



Heat stress mitigation by exploring UTCI hotspots and enhancing thermal comfort through street trees

Tiago Silva^{1,2} · Márcia Matias^{1,2} · Carolina Girotti^{1,3} · João Vasconcelos^{1,4} · António Lopes^{1,2}

Received: 31 October 2024 / Accepted: 7 February 2025 / Published online: 18 February 2025
© The Author(s) 2025

Abstract

Heat stress mitigation actions must be carefully planned in order to achieve effective outcomes. By integrating urban planning guidelines with urban climate knowledge, substantial benefits can be achieved for the community. In Lisbon, the study area, urban planning guidelines are strict in relation to the tree species which should be used for planting. This study examined these species environmental contributions to the community, especially in regard to heat stress mitigation in two urban canyons previously found as UTCI hotspots. For this, microclimatic Envi-met simulations were run which allowed recalculation of the UTCI hotspot analysis and to assess individual species contribution to possible mitigation efforts. Results demonstrated the ability of these trees to lower air temperature and the Universal Thermal Climate Index (UTCI). By reducing UTCI temperatures between 3.19 °C and 6.27 °C on a hot summer's day, these trees were also able to transform an identified UTCI hotspot into a coldspot. From the studied species, *Pyrus calleryana* was found to be the most effective species for mitigating thermal stress, although all three species performed well. Regarding community services, according to the iTree tool, *Cercis siliquastrum* had the greatest overall impact. These results give to the municipal urban planning which tree species should be prioritized in terms of climate action, as well as a methodological framework to assess at local scale which areas should be intervened.

Keywords Microclimate · Lisbon · Micrometeorological simulations · Thermal comfort · Climate action

1 Introduction

Cities around the world are expanding, along with their populations (The World Bank 2023). This expansion leads to an increase in impervious areas and to the artificialisation of the landscape and the human way of life. Consequently, the implementation of Nature-based Solutions (NBS) is emerging as highly valued (McPhearson et al. 2023). This is because human interaction with nature has become scarce in cities, leading to demand for more and better greenspaces (Fuller & Gaston 2009). According to Oke et al. (2017) and McPhearson et al. (2023) NBS offer opportunities for future and existing cities to address climatic issues and extreme weather. Sayad et al. (2021) consider that NBS are the best type of solutions to mitigate thermal stress in urban environments due to ecosystemic services. Kuttler & Weber (2023) compared artificial to natural solutions and concluded that natural solutions, contrary to artificial ones, partition energy through transpiration thus having better capabilities in reducing thermal stress. Cheung & Jim (2018) also concluded that trees were more effective in cooling down air temperature,

✉ Tiago Silva
silvatiago@edu.ulisboa.pt

Márcia Matias
marcia.a.matias@edu.ulisboa.pt

Carolina Girotti
cgirotti@usp.br

João Vasconcelos
j.vasconcelos@ipleiria.pt

António Lopes
antonio.lopes@edu.ulisboa.pt

¹ Institute of Geography and Spatial Planning (IGOT), Centre of Geographical Studies (CEG), University of Lisbon, Lisbon, Portugal

² Laboratório Associado Terra, Lisbon, Portugal

³ Faculty of Architecture and Urbanism, University of São Paulo, São Paulo, Brazil

⁴ Instituto Politécnico de Leiria, Leiria, Portugal

physiological equivalent temperature (PET), and the Universal Thermal Climate Index (UTCI) than artificial shelters.

Street trees are one of the possibilities within NBS and are considered the most common solutions (McPhearson et al. 2023). Kim & Brown (2021) and Rahman et al. (2020) note that the regulation of thermal conditions in urban environments relies on the presence of trees. Besides the regulation of thermal conditions, trees are also able to save energy, promote biodiversity, contribute to economic savings, provide well-being, improve air quality, and contribute to morbidity and mortality reduction due to thermal stress (Donovan & Butry 2009; Fuller & Gaston 2009; Kuttler & Weber 2023; Mullaney et al. 2015; Qi & He 2023; Santamouris 2020).

Tree uses in urban contexts can also act as preventive medical practices since trees and green spaces promote physical activity (Vanos et al. 2010). Andrade & Vieira (2007) found that isolated trees were less efficient than an agglomerate of trees in public spaces, indicating that a planned strategy is needed for urban heat island and thermal stress mitigation. Rahman et al. (2020) and Reis et al. (2020), mention that trees with more leaf area and more porous wood have higher capabilities of reducing PET and air temperature and increasing relative humidity. Yuan et al. (2023) and found that street trees with larger crowns are better to have in the summer. Antoniadis et al. (2018) found a relation between sky-view factor (SVF), T_{mrt}, and PET, in which lower SVF due to tree planting led to lower T_{mrt} and PET. According to these authors, this happens because tree canopies reduce the amount of direct radiation by 90%. Ornelas et al. (2023) study also agrees with Antoniadis. Gillner et al. (2015) who studied six different tree species, found that transpiration, stomatal conductance, and leaf-area coverage are important for cooling urban areas, and that different species provide

different results. In turn, Reis & Lopes (2019), concluded that an additional 50m² of vegetation cover can reduce air temperature by 1 °C. Among urban-morphological and climatic considerations, the tree species is considered one of the most important parameters when planning heat stress mitigation (Bowler et al. 2010; Jin et al. 2024; Kong et al. 2017; Morakinyo et al. 2017; Oke et al. 2017; Qi & He 2023; M. Rahman et al. 2020; Wong et al. 2021). The cover provided by trees not only decreases thermal stress and air temperature but also provides excellent UV protection to pedestrians (Kuttler & Weber 2023). In this line, some authors have studied the potential of tree species regarding thermal stress mitigation (Table 1). These studies guide this research by highlighting that not all tree species provide the same benefit; some may be more beneficial than others, particularly in mitigating thermal stress through the amount of coverage they provide to public spaces.

Following the work of Silva et al. (2024a, b), where 11 UTCI hotspots were identified in various areas of Lisbon, a research gap emerged regarding possible mitigation efforts in these areas. These hotspots were identified using climate field data collected during climate walking paths, combined with GIS technology and statistical analyses. This research also found that these hotspots arise due to urban morphology, air temperature, and radiation influence, particularly when wind is either insufficient or obstructed by urban structures (Silva et al. 2024a, b). From the identified UTCI hotspots, two urban canyons were chosen for modelling in Envi-met to address the current thermal stress situation. The mitigation actions were based upon trees from three different species, leading to the modelling of four scenarios (one representing the current situation and three representing one for each tree species) in the two urban canyons with UTCI

Table 1 Findings about tree species capacities on heat stress mitigation

Authors	Heat stress mitigation
Armson et al. (2013)	Tree lowers mean radiant temperature (MRT) by an average of 4 °C
Abreu-Harbic et al. (2014)	<i>Mangifera indica</i> , <i>Caesalpinia peltophoroides</i> , and <i>Syzygium cumini</i> reduce air temperature by 0.2–2.8 °C
Gillner et al. (2015)	<i>Corylus colurna</i> and <i>Tilia cordata</i> have the greatest cooling potential
Middel et al. (2015)	Augmenting tree canopy cover reduce air temperature by 0.14 °C to 2 °C
Kántor et al. (2016)	<i>Sophora japonica</i> can reduce air temperature by 0.5 °C, MRT by 22.1 °C, and PET by 9.3 °C
Lee et al. (2016)	Trees reduce PET by 17.4 K
Rahman et al. (2017)	<i>Tilia cordata</i> reduce air temperature by up to 3.5 °C
Antoniadis et al. (2018)	Tree species reduce MRT by 31 °C and PET by 19 °C
Cheung & Jim (2018)	<i>Ficus microcarpa</i> lower air temperature by 0.6 °C, PET by 3.9 °C, and UTCI by 2.5 °C
Nouri et al. (2018)	<i>Tipuana tipu</i> can lower PET by 15.6 °C and mPET by 11.6 °C
Zhao et al. (2018)	<i>Fraxinus velutina</i> , <i>Acacia salicina</i> , <i>Washingtonia filifera</i> reduce thermal stress
Rahman et al. (2020)	<i>Tilia cordata</i> and <i>Robinia pseudoacacia</i> reduce air temperature between 1.6 °C and 3 °C, surface temperature by up to 23 °C and PET by 11 °C
Ornelas et al. (2023)	Tilias reduce air temperature by 4.84 °C

hotspots. The process and reasoning for selecting the study areas and the tree species is explained in the methodology section.

This new research stems from the hotspots article and it differs from previous studies (Table 1) by exploring how UTCI hotspot areas can be mitigated through realistic climate action efforts, while also quantifying their impact in reducing heat stress conditions for pedestrians. Although research on heat stress mitigation in urban areas is well-established, the approach of identifying hotspots and recalculating them based on proposed solutions has not yet been explored.

This study hopes that this new urban climate knowledge will be incorporated into urban planning departments in an effort to more efficiently mitigate thermal stress. In the following manner this research aims to: 1) Simulate scenarios with proposals for mitigating thermal discomfort through specific tree species, in dense urban areas where UTCI hotspots have been found; 2) Recalculate UTCI hotspot scenarios based on the contribution of each species to heat stress mitigation; 3) Identify which species contribute most to mitigating thermal discomfort in two different urban canyons; 4) Evaluate the overall environmental contribution of each species to the community.

2 Methodology

To fulfil the objectives, the Envi-met software (a Computational Fluid Dynamics models – CFD) was used to model and simulate the presented scenarios and the Bio-met tool to simulate the UTCI. The Envi-met has already been used to simulate how trees can mitigate thermal stress in different layouts and spatial scales with good results (Lee et al. 2016; Lopes et al. 2014; Zhao et al. 2018). Before running the software, the spatial, temporal, data configurations, along the trees' data had to be set. The following subchapters discuss this process.

2.1 ENVI-met simulation

2.1.1 Domain configuration

The selection of both simulation domains is identified in Table 2 and was designed to include several variables.

As per the UTCI hotspots identified in Silva et al. (2024a, b) only study areas 2, 4, and 5 had the most prominent with 99% statistical confidence. Also study areas 4 and 5 had the highest number of elderly residents (≥ 65 years old) (Figure S1, in the supplementary materials). This age group is considered to be the most vulnerable to heat stress conditions (Pigliautile et al. 2022). To complement these two criteria, the biomass quantity and the percentage of canopy

Table 2 Simulation domains criteria

Study areas criteria
UTCI hotspots (Silva et al. 2024a, b)
Number of vulnerable individuals (≥ 65 years old) residing in the UTCI hotspots area
Biomass
Percentage of area covered by tree canopies per civil parish
3, 30, 300 rule
Suitability of the areas for mitigation efforts

cover in each civil parish where the roving missions took place along these three routes were analysed.

As seen in Table S1 (in the supplementary materials), study area 5 had on average, less biomass. This information is confirmed by the percentage of canopy cover (Table S1). Regarding the “3, 30, 300 rule”, which means 3 trees in sight from every home, 30% canopy cover, and 300 m distance from green infrastructure, as proposed by Konijnendijk (2021), it is clear that the three routes do not meet the requirements (Table S1). Nevertheless, study area 5 presents the worst scenario of the three.

Additionally, due to the complexity of the urban landscape, only routes 4 and 5 had sufficient space on the pavements to allow for intervention works in the public space. According to Lisbon's municipality regulations (Câmara Municipal de Lisboa 2017), the pavements on the streets identified with UTCI hotspots in routes 4 and 5 can be classified as moderate in terms of width (≥ 3.5 –6 m). Consequently, the UTCI critical area in study area 2 was excluded, as its street was classified as narrow (< 3.5 m).

Thus, Avenida Maria Helena Vieira da Silva (where route 4's second hotspot was located), as well as Rua José Ricardo (where route 5's first hotspot was found), were selected for the simulation (Fig. 1). For the purpose of this research, the former will be renamed Simulation Area 1 (SA1), while the latter will be referred to as Simulation Area 2 (SA2).

These areas are similar in terms of the materials composing the structures and surfaces (Table 3). The surfaces are primarily made up of asphalt and white limestone. The buildings in SA1 are composed of concrete and coated with white terracotta tiles, while the buildings in SA2 are also concrete but painted in various light colours (Table 3). These characteristics are crucial for the Envi-met simulation and were used as input data. The orientation of the areas differs: SA1 has a west–east orientation, whereas SA2 has a northwestern-southeastern orientation. Both areas have high to very high H/W ratios (Correia 2020). The northernmost area has taller buildings but a wider street canyon, whereas SA2 is the opposite. The urban layout was also included as input information for the Envi-met simulation. In terms of previously planted trees only SA1 has a few; however, most

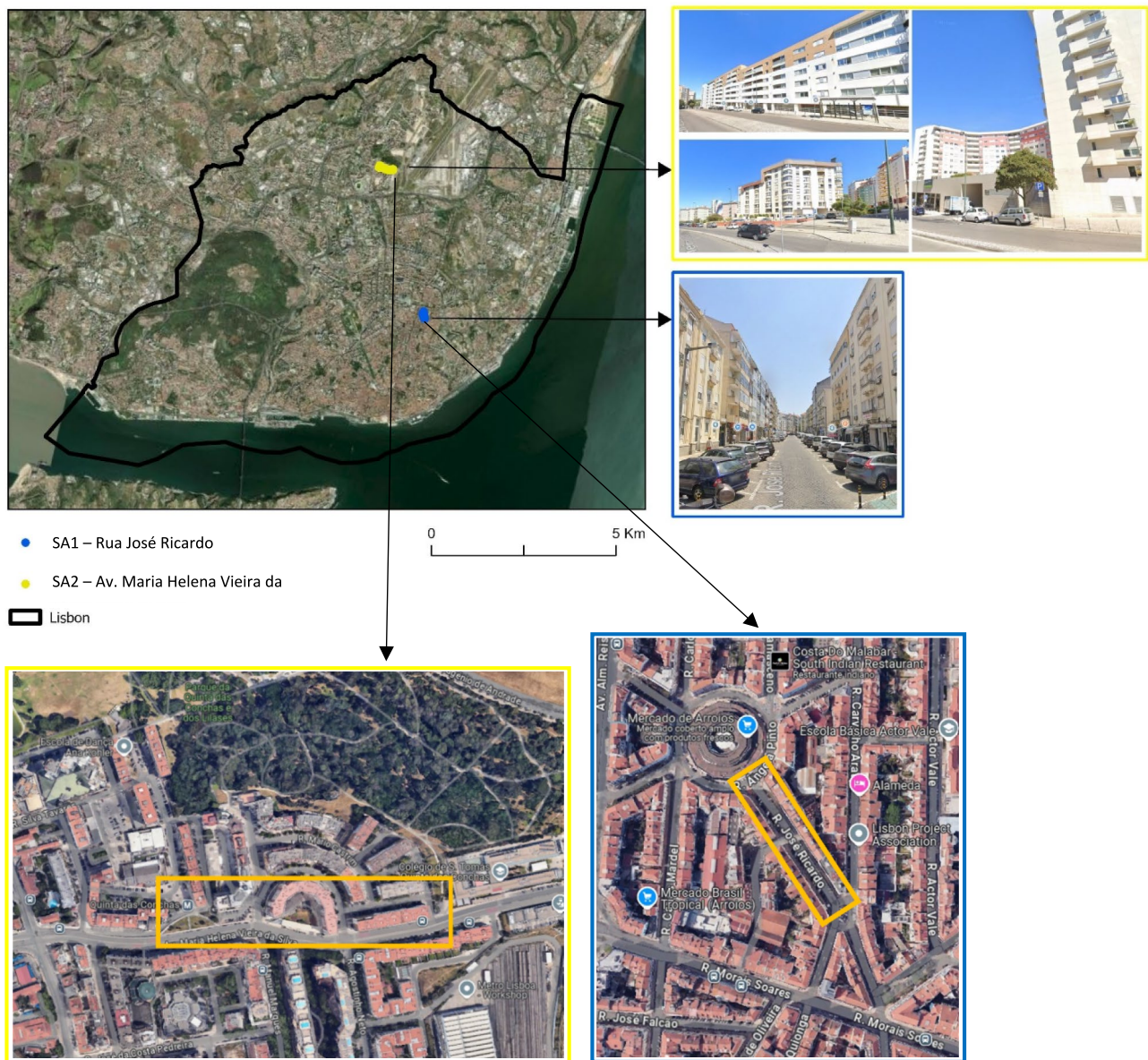


Fig. 1 Envi-met simulation areas. The orange boxes in the satellite images are the area of interest for the simulations

were planted on the shaded side of the street (due to the buildings), leaving almost none on the sunny side.

2.1.2 Mesh design, initial and boundary conditions

Initially, the models' resolution was set to 2 m in width for each cell and 1.5 m in height (Table 3). The simulations were conducted using 10 years of climatic data extracted from Lisbon airport.epw file. The atmospheric forcing was done using the Full Forcing option (Table 3). This option is more detailed and comprehensive regarding the atmospheric conditions than the simple forcing, because it allows the

introduction of more variables with higher temporal resolution (De Quadros et al. 2024).

The distance between the data source and the study areas is approximately 2.5 km from SA1 and 5 km from SA2. The modelling period lasted 72 h from 1st to 3rd July 2021, and the data analysed at 2 pm. The temporal scale of the simulation had to align with that used by Silva et al. (2024a, b), specifically being summer, a period within summer with very high temperatures, and during one of the hottest hours of the day. The inclusion of several days has to do with the simulation requirements regarding having sufficient hours for the simulation to run effectively. The three-dimensional model of ENVI-met was encapsulated within a one-dimensional

Table 3 Summary of Envi-met model's input. Sources of Envi-met external input information: 1—<https://www.ladybug.tools/epwmap/>; 2—<https://lisboaaberta.cm-lisboa.pt/index.php/pt/>; 3—(Anexo Geral

V—Catálogo de Propriedades Térmicas de Paredes, Coberturas e Vidros, 2013); 4—Matias (2018)

Model metadata	SA1	SA2
Spatial scale (lat, long, alt)	38.766682, -9.152823, 110 m	38.734277, -9.131862, 72 m
Temporal scale	01–03/07/2021 (72 h)	
Pixel resolution (Width x Height)	2 × 1.5 (m)	
Grid size dx, dy, dz	2.00 (298 x-Grids), 2.00 (167 y-Grids), 5.00 (10 z-Grids)	
Vertical	Dz of lowest gridbox is split into 5 subcells (20% Telescoping factor)	
Meteorological conditions (1)	Full forcing (Lisbon airport.epw data)	
Epw distance from study areas	2.5 (km)	5 (km)
Building information (shapefile) (2)	Lisboa aberta (open data)	
Short-wave albedo (α): Building Wall – light concrete (3)	Orange – 0.486; yellow – 0.664; light yellow – 0.745; light grey – 0.477; dark green – 0.202; light green – 0.600; pink – 0.505	
Short-wave albedo (α): Building – terracota tiles (3)	Dark grey – 0.255; blue – 0.3310; dark cyan – 0.202; light yellow – 0.664	
Short-wave albedo (α): Surface	Asphalt road – 0.12; basalt cobblestone – 0.20; worn out limestone cobblestone 0.40 (4); grass – 0.30	Asphalt road – 0.12; worn out limestone cobblestone 0.40;

model, which provided the necessary boundary conditions for simulating atmospheric processes within the boundary layer up to a height of 2500 m (Bruse & Fleer 1998).

The inflow profile was calculated using this one-dimensional model, accounting for surface roughness, and served as the reference and upper boundary condition for the nested three-dimensional model (Bruse & Fleer 1998). The three-dimensional mesh was divided into cells (x, y, z), with the dimension of each cell determining the model's resolution (Table 3). For the simulations conducted, the recommendation to subdivide the first five vertical cells to enhance precision in calculating processes near the surface were followed, as outlined by Bruse & Fleer (1998). The lateral and upper boundary conditions were computed using one-dimensional model (Bruse & Fleer 1998).

A 'no-slip' condition ($u = v = w = 0$) was applied to all surfaces, and a zero-gradient condition was imposed at the exit boundaries of the domain. At the ground surface ($z = 0$) and on the walls, E and ε were calculated based on the local friction velocity (u^*). Lateral boundary conditions adhered to the boundary layer profile derived from the one-dimensional model.

2.1.3 Strategic tree choices for simulations

As it was previously mentioned, the proposed mitigation scenario for SA1 and SA2 involves the creation of shaded areas through the introduction of trees. However, which tree species is most suitable for Lisbon? To address this question, several sources of information were considered.

Firstly, according to Lisbon's municipality regulations (CML, 2017) the selected areas, due to their width, can only

accommodate medium-sized trees (preferably up to 12 m tall and 6 m wide). This document provides a list of species already present in Lisbon's streets that are recommended for street planting (Table S2, in the supplementary materials). The proposed species have deciduous leaves, which is important to match the ecosystem services provided by the trees to the season (since in winter, UTCI hotspots are beneficial). This is also recommended by Jamei et al. (2016).

In the next step, these tree species were classified into three categories (good, ok, and bad) based on their allergenicity (pollen), growth rate, and canopy size (Table S2). Trees that are low in allergenicity, fast-growing, and have an appropriate canopy size were deemed "good". The allergenic parameter, though sometimes overlooked by urban planners or researchers, is crucial because trees can negatively impact human health due to their pollen (McPhearson et al. 2023).

To further narrow our list, information regarding tree fall percentage by species, leaf albedo, and leaf transmittance was also analysed (Table S2). In conclusion, only three species met the defined criteria and were subsequently selected for the simulation: *Cercis siliquastrum*, *Prunus dulcis*, and *Pyrus calleryana* var. "Chanticleer" (Fig. 2). All of these are already present in Lisbon streets, 1237 *Cercis siliquastrum*, 706 *Pyrus calleryana* and 150 *Prunus dulcis*.

Following this process, the tree species were quantified in terms of their monetary value regarding the benefits they provide to communities, including carbon dioxide uptake, air pollution removal, energy savings, stormwater mitigation, and avoided energy emissions. This was achieved using the MyTree tool from iTree software which demonstrates that these species, in addition to mitigating heat stress, are vital to communities in different dimensions. According to

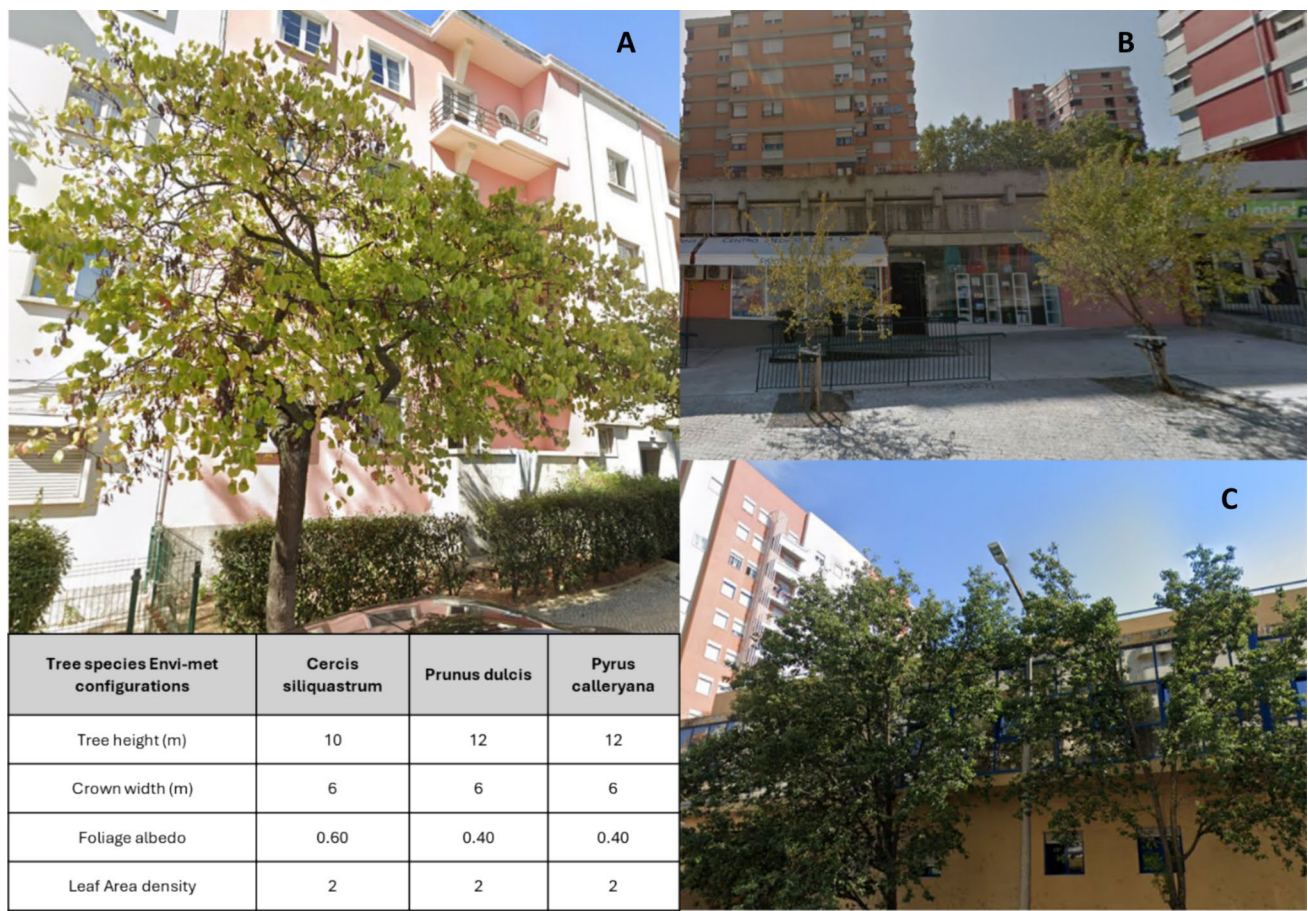


Fig. 2 Tree presence in Lisbon and configuration settings used in Envi-met. **A** *Cercis siliquastrum*; **B** *Prunus Dulcis*; **C** *Pyrus calleryana*

Mullaney et al. (2015) the quantification of the environmental benefits allows policymakers and decision-makers to easily comprehend and communicate the advantages of street trees. Unfortunately, this tool does not include a heat coefficient to calculate the added value of heat stress mitigation.

In Envi-met and Bio-met, UTCI scenarios were calculated both with and without trees. The UTCI calculation was configured according to information in Table 4. Regarding the trees, only *Cercis siliquastrum* was included in the tool's inventory, so the other two species had to be created using default tree settings, adjusting their height and crown width accordingly to the maximum permitted by the aforementioned Lisbon regulations (Fig. 2).

According to Jamei et al. (2016), the appropriate distance between trees and between trees and buildings must be considered. These distance parameters are also crucial for preventing wind blockage caused by the trees (Cortese et al. 2023). For the simulation, the trees were not placed randomly in the street; rather, Lisbon's municipality regulations (CML, 2017) specify the distance that each medium-sized tree must maintain from one another (8–9 m), which was adhered to. The configuration of the trees in the Envi-met

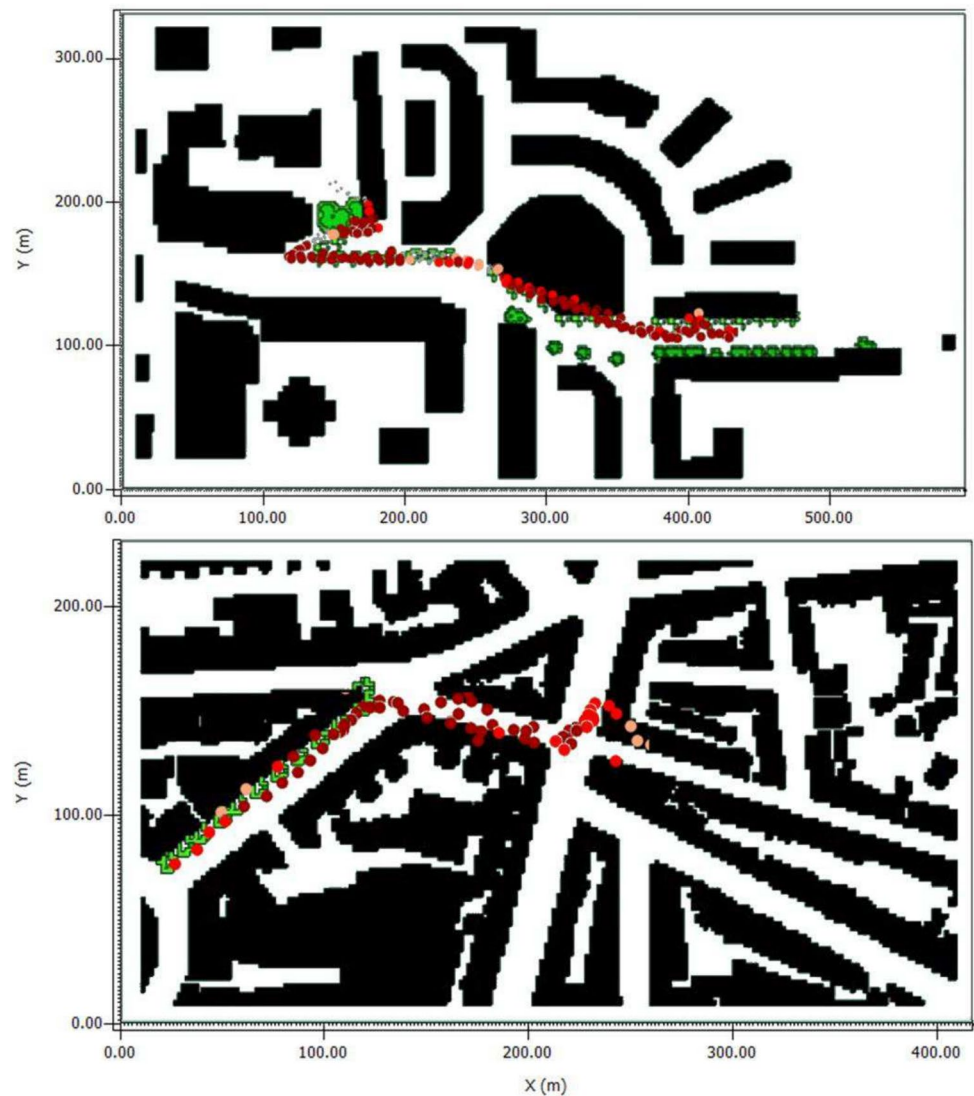
Table 4 UTCI specifications

UTCI personal parameters	Details
Age	27 years
Sex	Male
Weight	80 kg
Height	1.80 m
Body position	Standing – Walking
Walking speed	1.34 m/s (Alves et al., 2020)
Clothing insulation	0.49 clo (based on (Silva et al. 2024a, b))
Basal metabolic rate	91.89 W
Work metabolism	80 W
Total metabolic work	171.89 W

modelling can be seen in Fig. 3. The trees were only set in UTCI hotspots and in SA2 part of the route did not have trees because the pavements did not have enough space for street trees according to the municipality regulations.

Lastly, the UTCI data collected in the two studied hotspot areas, as presented in Silva et al. (2024a, b) was adjusted according to the influence of each tree based on the Envi-met

Fig. 3 Configuration of trees in Envi-met SA1 (top) and SA2 (bottom). The green spots represent the trees and mark the area of interest for this study. The red circles are the UTCI hotspots are represented in Silva et al. (2024a, b)



results. Hypothetical scenarios were then created in the study areas, incorporating the simulated influence of the trees as though they were actually present. This process is explained in Section 2.2.

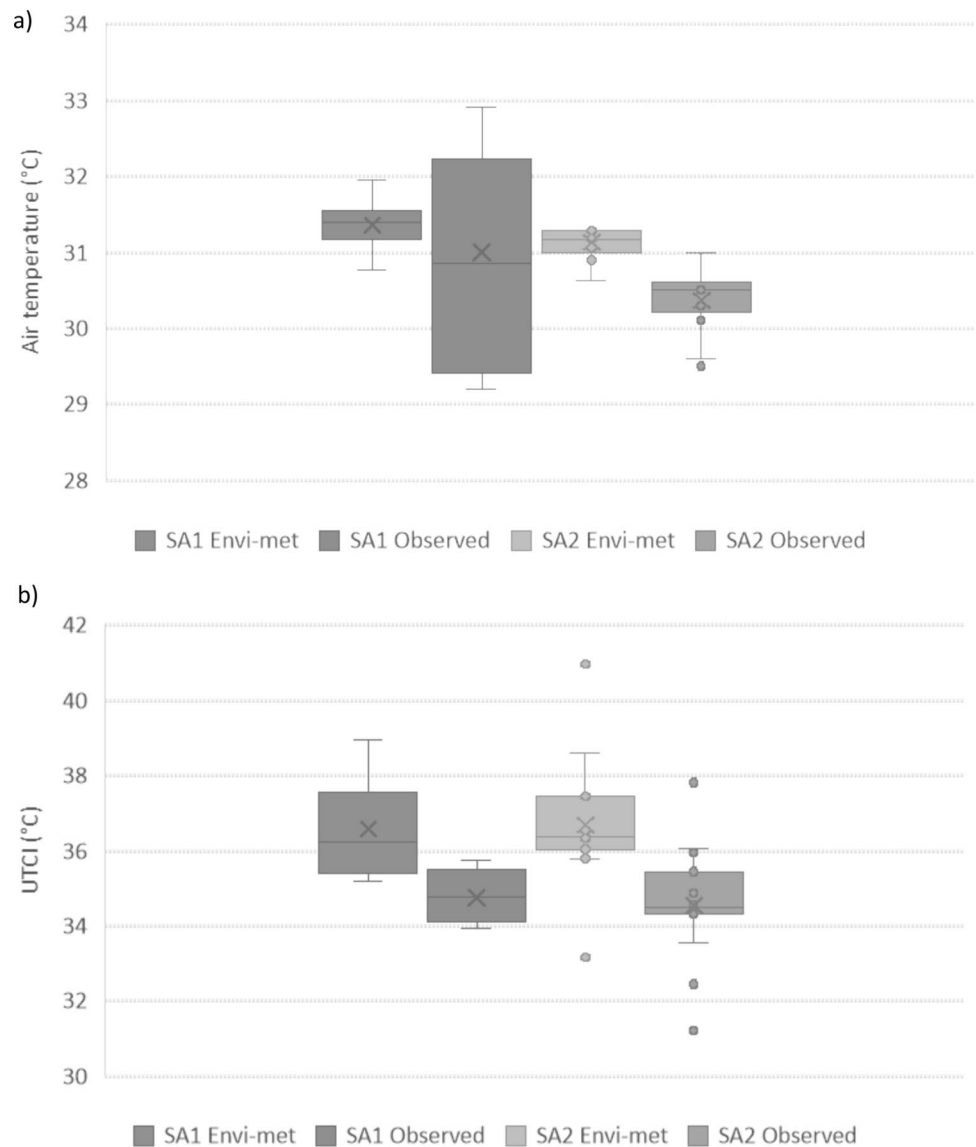
2.1.4 Validation

The validation of the model was carried out using observed data for the same period as the simulation, utilising the exact same equipment and procedure as in Silva et al. (2024a, b) climate walks. The validation results show that both observed and simulated values are similar. According to Fig. 4a, the median and average values of Envi-met for both study areas are higher than the observed values by approximately 0.6 °C. Naturally, the observed values exhibit greater heterogeneity and higher variability, most notably in SA1. The RMSE values were also calculated, with air temperature in SA1 being 1.34 °C and in SA2, 0.83 °C. The same

analysis was conducted for the UTCI (Fig. 4b). For this variable, the observed values were less heterogeneous and showed a similar behaviour to the simulated ones. However, the difference between them is more pronounced, and it can be observed that the median and average differences between observed and simulated values are greater (~1.5 °C in SA1 and ~1.8 °C in SA2). The RMSE value for SA1 is 2.01 °C and for SA2, 2.09 °C. According to Middel et al. (2014, 2015) and Zhao et al. (2018) the air temperature RSME values should be around 1 °C–2 °C, as is the case in this study. In both cases, Envi-met appeared to slightly overestimate the values, with higher quartiles, medians, and averages, with the observed values in SA1 being the exception.

This is in accordance with Lee et al. (2016) who found that Envi-met overestimates air temperature, mean radiant temperature and PET. Nonetheless, this author found that the Envi-met model demonstrated good performance when compared to thermal comfort field measurements. De Quadros

Fig. 4 Air temperature (a) and UTCI (n) variation according to observed and Envi-met simulated values in SA1 and SA2



et al. (2024) also found that CFD models overestimate values during the afternoon, and underestimate in the morning and evening. Crank et al. (2018) who conducted an extensive validation of Envi-met enumerates some of its limitations such as lack of grid independence, sensitivity regarding the scale, problems calculating shifts in wind profiles, poor representation of buildings influence to outdoor air temperature (heat transfer), underestimation of building shade effect, and it lacks a more detailed mesh adjacent to all types of surfaces. In turn, Tsoka et al. (2018) found that Envi-met also presents limitation regarding mean radiant temperature calculation. Even so, Crank et al. (2018) does not consider that Envi-met usage for heat mitigation research is invalid.

In regard to this study, some of the values regarding tree heat mitigation capabilities might be overestimated. Additionally, the ENVI-met model is quite resource-intensive, meaning it runs very slowly, even on computers with high

graphics and RAM capacities. For researchers and urban planners seeking more flexibility and faster results, this software may not be the most adequate. Nonetheless, ENVI-met is a highly valuable microclimatic tool that provides researchers and urban planners with insights into the potential for mitigating heat stress through changes in urban spaces.

2.2 New hotspots: tree mitigation effects

The hotspots calculation had as an inspiration the work presented in Silva et al. (2024a, b). The original data was collected in the field through mobile measurements as explained in Silva et al. (2024a, b). To calculate the hotspot statistical model the ArcGIS Pro Hot Spot Analysis tool was used. This tool makes use of the Getis-Ord G_i^* statistic (Eq. 1).

$$G_i^* = \frac{\sum_{j=1}^n w_{ij} x_j - \bar{x} \sum_{j=1}^n w_{ij}}{s \sqrt{\frac{\sum_{j=1}^n w_{ij}^2}{n} - \left(\frac{\left(\sum_{j=1}^n w_{ij} \right)^2}{n} \right)}} \quad (1)$$

Getis-Ord G_i^* equation is as follows: G_i^* denotes the statistic for feature i ; x_j is the attribute value being evaluated for feature j ; $\bar{x}$ is the average of the attribute values for all features; w_{ij} represents the spatial weight between features i and j ; s is the standard deviation of the attribute values; n is the total number of features in the dataset.

In this study the data was recycled and to the original observed values was subtracted the maximum potential mitigation effect of each species used in this research.

3 Results

To demonstrate if these trees can provide services beyond heat stress mitigation, it can be observed that in SA1, *Cercis siliquastrum* is expected to contribute approximately \$800 to the community in ecosystem services, while *Prunus dulcis* is estimated at around \$740, and *Pyrus calleryana* at about \$430 (Figure S2, in the supplementary materials). The largest portion of these values corresponds to energy savings,

which is particularly notable for *Cercis siliquastrum*. In contrast, *Pyrus calleryana* has the highest value for carbon dioxide uptake. In SA2, a similar situation occurs but with lower values, indicating that trees in this area may be less beneficial (Figure S3, in the supplementary materials).

3.1 *Cercis siliquastrum* scenario

The scenarios featuring *Cercis siliquastrum* in both study areas (Figs. 5 and 6) indicate a decrease in air temperature and UTCI. The influence of the species varied between the two areas, illustrating that urban morphology and surface materials can restrict heat mitigation efforts.

In SA1, *Cercis siliquastrum* can reduce potential air temperature by 0.14 °C (Fig. 5), with the greatest impact in the western part of the street. In the eastern part, the influence was not as strong, and in some areas, there is even an increase in potential air temperature. Regarding the UTCI, the presence of *Cercis siliquastrum* also managed to lower the equivalent temperature by 3.19 °C in the most affected area, which is the western part of the street. However, in the surroundings of each tree, away from the shade, the UTCI increased, particularly in the eastern part of the street.

In SA2, the influence of this tree species on air temperature and UTCI is greater in terms of absolute values (Fig. 6).

Fig. 5 Influence of *Cercis siliquastrum* in potential air temperature and UTCI in SA1

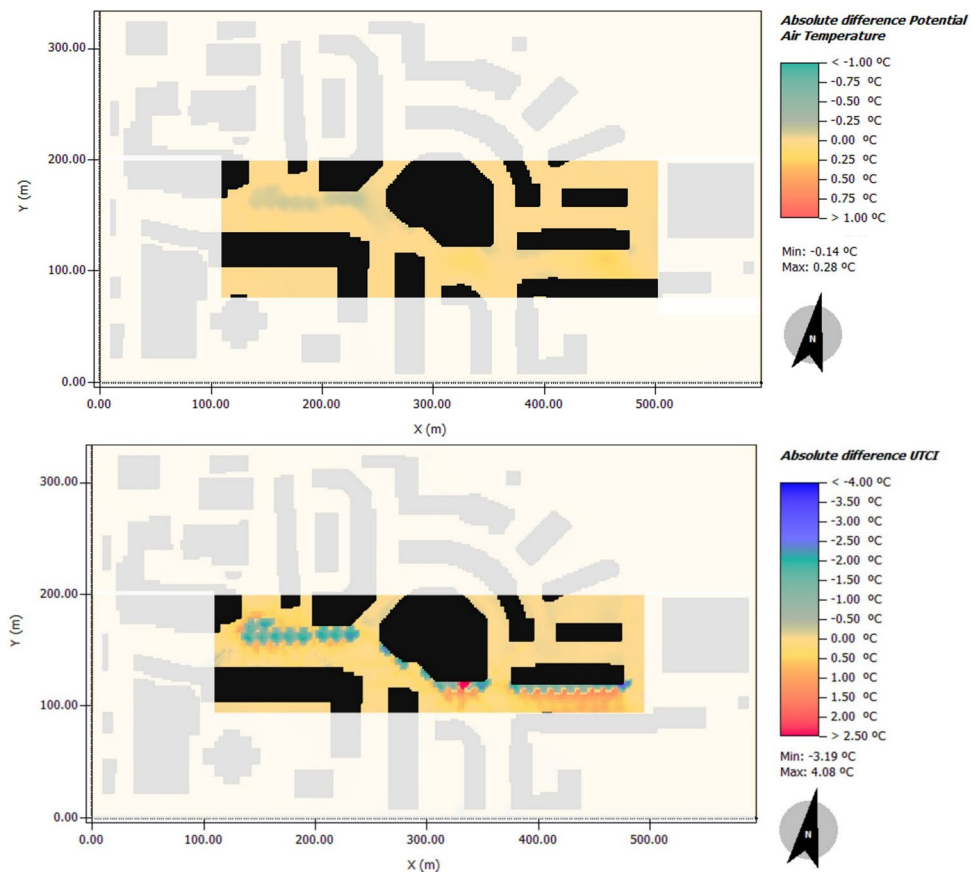
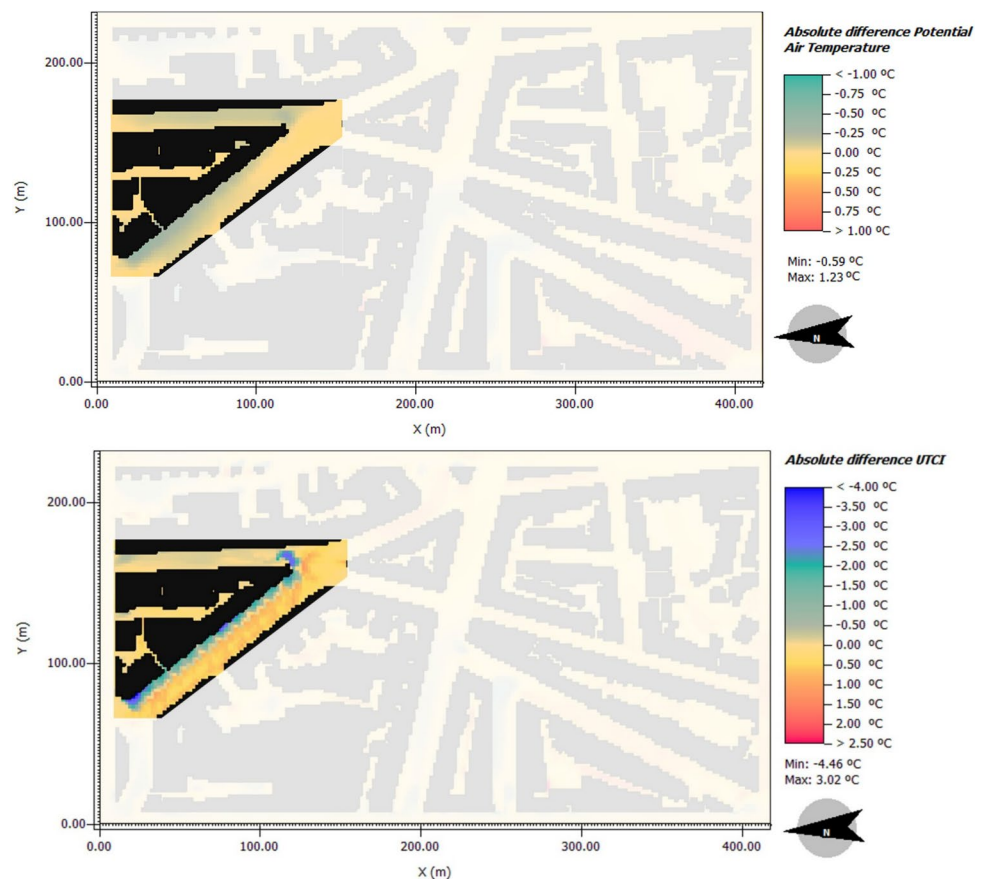


Fig. 6 Influence of *Cercis siliquastrum* in potential air temperature and UTCI in SA2



In this study area, the tree species can reduce potential air temperature by 0.59 °C relatively uniformly along the street. However, this effect is not as pronounced for UTCI, where the influence of the trees is primarily observed at the ends of the street. Nevertheless, this species can lower the UTCI by up to 4.11 °C, as seen in the extremities of the street.

3.2 *Prunus dulcis* scenario

The scenarios involving *Prunus dulcis* (Figs. 7 and 8) also indicate a decrease in air temperature and UTCI. Once again, the influence of the tree was primarily observed around its location and varied spatially within both study areas. The main difference from the previous tree species is notably seen in UTCI in SA2, with the other scenarios being equal or very similar.

In SA1, *Prunus dulcis* can reduce potential air temperature by 0.14 °C (Fig. 7), with the greatest impact occurring in the western part of the street. In the eastern part, the influence was less pronounced, and there was even a slight increase. Conversely, *Prunus dulcis* was able to decrease the UTCI by 3.19 °C in the area of greatest intensity, primarily around each tree. However, away from the shade, the UTCI increased, particularly in the eastern part of the street.

In SA2, the impact of *Prunus dulcis* on air temperature and UTCI is greater in terms of absolute values compared to SA1 and the *Cercis siliquastrum* tree (Fig. 8). In this scenario, *Prunus dulcis* can reduce potential air temperature by 0.60 °C fairly evenly across the street. The effect of these trees on UTCI is most evident at their specific location, lowering this index by between 3.64 °C and 5.27 °C, depending on the area of the street.

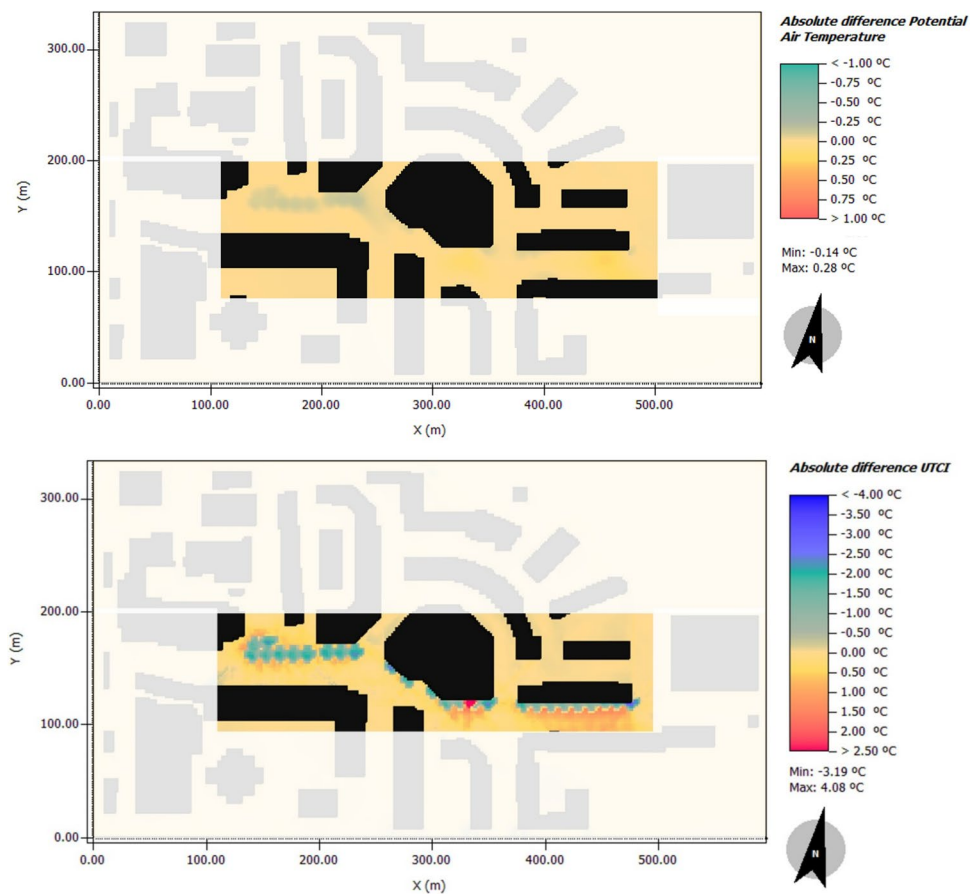
3.3 *Pyrus calleryana* scenario

The scenarios involving *Pyrus calleryana* (Figs. 9 and 10) also indicate a decrease in air temperature and UTCI. As before, the influence of the tree was primarily observed around its location and varied spatially within both study areas. This tree presents slightly different values compared to the other species.

In SA1, *Pyrus calleryana* can reduce potential air temperature by approximately 0.09 °C (Fig. 9), with the greatest impact occurring in the western part of the street. In this area, the species was also able to decrease the UTCI by 3.53 °C, which is mainly observed at the location of each tree.

In SA2, *Pyrus calleryana* demonstrates a greater potential for reducing both air temperature and UTCI compared

Fig. 7 Influence of *Prunus dulcis* in potential air temperature and UTCI in SA1



to SA1. The results for UTCI are more significant than for the other tree species (Fig. 10). In this scenario, it can lower potential air temperature by 0.59 °C, consistent with previous findings. The influence of these trees on UTCI is greater, but again, it is mostly observed around their location. This species can reduce the UTCI by between 2.51 °C and 6.27 °C, with the most substantial effect seen directly at the tree's position, gradually diminishing in its immediate surroundings.

3.4 New hotspot scenarios

Considering the contribution of each species to UTCI reduction, the hotspot scenarios were recalculated for the selected study areas based on the previously presented results. As illustrated in Fig. 11 a) and b) and in comparison, with Silva et al. (2024a, b), the modelled areas showed significant improvements in terms of outdoor thermal comfort.

In SA1 (Fig. 11a), the introduction of these tree species transformed the hotspot into a coldspot across all three scenarios. The most notable improvement, almost entirely with 99% confidence intervals, is associated with *Pyrus calleryana*. *Prunus dulcis* and *Cercis siliquastrum* exhibit

very similar behaviours, varying from 90 to 99% confidence levels in the same locations.

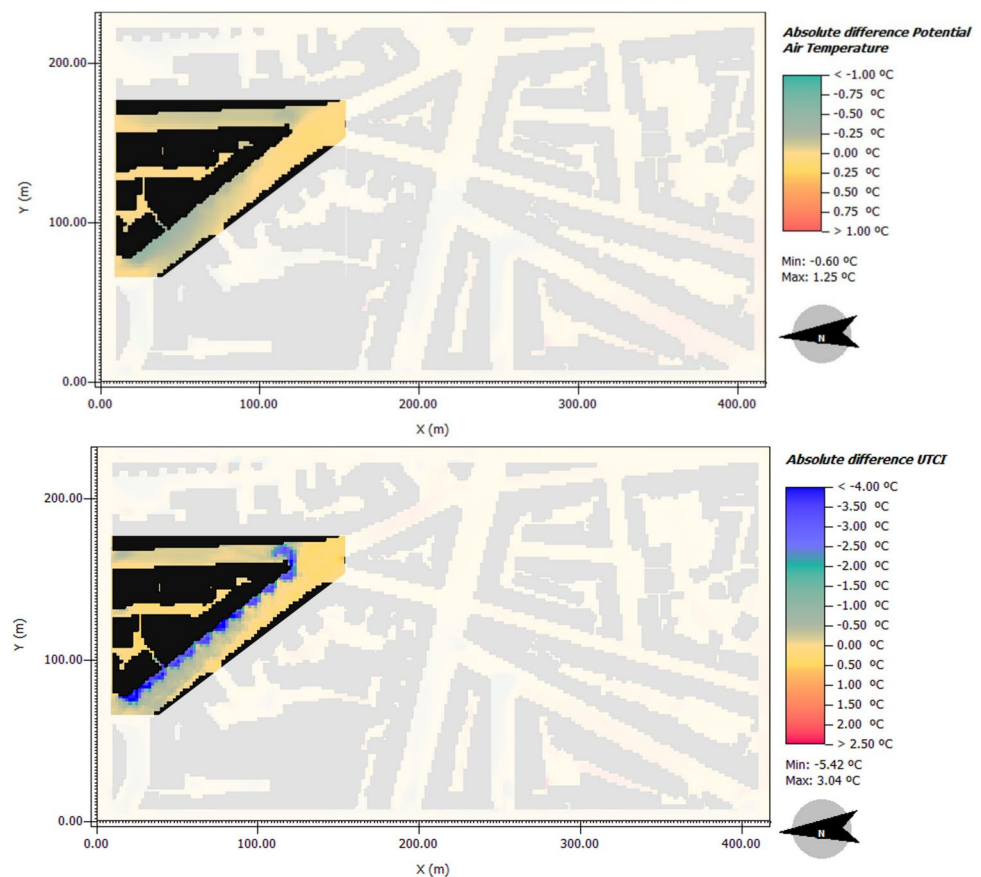
In SA2 (Fig. 11b), the introduction of these tree species also converted the hotspot into a coldspot. The results for the three tree species are quite similar, indicating that they mitigate heat stress equally at the same statistical level. However, *Prunus dulcis* shows a decline from 99 to 95% confidence at the end of the street.

4 Discussion

Studies on urban greening strategies clearly highlight their effectiveness in cooling streets and alleviating heat stress at pedestrian levels (Martinelli et al. 2015; Middel et al. 2016; Oke et al. 2017; M. Rahman et al. 2022; Reis & Lopes 2019).

The findings in this study also show that effectiveness. Previous studies which also assessed the cooling potential of various tree species, yielded slightly different but consistent results. These studies used other variables for this assessment, or studied other tree species, but they all show a decrease in air temperature, radiant temperature, UTCI, PET and surface temperature. Regarding air temperature,

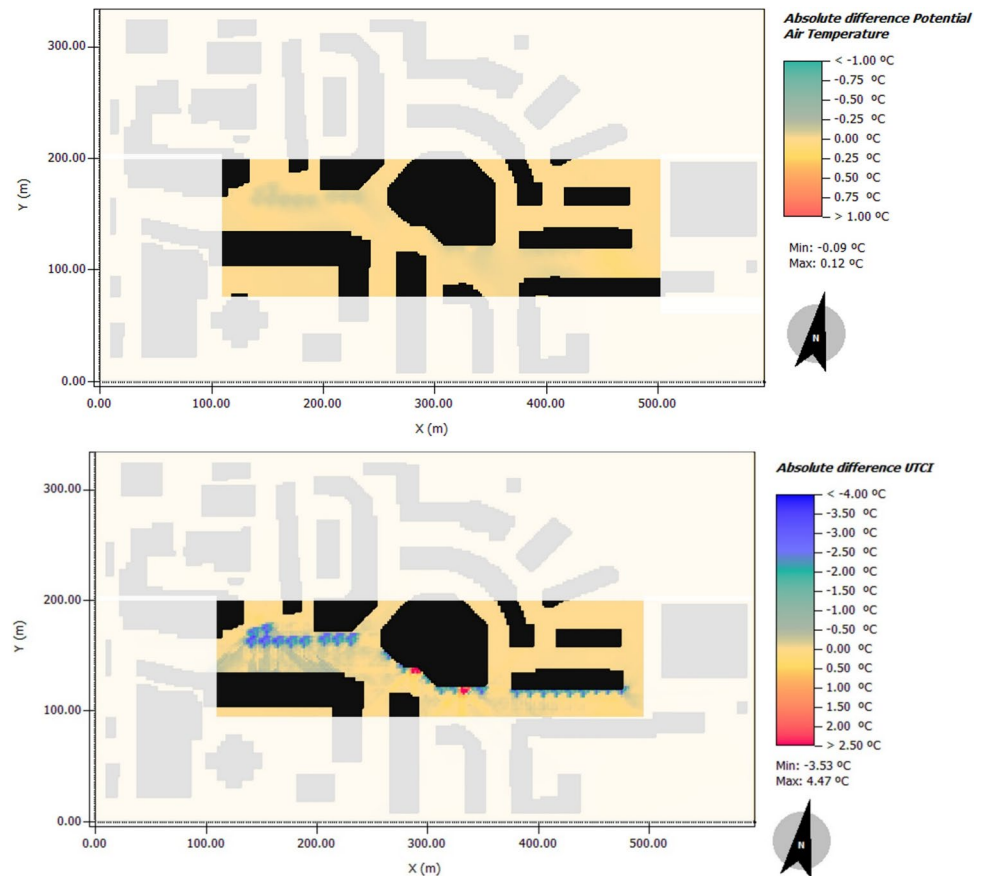
Fig. 8 Influence of *Prunus dulcis* in potential air temperature and UTCI in SA2



In this study, in SA1, *Cercis siliquastrum* and *Prunus dulcis* can reduce air temperature by up to 0.14 °C, while *Pyrus calleryana* can lower it by 0.09 °C (Table 5). In SA2, *Cercis siliquastrum* and *Pyrus calleryana* can reduce air temperature by up to 0.59 °C, and *Prunus dulcis* by up to 0.60 °C (Table 5). Several other research are in accordance with these results. Abreu-Harbic et al. (2014) found that *Mangifera indica*, *Caesalpinia peltophoroides*, and *Syzygium cumini* had the best results among 20 species in reducing air temperature (0.2–2.8 °C). Gillner et al. (2015) identified *Corylus colurna* and *Tilia cordata* as having the greatest cooling potential. Middel et al. (2015) concluded that an increase in tree canopy cover can reduce air temperature by 0.14 °C to 2 °C, depending on the extent of canopy cover. Kántor et al. (2016) stated that *Sophora japonica* can reduce air temperature by 0.5 °C. Rahman et al. (2017) also highlighted that *Tilia cordata* can reduce air temperature by up to 3.5 °C during the day. Cheung & Jim (2018) found that *Ficus microcarpa* can lower air temperature by 0.6 °C. Rahman et al. (2020) found that *Tilia cordata* and *Robinia pseudoacacia* can reduce air temperature by an average of 3 °C and 1.6 °C, respectively, beneath their canopies. *Tilia* species were also studied by Ornelas et al. (2023), who found they can reduce air temperature by 4.84 °C.

Regarding heat stress, namely through UTCI, in SA1, *Cercis siliquastrum* and *Prunus dulcis* can reduce it by 3.19 °C, and *Pyrus calleryana* by 3.53 °C (Table 5). In contrast, in SA2, *Cercis siliquastrum* can reduce UTCI by 4.11 °C, *Prunus dulcis* by up to 5.27 °C, and *Pyrus calleryana* by up to 6.27 °C (Table 5). Yet again, other studies have found similar values of heat stress mitigation potential. Armson et al. (2013) reported that trees can lower mean radiant temperature by an average of 4 °C. Kántor et al. (2016) stated that *Sophora japonica* can reduce mean radiant temperature by 22.1 °C, and PET by 9.3 °C. Lee et al. (2016) remarked that trees were able to reduce PET by 17.4 K. Antoniadis et al. (2018), who studied the effects of several tree species, determined that they can reduce mean radiant temperature and PET by 31 °C and 19 °C, respectively. Cheung & Jim (2018) found that *Ficus microcarpa* can lower PET by 3.9 °C, and UTCI by 2.5 °C. Nouri et al. (2018) concluded that the *Tipuana tipu* species, during extreme heat days (above 35 °C), can lower PET and mPET by 15.6 °C and 11.6 °C, respectively. Zhao et al. (2018) also found that *Fraxinus velutina*, *Acacia salicina*, *Washingtonia filifera* helped reduce thermal stress, especially if planted with equal intervals. Rahman et al. (2020) found that *Tilia cordata* and *Robinia pseudoacacia* can reduce surface temperature

Fig. 9 Influence of *Pyrus calleryana* in potential air temperature and UTCI in SA1



by up to 23 °C and PET by 11 °C. Huang et al. (2022) pointed out that *Cinnamomum camphora* has a noticeable transpirational cooling effect.

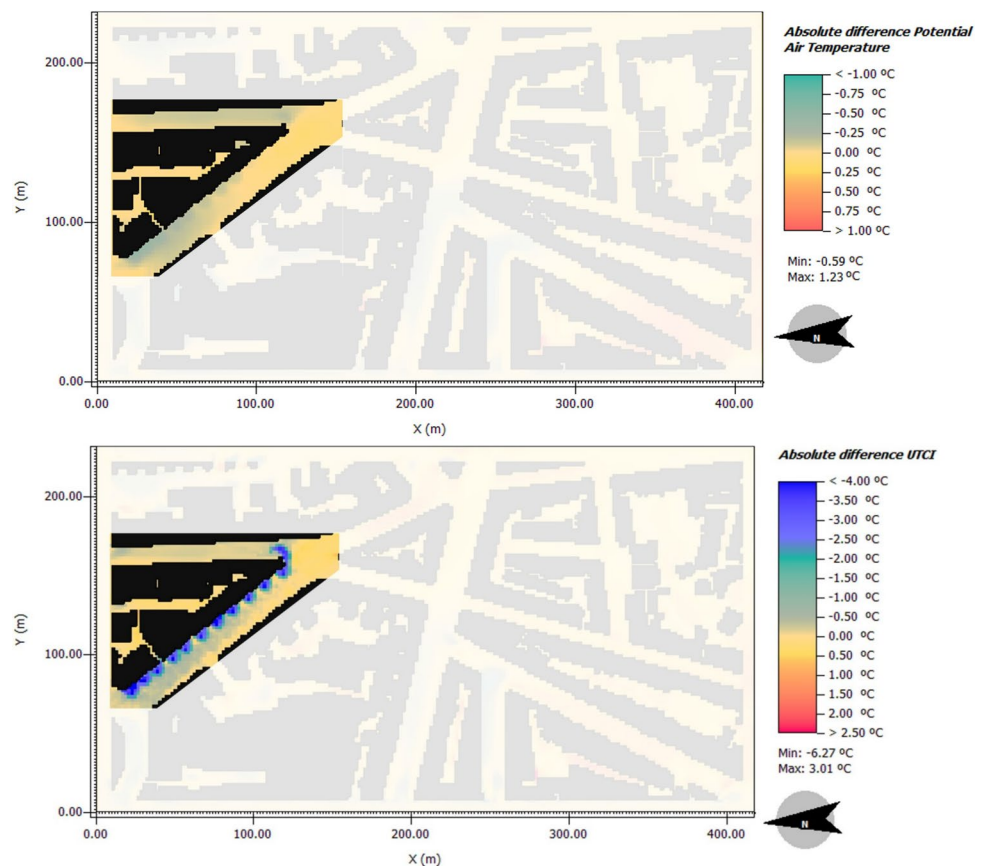
Each species contributed to an overall reduction in air temperature and UTCI, but with some notable differences, not only in relation to the trees themselves but also in terms of the spatial context. Overall, the three species were more effective in mitigating heat stress in SA2 (Table 5). The table also indicates that *Cercis siliquastrum* and *Prunus dulcis* perform better in lowering air temperature in SA1, with *Prunus dulcis* being more effective in SA2. Meanwhile, *Pyrus calleryana* proves to be the most efficient at reducing UTCI in both study areas.

According to Gillner et al. (2015) and Morakinyo et al. (2017) note that tree species vary, and some may be more suitable than others for this purpose. As shown by the literature, it is understandably difficult to choose trees for mitigating heat stress as this may depend on various criteria. This study, for instance, only considered trees that the Lisbon municipal urban planning department deems suitable for planting in the city, including exotic species, which Jin et al. (2024) argue may have limited climatic suitability. Nonetheless, an effort to link urban planning with climatic knowledge was made. Ultimately, the

importance is to reduce the city exposure to heat stress conditions by providing shaded areas as defined in the Lisbon Metropolitan Area Plan for Adaptation to Climate Change (AML, 2019).

Concerning the spatial context, factors such as street orientation, the height-to-width ratio (HW), and urban morphology can condition (positively or negatively) the cooling effect. This is also something reported in Middel et al. (2014). More specifically, it was observed that the effects of trees in SA2 were spatially homogeneous, whereas in SA1, the area was more heterogeneous, displaying two distinct zones influenced by the trees. The westerly zone which is relatively open, and the easterly zone, which has a higher HW, thus offering less space for trees, as shown in the figures. Compactness has been found to increase thermal stress in Lisbon, which hinders mitigation efforts (Silva et al. 2024a, b). The limited space and the presence of trees could create a windbreak, thereby reducing the wind's ability to mitigate heat stress (Yao et al. 2024). Additionally, this area contains more white materials, which are highly reflective, particularly on the lower sections of the buildings and the pavement, contributing to the increase in UTCI (Silva et al. 2024a, b). Consequently, the mitigation efforts were more effective in SA2 than in SA1. This spatial analysis where

Fig. 10 Influence of *Pyrus calleryana* in potential air temperature and UTCI in SA2



urban morphology and cooling potential of trees or other solutions needs to be better addressed, since this study only analysed two very specific urban canyons and very few tree species.

Considering the modelling results, it is essential to verify their significance. With this in mind, the hot and coldspot models from Silva et al. (2024a, b) were recalculated using the new UTCI values from the various scenarios modelled in Envi-met and Bio-met. The results obtained exceeded expectations, as they not only reversed the previously measured UTCI hotspots but also transformed them into coldspots, demonstrating the effectiveness of heat stress mitigation. These results could also serve as an indicator of potential improvements in thermal sensation, thermal perception, thermal preference, and thermal pleasure, as the study found that people did not enjoy these urban canyons during the summer due to heat stress (Silva et al. 2024a, b).

In SA1, *Pyrus calleryana* exhibited the most pronounced coldspot with greater certainty than other species, which also displayed high statistical confidence intervals. In SA2, both *Pyrus calleryana* and *Cercis siliquastrum* also recorded the highest statistical confidence intervals.

These results are particularly significant for areas with high numbers of elderly people, a concern highlighted when

selecting the study area. This issue is also raised by Pigliautile et al. (2022) regarding these urban planning efforts. Furthermore, this aligns with the work of Vanos et al. (2010), Alho et al. (2024) and Yao (2024) who suggest that urban planning can serve as a form of preventive medicine and promote human well-being, as heat stress can have both direct and indirect effects on the body and mind. In addition to promoting health and well-being, these trees can benefit the community by saving energy and capturing CO₂ from the urban atmosphere, as demonstrated by the results from the MyTree application. *Cercis siliquastrum* is the tree who contributed more to the community in both study areas, especially in energy savings. (Soares et al. 2011) found that this tree was one of the best for CO₂ removal in Lisbon. However, from the three studies trees *Pyrus calleryana* was found to be the best for CO₂ removal.

Thus, urban planners face difficult decisions when selecting tree species for urban areas, as they must address various societal demands and expectations (Jamei et al. 2016). In this field and at this spatial scale, urban planning must consider a wide range of demands, some of which are conflicting, often political, economic, climatic, societal, and related to health and well-being (Oke et al. 2017; Vanos et al. 2010; Yao et al. 2024). To minimise the negative climatic impacts on urban communities, urban design and planning professionals should incorporate climatic knowledge into their design strategies

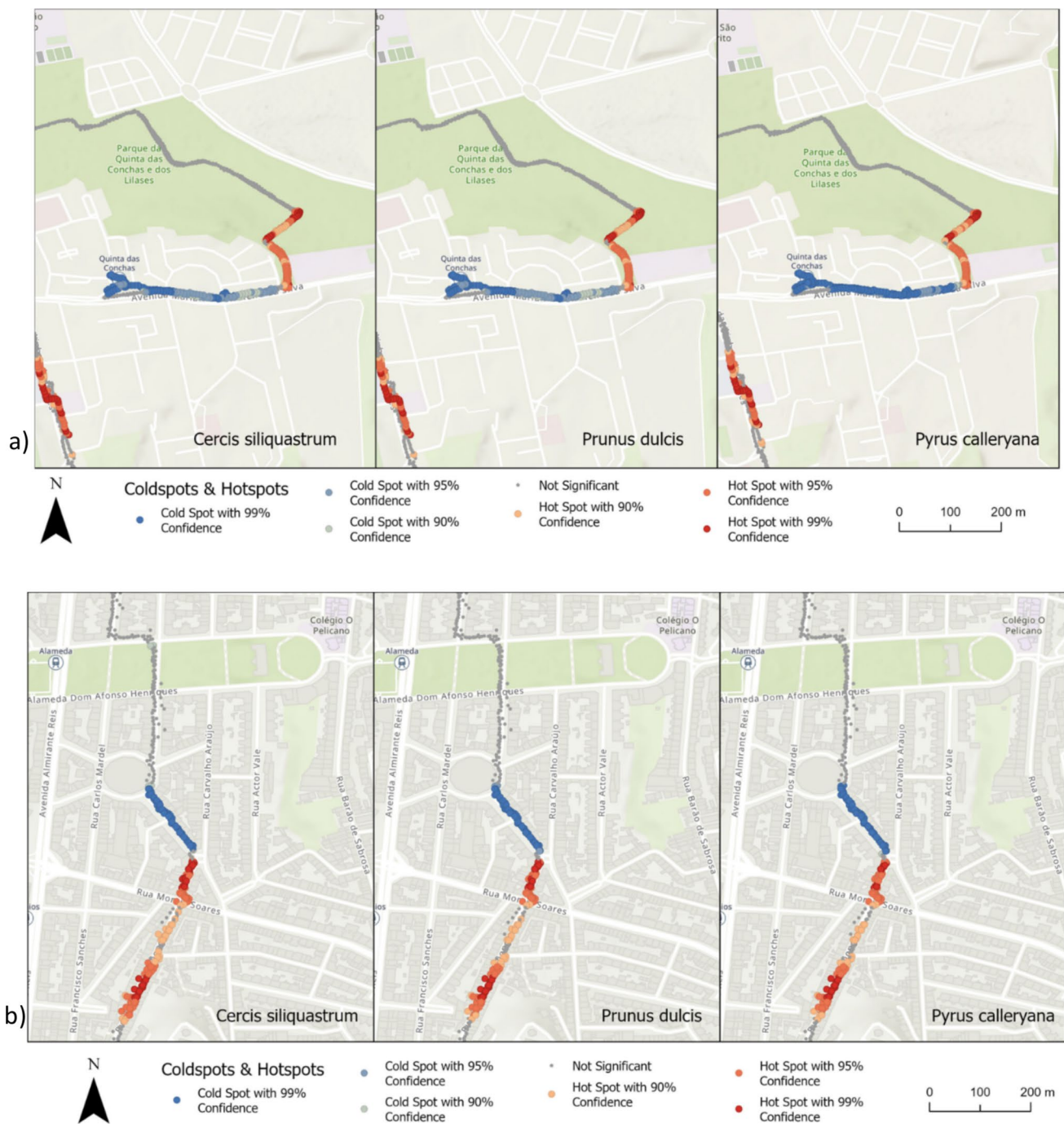


Fig. 11 Recalculated hotspot models from Silva et al. (2024a, b) for SA1 (a) and SA2 (b) based on the results obtained in the Envi-met models

(Alcoforado et al. 2009; Elnabawi & Hamza 2020; Lau et al. 2022; Oke et al. 2017). However, integrating this knowledge into the planning and design process can be challenging, primarily due to a lack of understanding between disciplines and experts (Elnabawi & Hamza 2020; Lau et al. 2022; Oke et al. 2017). To assist future urban planners with microclimatic knowledge, this study aimed to combine both fields to further their united ability to mitigate urban heat stress.

5 Conclusion

The integration of urban planning guidelines with microclimatic expertise offers a solution for addressing the urban heat stress problem. This study findings demonstrated that the studied tree species can lower air temperature and UTCI to varying degrees depending on the study area, underscoring the role of urban morphology.

Table 5 Tree species maximum air temperature (AT) and UTCI cooling capacity

Tree species	Variable	SA1	SA2
<i>Cercis siliquastrum</i>	AT (°C)	0.14	0.59
	UTCI (°C)	3.19	4.11
<i>Prunus dulcis</i>	AT (°C)	0.14	0.60
	UTCI (°C)	3.19	5.27
<i>Pyrus calleryana</i>	AT (°C)	0.09	0.59
	UTCI (°C)	3.53	6.27

Regarding air temperature reduction, the difference between the tree species was negligible; however, it was a different case with the UTCI, where more significant variations were observed. *Pyrus calleryana* was found to reduce UTCI more effectively in both study areas, with reductions reaching up to 6.27 °C in SA2. Heat stress mitigation was generally greater in SA2, despite the fact that the overall ecosystem services provided by the trees were lower there, according to the iTree tool results.

Based on a recalculated hotspot statistical analysis, all three species were able to transform a UTCI hotspot into a potential coldspot. The results demonstrated the effectiveness of trees in heat stress mitigation. In this model, *Pyrus calleryana* once again produced the best result, though by a very narrow margin.

This study has certain limitations that should be considered, as discussed in Chapter 2.1.4. For instance, as previously noted, these results are based on modelling, and like any model, they involve inherent margins of error. These include the overestimation of values, a limited ability to accurately calculate heat transfer between surfaces and the surrounding air, and the fact that the process is already resource intensive. Albeit its limitations the results from this study can still be significant for urban planning departments focused on reducing heat stress, as well as for other research labs. Furthermore, only a small number of tree species were studied, which, although intentional, does not provide a comprehensive perspective on the heat stress mitigation efficiency of other species which may even be better.

This methodological framework – focusing on compact urban areas, field data collection on heat stress during the critical period, the simulation of potential mitigation solutions, and the assessment of their effectiveness – can be refined further. However, at this stage, it already provides a sufficiently robust methodology for urban planners to establish a procedure for mitigating heat stress conditions at the human level. With this framework, urban planners can already define strategies on critical areas, thus helping decision-making act against climate change and urban heat stress.

To further improve this framework, future research should address analysing a wider variety of trees, and their influence according to urban morphological conditions. To enable this, however, the criteria for species selection should not be as restrictive as in this study. Species were chosen as a compromise between various factors and according to a politically approved regulation rather than expert knowledge. Moreover, potential reconfigurations of urban spaces should be considered. In addition to this, urban morphology influence on trees cooling effect should be studied, since there is a gap in the literature on this topic. In the future, aside from the addition of new trees and the resulting street adjustments, further urban morphological changes should be considered to explore other strategies, such as incorporating blue areas or human-made solutions, because trees take a long time to grow, to produce effects and they can be costly in terms of maintenance and eventual falls.

In conclusion, to tackle urban heat stress this study has shown that the alignment of urban planning guidelines with climatic knowledge can indeed come together, despite claims of difficult integration, provided that clear and proper rules are established for urban planning strategies.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s00704-025-05400-7>.

Acknowledgements The authors acknowledge the contribution of reviewers and the editor.

Authors' contributions Tiago Silva: Conceptualization, Data curation, Methodology, Software, Validation, Formal analysis, Investigation, Writing—Original Draft, Writing—Review & Editing, Visualization, Revision. Márcia Matias: Data curation, Methodology, Software, Validation, Writing—Review & Editing. Carolina Girotti: Data curation, Methodology, Software, Validation, Writing—Review & Editing. António Lopes: Conceptualization, Methodology, Validation, Supervision, Writing—Review & Editing, Revision. João Vasconcelos: Supervision, Writing—Review & Editing, Revision.

Funding Open access funding provided by FCTIFCCN (b-on). This research was funded by FCT—Fundação para a Ciência e Tecnologia, I.P., grant code: UI/BD/152225/2021. This research is developed under the eMOTIONAL CITIES' Project, which received funding from European Union's Horizon 2020 research and innovation programme, under the grant agreement No 945307. The eMOTIONAL CITIES Project is a consortium of 12 partners co-coordinated by IGOT and FMUL, taking place between 2021 and 2025.

Data availability No datasets were generated or analysed during the current study.

Declarations

Declaration of Generative AI and AI-assisted technologies in the writing process' No statement.

Competing interests The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Abreu-Harbic, L., Labaki, L., & Bueno-Barthlomei, C. (2014). How much does the shade provided by different trees collaborate to control the urban heat island in tropical climates? – a study in Campinas, Brazil. IC2UHI - Third International Conference on Countermeasures to Urban Heat Islands, 838–849. <https://doi.org/10.13140/2.1.1345.5360>
- Alcoforado, M., Andrade, H., Lopes, A., & Vasconcelos, J. (2009). Application of climatic guidelines to urban planning. The example of Lisbon (Portugal). *Landscape and Urban Planning*, 90(1–2), 56–65. <https://doi.org/10.1016/j.landurbplan.2008.10.006>
- Alho A, Oliveira A, Viegas S, Nogueira P (2024) Effect of heatwaves on daily hospital admissions in Portugal, 2000–18: an observational study. *The Lancet Planetary Health* 8(5):e318–e326. [https://doi.org/10.1016/S2542-5196\(24\)00046-9](https://doi.org/10.1016/S2542-5196(24)00046-9)
- Álvarez-López S, Fernández-González M, González-Fernández E, Garrido AI, Rodríguez-Rajo J (2020) Tree allergen pollen-related content as pollution source in the city of ourense (NW Spain). *Forests* 11(11):1–16. <https://doi.org/10.3390/f11111129>
- Alves, F., Cruz, S., Ribeiro, A., Silva, A., Martins, J., & Cunha, I. (2020). Walkability index for elderly health: A proposal. *Sustainability (Switzerland)*, 12(18). <https://doi.org/10.3390/SU12187360>
- American University of Beirut. (2024, July 16). AUB Landscape Plant Database. <https://Landscapeplants.Aub.Edu.Lb/>
- Andrade, H., & Vieira, R. (2007). A climatic study of an urban green space: the Gulbenkian Park in Lisbon (Portugal). *Finisterra*, XLII(84), 27–46. <https://doi.org/10.18055/finis1420>
- Anexo Geral V - Catálogo de Propriedades Térmicas de Paredes, Coberturas e Vidros, Pub. L. No. 50/2013, Anexo da Portaria INMETRO nº 50/2013 (2013).
- Antoniadis D, Katsoulas N, Kittas C (2018) Simulation of schoolyard's microclimate and human thermal comfort under Mediterranean climate conditions: effects of trees and green structures. *Int J Biometeorol* 62(11):2025–2036. <https://doi.org/10.1007/s00484-018-1612-5>
- Área Metropolitana de Lisboa. (2019). Plano metropolitano de adaptação às alterações climáticas.
- Armson, D., Rahman, M., & Ennos, A. (2013). A Comparison of the Shading Effectiveness of Five Different Street Tree Species in Manchester, UK. *Arboriculture & Urban Forestry*, 39(4).
- Bowler Di, Buyung-Ali L, Knight T, Pullin A (2010) Urban greening to cool towns and cities: A systematic review of the empirical evidence. *Landsc Urban Plan* 97(3):147–155. <https://doi.org/10.1016/j.landurbplan.2010.05.006>
- Bruse M, Fleer H (1998) Simulating surface–plant–air interactions inside urban environments with a three dimensional numerical model. *Environ Model Softw* 13(3–4):373–384. [https://doi.org/10.1016/S1364-8152\(98\)00042-5](https://doi.org/10.1016/S1364-8152(98)00042-5)
- Câmara Municipal de Lisboa. (2017). Regulamento Municipal do arvoredo de Lisboa.
- Cariñanos, P., & Marinangeli, F. (2021). An updated proposal of the Potential Allergenicity of 150 ornamental Trees and shrubs in Mediterranean Cities. *Urban Forestry and Urban Greening*, 63. <https://doi.org/10.1016/j.ufug.2021.127218>
- Cheung P, Jim C (2018) Comparing the cooling effects of a tree and a concrete shelter using PET and UTCI. *Build Environ* 130:49–61. <https://doi.org/10.1016/j.buildenv.2017.12.013>
- Correia, E. (2020). Mapas Climáticos Urbanos Geometria e densidade urbana futura Relatório.
- Cortesão J, Koopmans S, Lenzholzer S, Steeneveld G, Heusinkveld B (2023) The ‘cooling urban water environments’ concept: potential for application in practice. *J Urban des*. <https://doi.org/10.1080/13574809.2023.2240248>
- Crank, P., Sailor, D., Ban-Weiss, G., & Taleghani, M. (2018). Evaluating the ENVI-met microscale model for suitability in analysis of targeted urban heat mitigation strategies. *Urban Climate*, 26, 188–197.
- De Quadros B, Pigliautile I, Pisello A, Krüger E, Mizgier M (2024) Reliability of urban microclimate simulations: spatio-temporal validation through intra-urban canyon transects for outdoor thermal comfort analysis. *Int J Biometeorol*. <https://doi.org/10.1007/s00484-024-02784-5>
- Donovan G, Butry D (2009) The value of shade: Estimating the effect of urban trees on summertime electricity use. *Energy and Buildings* 41:662–668. <https://doi.org/10.1016/j.enbuild.2009.01.002>
- Elnabawi M, Hamza N (2020) Behavioural perspectives of outdoor thermal comfort in urban areas: A critical review. *Atmosphere* 11(1):1–23. <https://doi.org/10.3390/atmos11010051>
- Fuller R, Gaston K (2009) The scaling of green space coverage in European cities. *Biol Lett* 5(3):352–355. <https://doi.org/10.1098/rsbl.2009.0010>
- Gillner S, Vogt J, Tharang A, Dettmann S, Roloff A (2015) Role of street trees in mitigating effects of heat and drought at highly sealed urban sites. *Landsc Urban Plan* 143:33–42. <https://doi.org/10.1016/j.landurbplan.2015.06.005>
- Huang, J., Kong, F., Yin, H., Middel, A., Liu, H., Zheng, X., Wen, Z., & Wang, D. (2022). Transpirational cooling and physiological responses of trees to heat. *Agricultural and Forest Meteorology*, 320. <https://doi.org/10.1016/j.agrformet.2022.108940>
- Jamei E, Rajagopalan P, Seyedmahmoudian M, Jamei Y (2016) Review on the impact of urban geometry and pedestrian level greening on outdoor thermal comfort. *Renew Sustain Energy Rev* 54:1002–1017. <https://doi.org/10.1016/j.rser.2015.10.104>
- Jin, C., Hu, S., Da, L., Hu, Y., & Yang, Y. (2024). Biotic Homogenization and Rewilding of Urban Greening. In R. Yao (Ed.), *Resilient Urban Environments* (pp. 165–188). Springer Nature Switzerland. <https://doi.org/10.1007/978-3-031-55482-7>
- Kántor, N., Kovács, A., & Takács, Á. (2016). Small-scale human-biometeorological impacts of shading by a large tree. 8(1), 231–245. <https://doi.org/10.1515/geo-2016-0021>
- Kim Y, Brown R (2021) A multilevel approach for assessing the effects of microclimatic urban design on pedestrian thermal comfort: The High Line in New York. *Build Environ* 205(108244):1–15. <https://doi.org/10.1016/j.buildenv.2021.108244>
- Kong L, Lau K, Yuan C, Chen Y, Xu Y, Ren C, Ng E (2017) Regulation of outdoor thermal comfort by trees in Hong Kong. *Sustain Cities Soc* 31:12–25. <https://doi.org/10.1016/j.scs.2017.01.018>
- Konijnendijk C (2021) The 3–30–300 Rule for Urban Forestry and Greener Cities. *Biophilic Cities Journal*. <https://doi.org/10.1016/j.ssmph.2019.100497>
- Kuttler W, Weber S (2023) Characteristics and phenomena of the urban climate. *Meteorol Z*. <https://doi.org/10.1127/metz/2023/1153>
- Lau, K., Tan, Z., Morakinyo, T., & Ren, C. (2022). Outdoor Thermal Comfort in Urban Environment: Assessments and Applications in

- Urban Planning and Design (1st ed.). Springer, Singapore. <https://doi.org/10.1007/978-981-16-5245-5>
- Lee H, Mayer H, Chen L (2016) Contribution of trees and grasslands to the mitigation of human heat stress in a residential district of Freiburg, Southwest Germany. *Landsc Urban Plan* 148:37–50. <https://doi.org/10.1016/j.landurbplan.2015.12.004>
- Lopes, A., Correia, E., Nascimento, J., & Canário, P. (2014). Urban bioclimate and comfort assesment in the african city of praia (Cape verde). *Finisterra*, XLIX(98), 33–48.
- Martinelli L, Lin T, Matzarakis A (2015) Assessment of the influence of daily shadings pattern on human thermal comfort and attendance in Rome during summer period. *Build Environ* 92:30–38. <https://doi.org/10.1016/j.buildenv.2015.04.013>
- Matias, M. (2018). O balanço radiativo de um conjunto de edifícios em Telheiras com recurso a termografia infravermelha [Master]. University of Lisbon.
- McPhearson T, Kabisch N, Frantzeskaki N (2023) Nature-based solutions for cities. Edward Elgar Publishing Ltd., In *Nature-Based Solutions for Cities*. <https://doi.org/10.4337/9781800376762>
- Mendes, F. (2021). Quantificação dos serviços ecossistémicos da arborização urbana [Doctoral]. Escola Superior de Agricultura “Luiz de Queiroz.”
- Mendes, F., Petean, F., Correia, E., & Lopes, A. (2024). A Proximity-Based Approach for the Identification of Fallen Species of Street Trees during Strong Wind Events in Lisbon. *Land*, 13(5). <https://doi.org/10.3390/land13050708>
- Middel, A., Häb, K., Brazel, A., Martin, C., & Guhathakurta, S. (2014). Impact of urban form and design on mid-afternoon microclimate in Phoenix Local Climate Zones. *Landscape and Urban Planning*, 122, 16–28. <https://doi.org/10.1016/j.landurbplan.2013.11.004>
- Middel, A., Chhetri, N., & Quay, R. (2015). Urban forestry and cool roofs: Assessment of heat mitigation strategies in Phoenix residential neighborhoods. *Urban Forestry & Urban Greening*, 14(1), 178–186. <https://doi.org/10.1016/j.ufug.2014.09.010>
- Middel A, Selover N, Hagen B, Chhetri N (2016) Impact of shade on outdoor thermal comfort—a seasonal field study in Tempe, Arizona. *International Journal of Biometeorology* 60(12):1849–1861. <https://doi.org/10.1007/s00484-016-1172-5>
- Morakinyo T, Kong L, Lau K, Yuan C, Ng E (2017) A study on the impact of shadow-cast and tree species on in-canyon and neighborhood’s thermal comfort. *Build Environ* 115:1–17. <https://doi.org/10.1016/j.buildenv.2017.01.005>
- Mullaney J, Lucke T, Trueman S (2015) A review of benefits and challenges in growing street trees in paved urban environments. *Landsc Urban Plan* 134:157–166. <https://doi.org/10.1016/j.landurbplan.2014.10.013>
- Nouri, A., Fröhlich, D., Silva, M., & Matzarakis, A. (2018). The Impact of Tipuana tipu Species on Local Human Thermal Comfort Thresholds in Different Urban Canyon Cases in Mediterranean Climates: Lisbon, Portugal. *Atmosphere*, 9(1). <https://doi.org/10.3390/atmos9010012>
- Oke T, Mills G, Christen A, Voogt J (2017) *Urban Climates*. Cambridge University Press. <https://doi.org/10.1017/9781139016476>
- Ornelas, A., Cordeiro, A., & Lameiras, J. (2023). Thermal Comfort Assessment in Urban Green Spaces: Contribution of Thermography to the Study of Thermal Variation between Tree Canopies and Air Temperature. *Land*, 12(8). <https://doi.org/10.3390/land12081568>
- Pigliautile, I., Cureau, R., & Pisello, A. (2022). Human Adaptation to Higher Ambient Temperature. In *Urban Overheating: Heat Mitigation and the Impact on Health* (pp. 109–128).
- Qi, J., & He, B. (2023). Urban Heat Mitigation Strategies. In A. Cheshmehzangi, B.-J. He, A. Sharifi, & A. Matzarakis (Eds.), *Climate Change and Cooling Cities* (pp. 21–44). Springer Nature Singapore. <https://doi.org/10.1007/978-981-99-3675-5>
- Rahman, M. A., Moser, A., Rötzer, T., & Pauleit, S. (2017). Within canopy temperature differences and cooling ability of *Tilia cordata* trees grown in urban conditions. *Building and Environment*, 114, 118–128. <https://doi.org/10.1016/j.buildenv.2016.12.013>
- Rahman, M., Hartmann, C., Moser-Reischl, A., von Strachwitz, M., Paeth, H., Pretzsch, H., Pauleit, S., & Rötzer, T. (2020). Tree cooling effects and human thermal comfort under contrasting species and sites. *Agricultural and Forest Meteorology*, 287(107947). <https://doi.org/10.1016/j.agrformet.2020.107947>
- Rahman M, Franceschi E, Pattnaik N, Moser-Reischl A, Hartmann C, Paeth H, Pretzsch H, Rötzer T, Pauleit S (2022) Spatial and temporal changes of outdoor thermal stress: influence of urban land cover types. *Sci Rep* 12(1):1–13. <https://doi.org/10.1038/s41598-021-04669-8>
- Reis, C., & Lopes, A. (2019). Evaluating the cooling potential of urban green spaces to tackle urban climate change in Lisbon. *Sustainability*, 11(9). <https://doi.org/10.3390/su11092480>
- Reis C, Lopes A, Correia E, Fragoso M (2020) Local weather types by thermal periods: Deepening the knowledge about Lisbon’s urban climate. *Atmosphere* 11(840):1–20. <https://doi.org/10.3390/atmos11080840>
- Santamouris, M. (2020). Recent progress on urban overheating and heat island research. Integrated assessment of the energy, environmental, vulnerability and health impact. Synergies with the global climate change. *Energy and Buildings*, 207. <https://doi.org/10.1016/j.enbui.2019.109482>
- Sayad B, Alkama D, Ahmad H, Baili J, Aljahdaly N, Menni Y (2021) Nature-based solutions to improve the summer thermal comfort outdoors. *Case Studies in Thermal Engineering* 28(101399):1–12. <https://doi.org/10.1016/j.csite.2021.101399>
- Silva T, Lopes A, Vasconcelos J (2024a) A micro-scale look into pedestrian thermophysiological comfort in an urban environment. *Bulletin of Atmospheric Science and Technology* 5(1):18. <https://doi.org/10.1007/s42865-024-00082-x>
- Silva T, Reis C, Braz D, Vasconcelos J, Lopes A (2024b) Climate walking and linear mixed model statistics for the seasonal outdoor thermophysiological comfort assessment in Lisbon. *Urban Climate* 55:101933. <https://doi.org/10.1016/j.uclim.2024.101933>
- Soares A, Rego F, McPherson E, Simpson J, Peper P, Xiao Q (2011) Benefits and costs of street trees in Lisbon. *Portugal Urban Forestry and Urban Greening* 10(2):69–78. <https://doi.org/10.1016/j.ufug.2010.12.001>
- The World Bank. (2023, April). Urban Development. <https://www.Worldbank.Org/En/Topic/Urbandevelopment/Overview>.
- Tsoka, S., Tsikaloudaki, A., & Theodosiou, T. (2018). Analyzing the ENVI-met microclimate model’s performance and assessing cool materials and urban vegetation applications—A review. *Sustainable Cities and Society*, 43, 55–76. <https://doi.org/10.1016/j.scs.2018.08.009>
- Vanos J, Warland J, Gillespie T, Kenny N (2010) Review of the physiology of human thermal comfort while exercising in urban landscapes and implications for bioclimatic design. *Int J Biometeorol* 54(4):319–334. <https://doi.org/10.1007/s00484-010-0301-9>
- Vusthepalli, P., Vusthepalli, G., Manne, A., Nannapaneni, S., Veeravilli, S., Setti, R., & Vemuri, P. (2022). Comprehensive Study on Key Pollen Allergens. *Journal of Pure and Applied Microbiology*, 16(1), 110–115. <https://doi.org/10.22207/JPAM.16.1.26>
- Wania A, Bruse M, Blond N, Weber C (2012) Analysing the influence of different street vegetation on traffic-induced particle dispersion using microscale simulations. *J Environ Manage* 94(1):91–101. <https://doi.org/10.1016/j.jenvman.2011.06.036>
- Wong N, Tan C, Kolokotsa D, Takebayashi H (2021) Greenery as a mitigation and adaptation strategy to urban heat. *Nature Reviews Earth & Environment* 2(3):166–181. <https://doi.org/10.1038/s43017-020-00129-5>
- Yao, R. (2024). *Resilient Urban Environments* (R. Yao, Ed.). Springer Nature Switzerland. <https://doi.org/10.1007/978-3-031-55482-7>
- Yao, R., Huang, X., Xu, T., & Zhu, Y. (2024). Outdoor Thermal Comfort and Heat Exposure Risks. In R. Yao (Ed.), *Resilient Urban Environments* (pp. 13–58). Springer Nature Switzerland. <https://doi.org/10.1007/978-3-031-55482-7>
- Yuan, T., Qu, H., & Hong, B. (2023). Climate-Responsive Designs to Enhance Outdoor Thermal Comfort in Urban Residential Areas.

In A. Cheshmehzangi, B.-J. Sharifi, & A. Matzarakis (Eds.), *Climate Change and Cooling Cities* (Vol. 1).

Zhao Q, Sailor D, Wentz E (2018) Impact of tree locations and arrangements on outdoor microclimates and human thermal comfort in an urban residential environment. *Urban Forestry and Urban Greening* 32:81–91. <https://doi.org/10.1016/j.ufug.2018.03.022>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.