (2018). Evaluating the cooling effects of green infrastructure: A systematic review of methods, indicators and data sources. *Solar Energy, 166*, 486–508. https://doi.org/10.1016/j.solener.2018.03.008.

Biagi, B., Brattich, E., Cintolesi, C., Barbano, F., & Di Sabatino, S. (2025). Dynamical and chemical impacts of urban green areas on air pollution in a city environment. *Urban Climate, 60*, 102343. https://doi.org/10.1016/j.uclim.2025.102343.

Calfapietra, C., Fares, S., Manes, F., Morani, A., Di Sgrigna, G., & Loreto, F. (2013). Role of biogenic volatile organic compounds (BVOC) emitted by urban trees on ozone concentration in cities: A review. *Environmental Pollution, 183*, 71–80. https://doi.org/10.1016/j.envpol.2013.03.012.

Chatzimentor, A., Apostolopoulou, E., & Mazaris, A. D. (2020). A review of green infrastructure research in Europe: Challenges and opportunities. *Landscape and Urban Planning, 198*, 103775. https://doi.org/10.1016/j.landurbplan.2020.103775.

Chen, J. M., & Black, T. A. (1992). Defining leaf area index for non-flat leaves. *Plant, Cell & Environment, 15*(4), 421–429. https://doi.org/10.1111/j.1365-3040.1992.tb00992.x.

de Wit, S. I., & van der Velde, J. R. T. (2024). How trees shape urban spaces: Multiplicity and differentiation of the urban forest viewed from a visual-spatial perspective. *Arboriculture and Urban Forestry, 50*(1), 4–17. https://doi.org/10.48044/jauf.2023.024. Available from https://auf.isa-arbor.com/content/50/1/4.

Fan, H., Yu, Z., Yang, G., Liu, T. Y., Liu, T. Y., Hung, C. H., & Vejre, H. (2019). How to cool hot-humid (Asian) cities with urban trees? An optimal landscape size perspective. *Agricultural and Forest Meteorology, 265*, 338–348. https://doi.org/10.1016/j.agrformet.2018.11.027.

Fitzky, A. C., Sandén, H., Karl, T., Fares, S., Calfapietra, C., Grote, R., Saunier, A., & Rewald, B. (2024). The Interplay Between Ozone and Urban Vegetation—BVOC Emissions, Ozone Deposition, and Tree Ecophysiology. *Frontiers in Forests and Global Change, 2*(50). https://doi.org/10.3389/ffgc.2019.00050.

Gao, K., Feng, J., & Santamouris, M. (2024). Are grand tree planting initiatives meeting expectations in mitigating urban overheating during heat waves? *Sustainable Cities and Society, 113*, 105671. https://doi.org/10.1016/j.scs.2024.105671.

Giridharan, R., Lau, S. S. Y., Ganesan, S., & Givoni, B. (2008). Lowering the outdoor temperature in high-rise high-density residential developments of coastal Hong Kong: The vegetation influence. *Building and Environment, 43*(10), 1583–1595. https://doi.org/10.1016/j.buildenv.2007.10.003.

Hiemstra, J. A., Saaroni, H., & Amorim, J. H. (2017). *The Urban heat island: Thermal comfort and the role of urban greening*. Springer Science and Business Media LLC, 7–19. 10.1007/978-3-319-50280-9_2.

Jacobs, S. J., Gallant, A. J. E., Tapper, N. J., & Li, D. (2018). Use of cool roofs and vegetation to mitigate urban heat and improve human thermal stress in Melbourne, Australia. *Journal of Applied Meteorology and Climatology, 57*(8), 1747–1764. https://doi.org/10.1175/jamc-d-17-0243.1.

Marando, F., Heris, M. P., Zulian, G., Udías, A., Mentaschi, L., Chrysoulakis, N., Parastatidis, D., & Maes, J. (2022). Urban heat island mitigation by green infrastructure in European Functional Urban Areas. *Sustainable Cities and Society, 77*, 103564. https://doi.org/10.1016/j.scs.2021.103564.

Morakinyo, T. E., Lau, K. K.-L., Ren, C., & Ng, E. (2018). Performance of Hong Kong's common trees species for outdoor temperature regulation, thermal comfort and energy saving. *Building and Environment, 137*, 157–170. https://doi.org/10.1016/j.buildenv.2018.04.012.

Oke, T. R. (1989). The micrometeorology of the urban forest. *Philosophical Transactions – Royal Society of London, B, 324*(1223), 335–349.

Ramyar, R., Ackerman, A., & Johnston, D. M. (2021). Adapting cities for climate change through urban green infrastructure planning. *Cities (London, England), 117*, 103316. https://doi.org/10.1016/j.cities.2021.103316.

Van der VELDE, R., de WIT, S., & POUDEROIJEN, M. (2023). Cool tree architecture: A descriptive framework for a tree architecture typology to temper urban microclimates. *Landscape Architecture Frontiers, 11*(5), 30. https://doi.org/10.15302/j-laf-1-020084.

Wilby, R. L. (2007). A review of climate change impacts on the built environment. *Built Environment, 33*(1), 31–45. https://doi.org/10.2148/benv.33.1.31.

Wullschleger, S. D., Meinzer, F. C., & Vertessy, R. A. (1998). A review of whole-plant water use studies in tree. *Tree Physiology, 18*(8-9), 499–512. https://doi.org/10.1093/treephys/18.8-9.499.

Yan, H., Wu, F., & Dong, L. (2018). Influence of a large urban park on the local urban thermal environment. *Science of the Total Environment, 622-623*, 882–891. https://doi.org/10.1016/j.scitotenv.2017.11.327.

Yu, Z., Xu, S., Zhang, Y., Jørgensen, G., & Vejre, H. (2018). Strong contributions of local background climate to the cooling effect of urban green vegetation. *Scientific Reports, 8*(1). https://doi.org/10.1038/s41598-018-25296-w.

Zhao, L., Oppenheimer, M., Zhu, Q., Baldwin, J. W., Ebi, K. L., Bou-Zeid, E., Guan, K., & Liu, X. (2018). Interactions between urban heat islands and heat waves. *Environmental Research Letters, 13*(3), 034003. https://doi.org/10.1088/1748-9326/aa9f73.