



The role of soil moisture and shading in influencing the capacity of urban street trees to reduce heat stress[☆]

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ABSTRACT

Street trees can significantly reduce urban heat through shading and transpirative cooling, but their effectiveness may be compromised during heat waves with dry soil conditions. This study assesses the cooling potential of street trees using a modified BEP-Tree model incorporating soil moisture dynamics and thermos-physiological indices like the Universal Thermal Climate Index (UTCI). The model is first validated with a micrometeorological measurement campaign during hot summer days in a town in the Metropolitan Area of Barcelona, Spain, yielding a good model performance representing the spatial variability of the mean radiant temperature and UTCI inside the studied neighbourhood. Then, BEP-Tree is used to simulate two highly-compact neighbourhoods with differing tree densities in the city of Barcelona, combined with varying soil moisture levels during a heat wave. Results show that street trees in moist soil reduced air temperatures by an average of 1.2 ± 0.4 °C, leading to UTCI reductions up to 3.2 °C. Albeit air-cooling effects were reduced under dry-soil conditions, shade-driven temperature reductions remained substantial, retaining 71–97% of the cooling effect. The findings highlight the importance of tree shading rather than air-cooling in maximising the cooling capabilities of street trees during extreme heat events. Additionally, it is crucial to maintain adequate soil moisture to preserve tree health and substantial foliage to provide consistent microclimatic benefits, particularly during periods of strong heat stress.

1. Introduction

Street trees are a potential solution for mitigating heat in highly compact cities that have limited areal coverage but high building density since they can be implemented easier than larger green infrastructures such as urban parks (Baró et al., 2019). Street trees contribute to reducing urban air temperatures through transpiration and shading, thereby decreasing radiation absorption by surfaces

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such as the ground and building walls (Bowler et al., 2010). Yet, the impact of street trees on human thermal stress goes beyond their air-cooling effect, since other micrometeorological variables affected by trees are also important factors determining how human experience thermal stress, such as humidity, wind and radiation (Jendritzky et al., 2012).

Several studies explore the impact of street trees on the urban heat island effect (UHI) at the local scale (Loughner et al., 2012) and human thermal stress at the microscale (Coutts et al., 2016; Huang et al., 2020; Jia and Wang, 2021; Miao et al., 2023; Shashua-Bar and Hoffman, 2000). Coutts et al. (2016) investigated the cooling capacity and improvement of thermal comfort of street trees in Melbourne, Australia, using micrometeorological observations. They found that the magnitude of daytime cooling depended on shading amount, street canyon geometry, and local meteorological conditions. Street trees in low-rise neighbourhoods were highly effective in reducing daytime thermo-physiological heat stress indices, such as the Universal Thermal Climate Index (UTCI) (Jendritzky et al., 2012), due to the reduction of mean radiant temperature (T_{MRT}) from shading. T_{MRT} is a crucial factor in thermo-physiological heat stress (Thorsson et al., 2007), because it determines the effect of shortwave and longwave radiation exposure on the human body (Jia and Wang, 2021). Jia and Wang (2021) studied thermal stress variability in a high-density urban area in Hong Kong under various heat mitigation strategies using a micro-scale computation fluid dynamics model. Their findings suggest that the largest reductions in T_{MRT} and UTCI were achieved with the street trees strategy, with peak reductions of 4.23 °C and 0.88 °C during daytime, respectively.

However, the capacity of street trees to cool air and reduce human thermal stress in highly-compact cities and especially during extreme heat events is still uncertain, which can impact physiological processes and structural components of trees (Qu et al., 2024). The warmer urban temperatures, compared to their rural surroundings, can intensify during heat waves due to non-linear interactions (Li and Bou-Zeid, 2013), intensifying heat stress on urban vegetation and citizens. While heat stress may increase water evapotranspiration from tree leaves and soil when water is not limited (Drake et al., 2018), heat events are often accompanied by droughts. Droughts restrict soil water availability, limiting transpiration and prompting the closure of the stomata on the surfaces of leaves to prevent further soil water depletion and reduce the risk of “hydraulic failure” in plants (McDowell et al., 2008). Soil water availability can be a crucial factor in the capacity of trees to mitigate thermal stress, though other factors such as drought occurrence, irrigation restrictions, and high urban surface impermeability can compromise the retention of water in the soil, and consequently, affecting tree transpiration (Coutts et al., 2013). Understanding the complex interactions of street trees during heat waves is crucial for supporting their management and implementation in highly-compact cities, particularly in regions where heat waves are projected to increase due to climate change, such as the Mediterranean region (Essa et al., 2023; Tejedor et al., 2024).

Microscale computational fluid dynamic models are used to understand the complexities of urban geometry and urban vegetation on the human thermal stress inside street canyons (Jia and Wang, 2021; Perini et al., 2017). These models simulate airflow around explicitly resolved buildings and trees with three spatial dimensions, and determine the energy balance of multiple surfaces as well as the spatial variability of wind speed and radiation. These models are computationally expensive and are valid for a street block during short periods of time (Martilli et al., 2024). By contrast, urban canopy models (UCMs) simulate the interactions between buildings and the urban canopy layer atmosphere at a neighbourhood scale and can be coupled with mesoscale atmosphere models to study the effects of urban areas and urban heat mitigation strategies at regional scales (Chen et al., 2011). Recently, Martilli et al. (2024) developed a methodology to quantify the spatial variability of wind speed and T_{MRT} within the UCM Building Effect Parameterization and Building Energy Model (BEP-BEM) (Martilli et al., 2002; Salamanca and Martilli, 2010), to provide the variability of thermal exposure within each mesoscale atmosphere model grid. Although, this BEP-BEM version can represent the impact of street trees on the thermal exposure and shading, based on a simple approach proposed by Stone et al. (2021), BEP-BEM does not consider the impact of street trees on the wind flow and longwave radiation exchange and strongly simplifies the estimation of the tree's transpiration.

Alternatively, the BEP-Tree model (Krayenhoff et al., 2020) is a multi-layer UCM that accounts for the integrated effects of streets trees on the neighbourhood-scale climate, in terms of radiation exchange, energy balance, wind drag, turbulence and pedestrian level climate. BEP-Tree has been evaluated and improved for the representation of the meteorology during summer days in highly-compact cities, specifically the Mediterranean coastal city of Barcelona (Spain) (Segura et al., 2022). However, BEP-Tree model in its standard version does not estimate thermo-physiological heat stress indices, nor does it include the hydrology of permeable urban soil, omitting the impacts of soil water availability on tree transpiration (Krayenhoff et al., 2020; Segura et al., 2022).

To more appropriately assess the cooling capacity of street trees, this study modifies the BEP-Tree model to calculate the mean radiant temperature (T_{MRT}) and tree-soil moisture interactions, considering soil water availability impacts on the tree transpiration and computing heat stress indices. A measurement campaign is carried out in the Metropolitan Area of Barcelona to validate the model modifications for a highly-compact, heterogeneous urban landscape. Then, simulations are performed for two neighbourhood configurations with different tree densities but similar geometry in the city of Barcelona for a heat wave that occurred in July 2015, combining varying soil moisture conditions. We first evaluate how compound heat and water stress affect air temperature, relative humidity and T_{MRT} . Then we explore how these meteorological variables influence UTCI. This study aims to provide the tools to effectively implement street trees for optimising heat regulation during intense heat events.

2. Materials and methods

2.1. BEP-Tree model description

In this study, we include the calculation of the mean radiant temperature and thermal stress indicator UTCI in the BEP-Tree model developed by Krayenhoff et al. (2020), which integrates the effect of street trees in the Building Effect Parameterization (BEP) model (Martilli et al., 2002). The model is formulated as a one-dimensional single-column framework with a vertical resolution of 1 m from

the street surface to the top boundary, situated at 2–3 times the height of the tallest building. BEP represents idealized, infinitely long urban canyons in two orthogonal street directions, assuming spatially uniform building configurations. Horizontal variability within the street canyon is not explicitly resolved; instead, microclimatic variables are estimated using a canyon-averaged approach. A description of the standard BEP-Tree model and a more detailed description of the modifications are presented in Appendix A1 of the Supplementary material.

2.1.1. Mean radiant temperature and UTCI variability in urban canyons

This study implements a method for computing the T_{MRT} in the BEP-Tree model, following Martilli et al. (2024). The T_{MRT} quantifies the radiation absorbed by the human body, including shortwave and longwave radiation, and varies within street canyons depending on sunlight exposure, shading from buildings or trees, and proximity to warm surfaces. Consequently, T_{MRT} varies significantly within street canyons, influenced by the distance from building walls and shadow distribution. To capture this variability, BEP-Tree computes T_{MRT} at 12 locations per simulated neighbourhood—six per street orientation (North-South and East-West). T_{MRT} is assessed at three positions per case (under tree cover and outside tree cover) for each orientation: the street centre and 1.5 m from each building wall, representing the sidewalks.

To depict the variability in the UTCI, computations are performed separately for locations under and outside tree crowns, involving six T_{MRT} values, three air temperature values, and three wind speed values. The wind speed values are derived from BEP-Tree and undergo the methodology outlined in Martilli et al. (2024), incorporating parameterisations obtained from computational fluid dynamic models to represent airflow variability. For air temperature, a variation of $\pm 1^\circ\text{C}$ is applied to the simulated values, since urban canopy model simulations lack microscale representation of temperature variability. This value aligns with a realistic estimate of the variability observed in urban neighbourhoods. This results in 54 possible combinations of variables to produce a unique UTCI. Both scenarios, under tree cover and outside tree cover, share identical air temperature and wind speed values but differ in T_{MRT} values, yielding two sets of 54 UTCI estimates. Tree crown coverage fraction within the street canyons (tree_cov) is used to combine these two UTCI distributions, maintaining the shading fraction within the canyon. From the resulting distribution, the 10th, 50th, and 90th

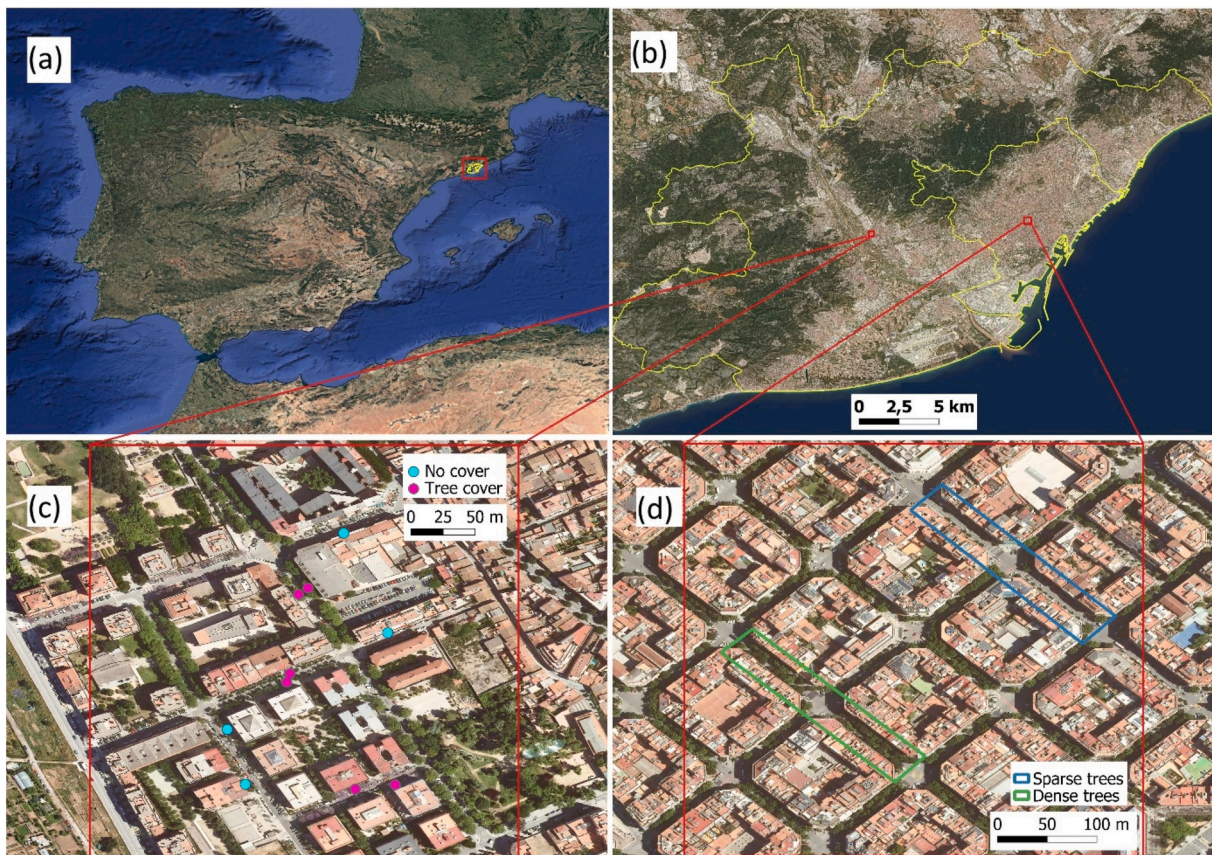


Fig. 1. (a) Location of the Metropolitan Area of Barcelona in the Iberian Peninsula; (b) Administrative boundaries of the Metropolitan Area of Barcelona and the city of Barcelona (yellow), and the location of the Eixample District and the measurement campaign neighbourhoods; (c) measurement campaign neighbourhood in Sant Feliu del Llobregat and sampling locations classified by the presence of tree cover; (d) case study neighbourhood in the Eixample District and the location of Sparse and Dense trees streets. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

percentiles are extracted to represent the average thermal stress and the extremes within each neighbourhood. More detailed information on the computation of the T_{MRT} and the UTCI are detailed in Appendix 2 of the Supplementary material.

2.1.2. Soil moisture vertical diffusion model

To derive the temporal evolution of soil moisture and temperature in the permeable soil inside the tree pits, a prognostic multi-layer soil model is implemented in BEP-Tree based on the bare soil scheme used in the Regional Atmospheric Modeling System (RAMS) described by Tremback and Kessler (1985). This model assumes a finite depth soil/atm interface layer to derive the prognostic equations for soil temperature and moisture. The soil model implemented presents 13 vertical layers from 1 cm depth down to 2 m in depth. The model equations can be seen in Appendix A3 of the Supplementary Material.

The sensible heat and latent heat fluxes from the street ground, and the street ground surface temperature are averaged between the impervious surface fraction and pervious soil fraction using the variable a_{perv} , defined as the street width section covered by pervious soil.

To represent the impact of soil moisture depletion on tree transpiration we apply a factor (F_4) in the leaf stomatal conductance (g_{vs}) to determine the effect of soil moisture based on Chen and Duthia (2001).

$$g_{vs} = g_{vs,max} F_1 F_2 F_3 F_4 \quad (1)$$

$$F_4 = \sum_{i=1}^{13} \frac{(\eta_i - \eta_w) \Delta z_i}{(\eta_{ref} - \eta_w) \sum_{i=1}^{13} \Delta z_i} \quad (2)$$

where $g_{vs,max}$ is species-dependent maximum stomatal conductance, and F_1 , F_2 , and F_3 are bounded coefficients between 0 and 1, as F_4 , that represent the effect of photosynthetically-active radiation, vapor pressure deficit and air temperature on the opening of stomata (Chen and Duthia, 2001). η_i is the soil moisture content with units of volume of water per volume of soil ($m^3 m^{-3}$) in the soil layer i , with layer depth Δz_i . η_{ref} and η_w are the field capacity and wilting point of the soil and depend on the soil texture class.

2.2. Measurement campaign for model validation

To validate the implementation of the T_{MRT} and UTCI estimates in BEP-Tree, we conducted an evaluation comparing the T_{MRT} and UTCI modelled by BEP-Tree with observations from a micrometeorological measurement campaign. This campaign was conducted between July 15 and July 26, 2024, in a neighbourhood situated in the municipality of Sant Feliu del Llobregat, in the Metropolitan Area of Barcelona (Fig. 1b). The campaign consisted of microclimate transects over this neighbourhood using a custom-built human-biometeorological platform (MaRTy) as it is described in Middel and Krayenhoff (2019). This platform recorded location, air temperature, relative humidity, wind speed; and longwave and shortwave radiant flux densities in a 6-directional setup, at pedestrian-level height. Each transect stopped in 23 locations distributed between the urban parks and streets inside the neighbourhood to understand the microclimatic determinants of human thermal stress during extreme heat episodes. For this study, only the measurements inside the streets are considered, distinguishing between 4 locations without tree cover, and 6 locations with tree cover (Fig. 1c). The two street orientations are considered, and the measurement locations are situated between 1 and 3 m from the closest building wall. Four transects were conducted every day, starting at 11:00, 12:00, 15:00 and 16:00 UTC (13, 14, 17 and 18 local time), with a duration of less than an hour. Measurements were temporally interpolated to 12 UTC and 16 UTC for cross-site comparison. More details on measurement campaign location, equipment, data processing and BEP-Tree implementation can be found in Appendix A4 of the Supplementary material.

2.3. Study area and period of study

The improved BEP-Tree model is used to simulate the Eixample district of the Mediterranean coastal city of Barcelona (Fig. 1b and d), characterised by symmetrical blocks, wide avenues and perpendicular streets (Northeast to Southwest and Northwest to Southeast), high population density (361 inhabitants/ha), and high number of street trees (80 trees/1000 inhabitants). The simulations are conducted over two streets that are previously detailed and studied in Segura et al. (2022): the Balmes street exhibits a sparse and short tree cover with a low tree canopy fraction in the urban canyon (from now on referred to as “Sparse trees”) ($tree_{cov} = 0.16$), while the Aribau street (Dense trees) exhibits a dense and tall tree cover ($tree_{cov} = 0.65$). More details about building height, geometry, pervious fraction are given in the Supplementary material, Appendix A5.

The simulation period lasts one month from June 25 to July 25, 2015 (with 5 more days for model spin-up), during which a 4-day heat wave occurred, maximum daily temperatures typically exceeded 27 °C, and the mean daily temperatures were well above 25 °C during the entire month. Night-time temperatures were also considerably high, with minimum temperatures typically above 24 °C and higher than 27 °C in a few occasions. No precipitation was observed during the entire period. Air temperatures reach a maximum of 35 °C during the heat wave.

Six simulations with various combinations of moisture and tree coverage are run with the BEP-Tree model to analyse the relative contribution of the different tree mechanisms for air-cooling and thermal stress reduction. First, two simulations are conducted for the streets “Sparse trees” and “Dense trees” without the soil moisture model implemented in BEP-Tree, assuming an infinite availability of moisture in the soil and the trees transpiring the maximum they can. We refer to these simulations as the moist soil case and represent how the trees would behave if they were irrigated as much as needed for their full development and maintenance. Two more realistic

simulations are conducted, which include the soil moisture vertical diffusion model (see section 2.1). These simulations are the “dry soil” case and use initial soil moisture values obtained from Weather Research and Forecasting (WRF) simulations for the same study period (Segura-Barrero et al., 2024), representing soil moisture during the summer under the drought conditions experienced by the Mediterranean coastal areas. The last two simulations, the “very dry soil” case, represent severe drought conditions where the trees are wilting. The details for model implementation and meteorological forcing at the top boundary are described in Segura et al. (2022).

3. Results

3.1. BEP-Tree evaluation with observations

In this section, the implementation of the T_{MRT} and UTCI estimates by BEP-Tree is evaluated using observations from the micro-meteorological measurement campaign in the Sant Feliu de Llobregat neighbourhood. Three BEP-Tree simulations are conducted (“High tree density”, “Medium tree density” and “Low tree density”) as it is detailed in the Supplementary material, to represent the heterogeneous tree distribution inside the modelled neighbourhood. BEP-Tree simulations closely match the observations at 16 UTC, but overestimate temperatures at 12 UTC by 1.2–1.3 °C (Fig. B.1 in Supplementary information). This overestimation could be attributed to an overestimation in the forcing data in the model, which has been derived from a WRF simulation, instead of a nearby meteorological station.

During midday, BEP-Tree accurately simulates the T_{MRT} in the hotspot without tree cover but overestimates the cold spot by 8.2 °C (Fig. 2a). In the afternoon, it performs well in cold spots without trees, but underestimates the maximum T_{MRT} by 6.0 °C. These biases arise from air temperature errors and the model averaging shaded and unshaded areas, unlike point-specific observations. For tree-covered locations (Fig. 2b), the model captures midday cold spot T_{MRT} with slight overestimation (2.4–3.7 °C) and afternoon variability, but significantly overestimates hotspot T_{MRT} under trees (9.6–13.8 °C). This can be attributed to a mismatch between the point observations and the BEP-Tree model, which represents the canyon-average effect of street trees, whose leaves are distributed randomly in the canyon with a clumping factor representing tree aggregation (and associated reduction in shading; see Krayenhoff et al., 2020).

The model captures the median and spatial variability of the UTCI during the afternoon (16 UTC), slightly overestimating the cold spot by 1.6 °C (Fig. 3). At midday, it overestimates UTCI by up to 3.3 °C, due to biases in air temperature and T_{MRT} . The observations show that tree-covered areas have lower UTCI than non-covered ones (2.2 °C at 12 UTC, 1.0 °C at 16 UTC), while the model underestimates these differences due to averaging shaded and unshaded conditions within the canyons. When observed air temperature and wind speed are combined with modelled T_{MRT} , and only the T_{MRT} with no tree cover is used for the “Low tree density”, and the opposite for the “High tree density”, and “Medium tree density” cases, the UTCI differences between tree and non-tree locations align more closely with observations, showing up to 1.6 °C difference at 12 UTC (Fig. B.2).

3.2. Compound impacts of heat and water stress on air temperatures and relative humidities

The modelled pedestrian-level air temperatures illustrate the pronounced impact of street trees on air-cooling in the highly-compact Eixample neighbourhood (Fig. 4), especially during the periods of heightened heat stress and moist soils. With moist soils, trees reduce air temperatures by up to 1.4 °C at 8 UTC, and by an average of 1.2 ± 0.4 °C during midday/mid-afternoon (Fig. 4c). During the heat wave, this cooling increases to 1.7 ± 0.5 °C, compared to 1.1 ± 0.4 °C on non-heat wave days. The air-cooling effect persists even during nighttime (20–5 UTC), presenting temperature reductions of 0.7 ± 0.1 °C throughout the study period.

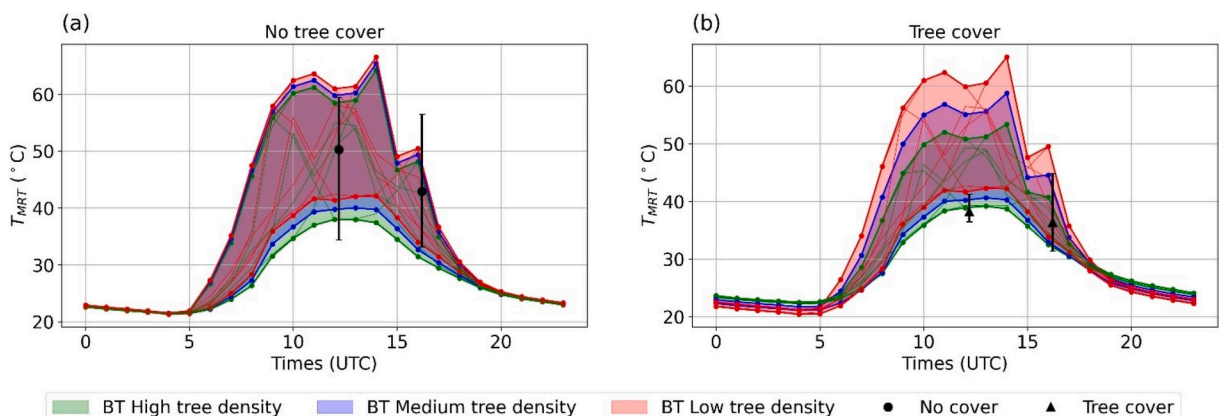


Fig. 2. Comparison between BEP-Tree (BT) modelled diurnal cycles of the T_{MRT} and observations averaged over the whole campaign period for (a) locations with no tree cover, (b) locations with tree cover. BEP-Tree simulations are the ‘High tree density’ (green line), ‘Medium tree density’ (blue line) and ‘Sparse tree density’ (red line). The vertical error bar represents the spatial variability of the observations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

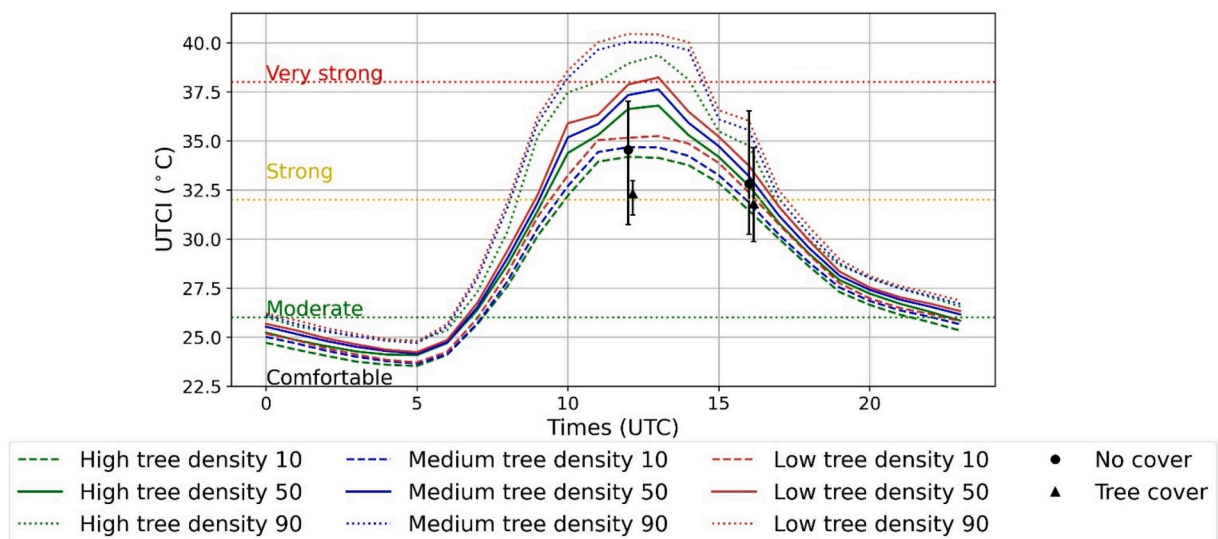


Fig. 3. Comparison between BEP-Tree (BT) modelled diurnal cycles of the UTCI and observations averaged over the whole campaign period for the 10th, 50th, and 90th percentiles. BEP-Tree simulations are the ‘High tree density’ (green line), ‘Medium tree density’ (blue line) and ‘Sparse tree density’ (red line). The vertical error bar represents the spatial variability of the observations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

However, dry soils have a detrimental effect on the air-cooling capacity of street trees. With dry soils, Dense trees produce an air temperature reduction of 0.4 ± 0.2 °C during midday/mid-afternoon compared to Sparse trees. With very dry soils, Dense trees produce an air temperature increase of 0.3 ± 0.1 °C compared to Sparse trees (Fig. 4c). Over the heat wave episode (Fig. 4b), neighbourhoods with dry and very dry soils present higher average temperatures during the midday/mid-afternoon (up to 35.4 °C and

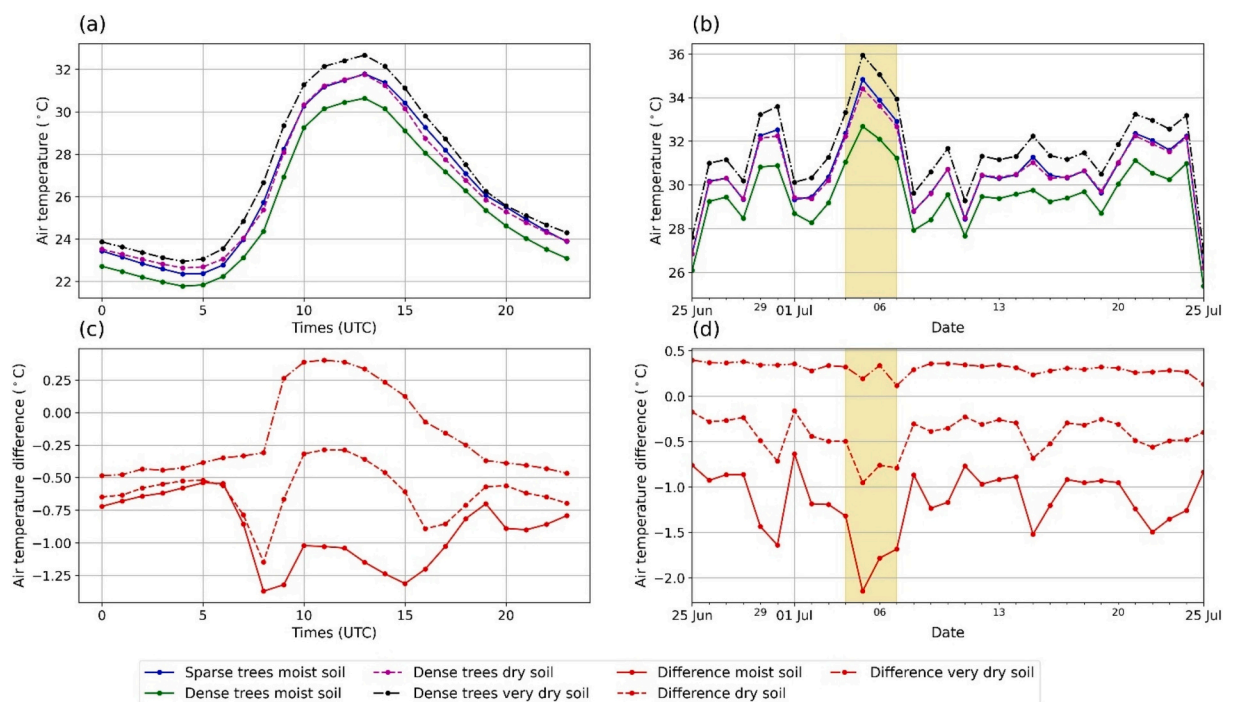


Fig. 4. BEP-Tree modelled diurnal cycles (left) and midday/mid-afternoon (between 9 and 15 UTC, 11–17 LT) averages in the study period of the air temperatures at 1.5 m from the ground; (a,b) for the Sparse trees with moist soil (blue), Dense trees with moist soil (green), Dense trees with dry soil (magenta), and Dense trees with very dry soil (black); (c,d) and difference between Dense trees and Sparse trees for moist soils, dry soils and very dry soils. Lines for Sparse trees with dry soil and very dry soil have not been plotted for convenience. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

34.4 °C for Sparse trees and Dense trees with dry soils, and up to 35.8 °C and 35.9 °C for very dry soils), compared to the neighbourhoods with moist soils (up to 34.8 °C and 32.7 °C, respectively).

The evapotranspiration mechanism of street trees increases the relative humidity of air during the daytime for Dense trees in comparison to Sparse trees (Fig. 5a), especially during the morning (between 7 and 9 UTC), and the late afternoon (between 15 and 19 UTC). This increase reaches up to 12.8% for moist soils (at 17 UTC), and up to 9.8% for dry soils (at 8 UTC). The larger differences in midday/mid-afternoon relative humidity during the study period are found during the heat wave episode, when Dense trees presents up to 14.1% higher relative humidity than Sparse trees with moist soil, and only 5.8% with dry soil (Fig. 5d). However, with very dry conditions, dense street trees produce a decrease in relative humidity ($0.9 \pm 0.5\%$ lower), due to the combination of no evapotranspiration and larger air temperatures. During the night, street trees increase relative humidity by $6.2 \pm 3.9\%$, $4.3 \pm 1.9\%$, and $2.2 \pm 1.5\%$ on average for moist, dry and very dry soils, respectively.

3.3. The mean radiant temperature cooling from street trees

Street trees have an impact on T_{MRT} by two main mechanisms: (1) lowering canyon surface temperatures by shading, which decreases longwave radiation from walls and ground, and (2) directly blocking solar radiation and reducing reflected shortwave radiation. Even in locations without tree cover, BEP-Tree captures the canyon-average lower surface temperatures effect due to shading, reducing T_{MRT} in the hotspot (street location with highest T_{MRT}) by up to 3.7 °C (at 10 UTC) and a reduction in the cold spot (street location with lowest T_{MRT}) by up to 4.8 °C (at 11 UTC) (Fig. 6c). Notably, this cooling mechanism remains largely unaffected by soil moisture stress effects on trees (Fig. B.3a). The maximum decrease in T_{MRT} by trees varies from 3.7 °C and 4.8 °C, for moist soils, to 3.4 °C and 4.2 °C for dry soils, and 3.0 °C and 3.6 °C for very dry soils, for the hotspot and cold spot, respectively.

The combined mechanisms further decrease the T_{MRT} experienced by the pedestrians by up to 12.3 °C (at 9 UTC) in hotspots, and by 5.3 °C (at 12 UTC) in the cold spots (Fig. 6d). On average, during midday/mid-afternoon, street trees decrease T_{MRT} experienced by pedestrians by 11.5 ± 2.2 °C in the hotspot and by 3.8 ± 1.2 °C in the cold spot. Like the first mechanism, shading is not significantly affected by soil moisture (assuming no variations in tree phenology), maintaining differences in T_{MRT} in hotspots and cold spots of the two neighbourhoods during midday/mid-afternoon, of 11.1 ± 2.1 °C and 3.2 ± 1.1 °C for dry soil, and of 10.6 ± 2.0 °C and of 2.6 ± 1.1 °C for very dry soil, respectively (Fig. B.3b).

The evolution of the midday/mid-afternoon T_{MRT} during the study period (Fig. 7) highlights that the peak modelled T_{MRT} does not coincide with the heat wave event. Instead, it occurs on June 29, registering values of 45.9 °C and 42.1 °C for Sparse trees and Dense trees with moist soil, respectively. T_{MRT} during midday/mid-afternoon is predominantly influenced by solar radiation and sun angles. The cooling effect of street trees on T_{MRT} decreases over the study period due to declining solar radiation after the summer solstice. For tree-covered locations, T_{MRT} differences between Sparse and Dense trees neighbourhoods decline from 7.3 to 8.5 °C (hotspot) and 5.8–6.7 °C (cold spot) on June 25 to 5.5–6.6 °C and 3.7–5.0 °C, respectively, on July 24.

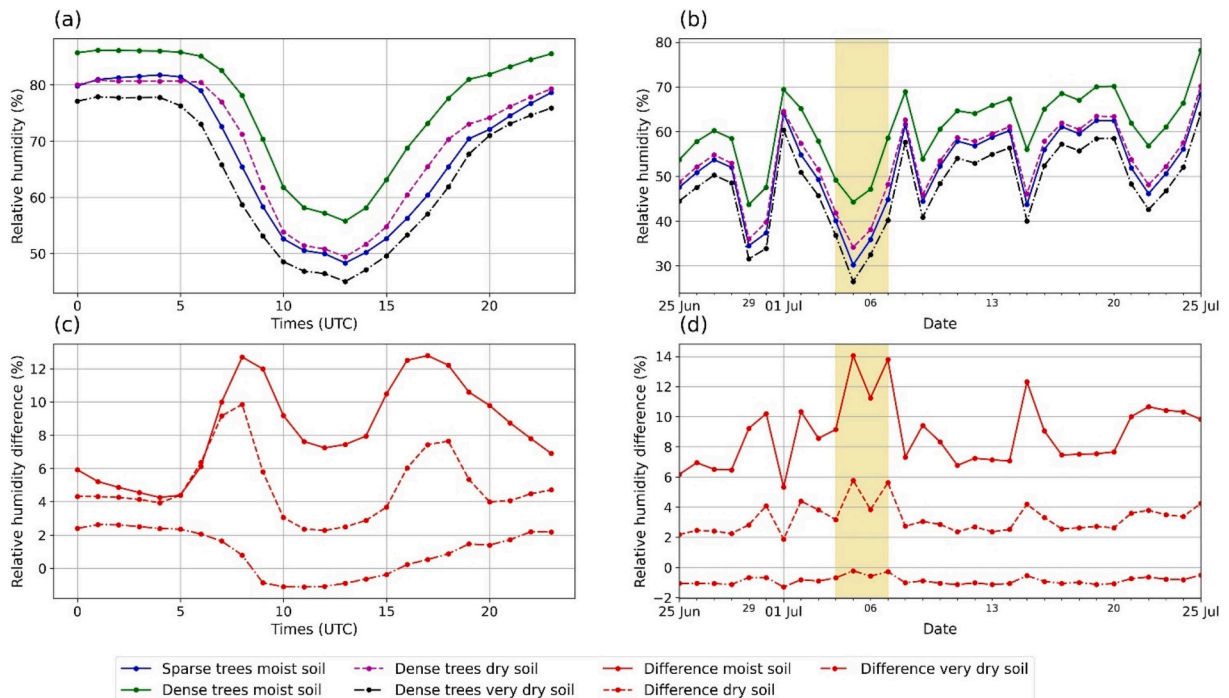


Fig. 5. As Fig. 4 but for the relative humidity of air at 1.5 m above the ground.

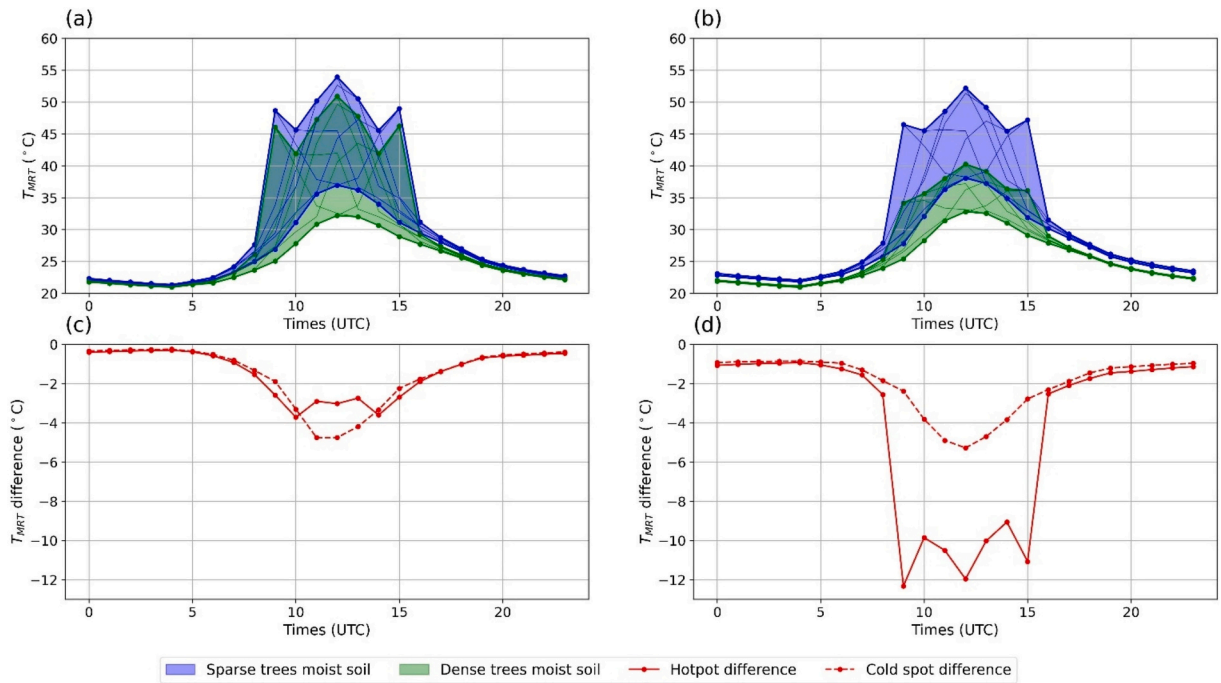


Fig. 6. BEP-Tree modelled diurnal cycles of (a) T_{MRT} in the locations without tree cover and moist soil, (b) with tree cover and moist soils, (c) difference between T_{MRT} for Dense trees and Sparse trees in the locations without tree cover and moist soil, (d) with tree cover and moist soil. The shaded areas represent the range of spatial variability of the T_{MRT} inside the neighbourhoods.

3.4. Compound impacts of heat and water stress on the Universal Thermal Climate Index

Fig. 8a shows that under moist soils and normal summer heat, street trees reduce UTCI by up to 1.4 °C (at 12 UTC), 2.2 °C (at 12 UTC), and 3.2 °C (at 9 UTC), for the 10th, 50th, and 90th percentiles, respectively. This shifts the thermal stress levels from strong to

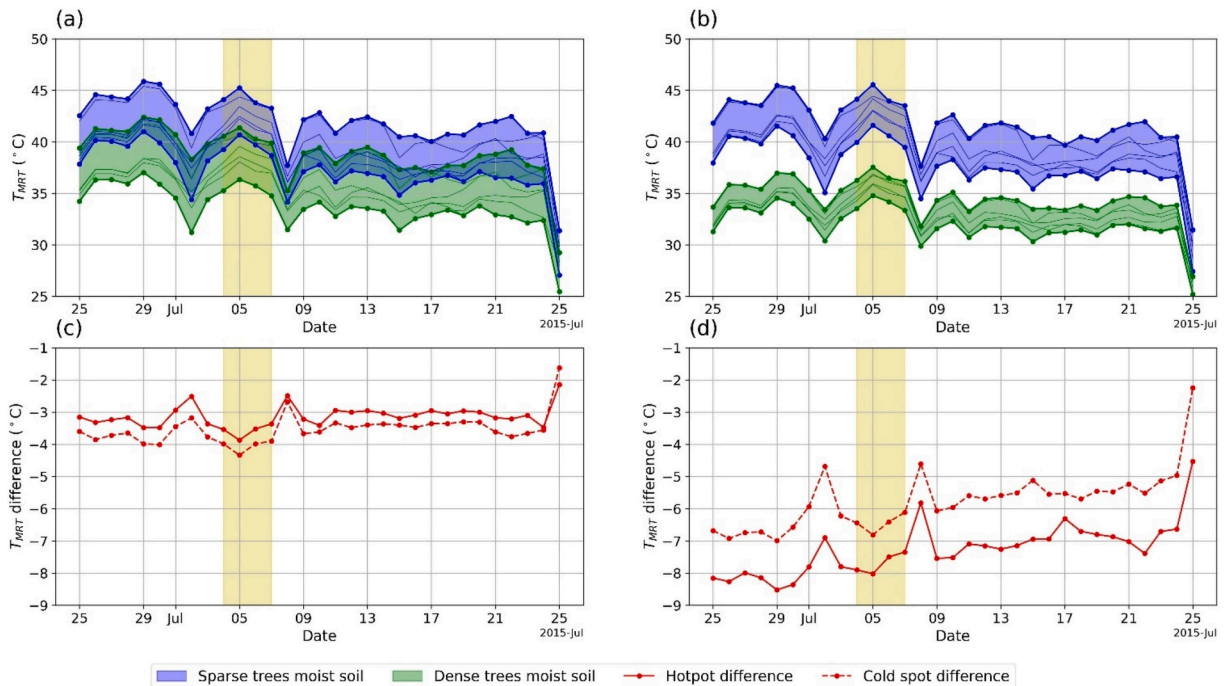


Fig. 7. as Fig. 6 but for midday/mid-afternoon averages in the study period.

moderate in the cold spot, and from very strong to strong in the hotspot at 12 UTC. During nighttime, street trees have a minimal effect, only being appreciable a non-significant decrease of 0.3 ± 0.3 °C. However, considering the effects of soil moisture, thermal stress increases in both neighbourhoods, reducing the impact of street trees (Fig. 8b and c). Under dry soils, a maximum reduction of UTCI is found to be of 1.0 °C (at 12 TC), 1.8 °C (at 12 UTC), and 3.1 °C (at 11 UTC) for the 10th, 50th, and 90th percentiles, respectively (Fig. B.5b). While under very dry soils, the maximum reduction of UTCI is found to be of 0.6 °C (at 12 TC), 1.3 °C (at 12 UTC), and 2.7 °C (at 11 UTC) for the 10th, 50th, and 90th percentiles, respectively (Fig. B.5c). Still, 71–97% of the cooling effect of street trees is preserved under dry soils, and 43–84% under very dry soils.

The effectiveness of street trees in reducing thermal stress during a heat wave depends on soil moisture and varies during the heat wave (Fig. 9). On the hottest day (July 5), UTCI reductions with moist soil reach 1.6 °C (cold spot), 2.1 °C (median spot) and 3.1 °C (hot spot), although these reductions decrease on the last day of the heat wave (1.0 °C, 1.6 °C, and 2.6 °C, respectively). When considering the compounded effects of heat and water stress, the UTCI reductions from the street trees effects are reduced for the 10th (0.9–1.1 °C for dry soil, and 0.2–0.4 °C for very dry soil), 50th (1.4–1.5 °C, and 0.7–0.9 °C, respectively) and 90th (2.5–2.6 °C, and 1.8–2.0 °C, respectively) percentiles. Even though, Dense trees neighbourhoods consistently show lower thermal stress, with 69–96% of the tree impacts maintained during dry soils, and 20–69% under very dry soils.

Fig. 10 shows the UTCI differences between Dense trees and Sparse trees, decomposed in the partial effects of the air temperature, T_{MRT} , humidity and wind speed, for the days outside the heat wave and during the heat wave. The cooling effect of the T_{MRT} is the principal driver of the UTCI for heat wave and non-heat wave days, as well as for all the soil moisture conditions. On the contrary, the positive effects of air-cooling, and the negative effects of humidity increase are minimised with dry and very dry soils. It is worth pointing that street trees can increase the thermal stress during heat wave days with moist (up to 0.9 °C) and dry conditions (up to 0.4 °C) between 17 and 20 UTC, because of the increase in the air humidity, which is not compensated by the air-cooling and shading at this period of the day.

4. Discussion

4.1. The impact of street trees on human thermal stress

Our findings confirm that street trees can substantially mitigate pedestrian heat stress in highly-compact Mediterranean cities through the combined effects of air-cooling and shading, although the relative contribution and climatic resilience of these mechanisms differ considerably. Under favourable soil moisture conditions, transpiration provides significant reductions in near-surface air temperature (1.2 ± 0.4 °C during midday and mid-afternoon), consistent with observational and modeling studies from other urban environments such as Tel Aviv (Shashua-Bar and Hoffman, 2000), Melbourne (Coultas et al., 2016), and previous work in Barcelona (Segura et al., 2022). However, this cooling mechanism is strongly constrained by soil water availability. As the soil dries, reduced stomatal conductance limits evapotranspiration (see Fig. B.6a and B.6b), progressively weakening the air-cooling potential of street trees. Under severe drought, the physiological cooling function may become sufficiently suppressed so that tree canopies contribute to

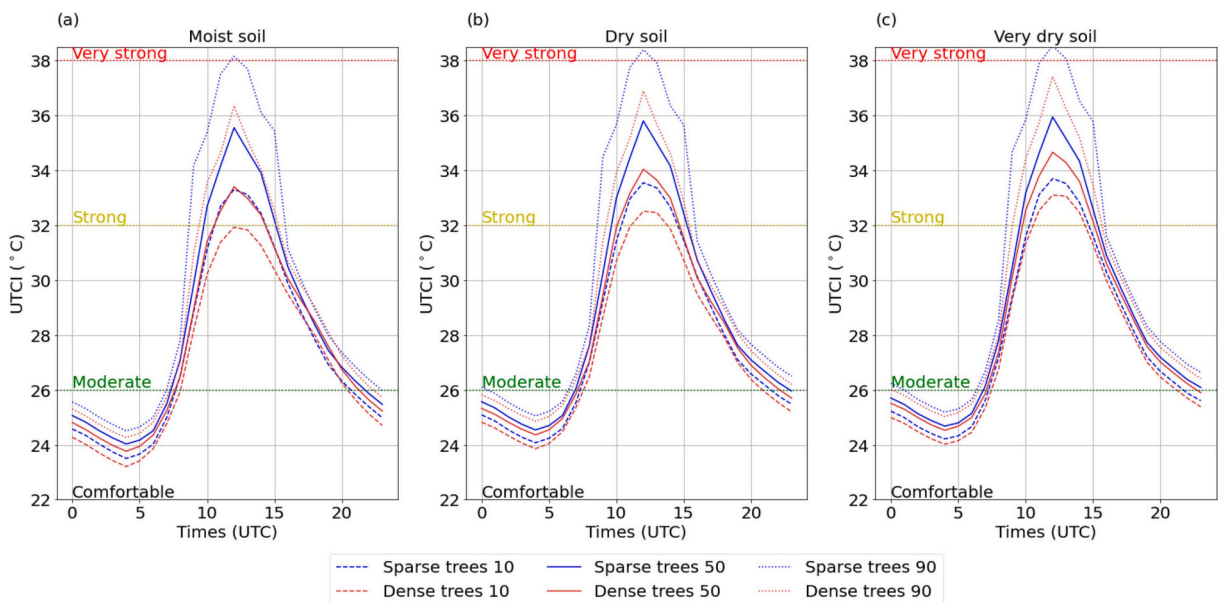


Fig. 8. BEP-Tree modelled diurnal cycles of the UTCI for the comparison between Sparse trees (blue) and Dense trees (red) neighbourhoods (a) under moist soil, (b) dry soils, and (c) very dry soils, for the 10th, 50th, and 90th percentiles. The horizontal lines represent the levels of thermal stress for the UTCI. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

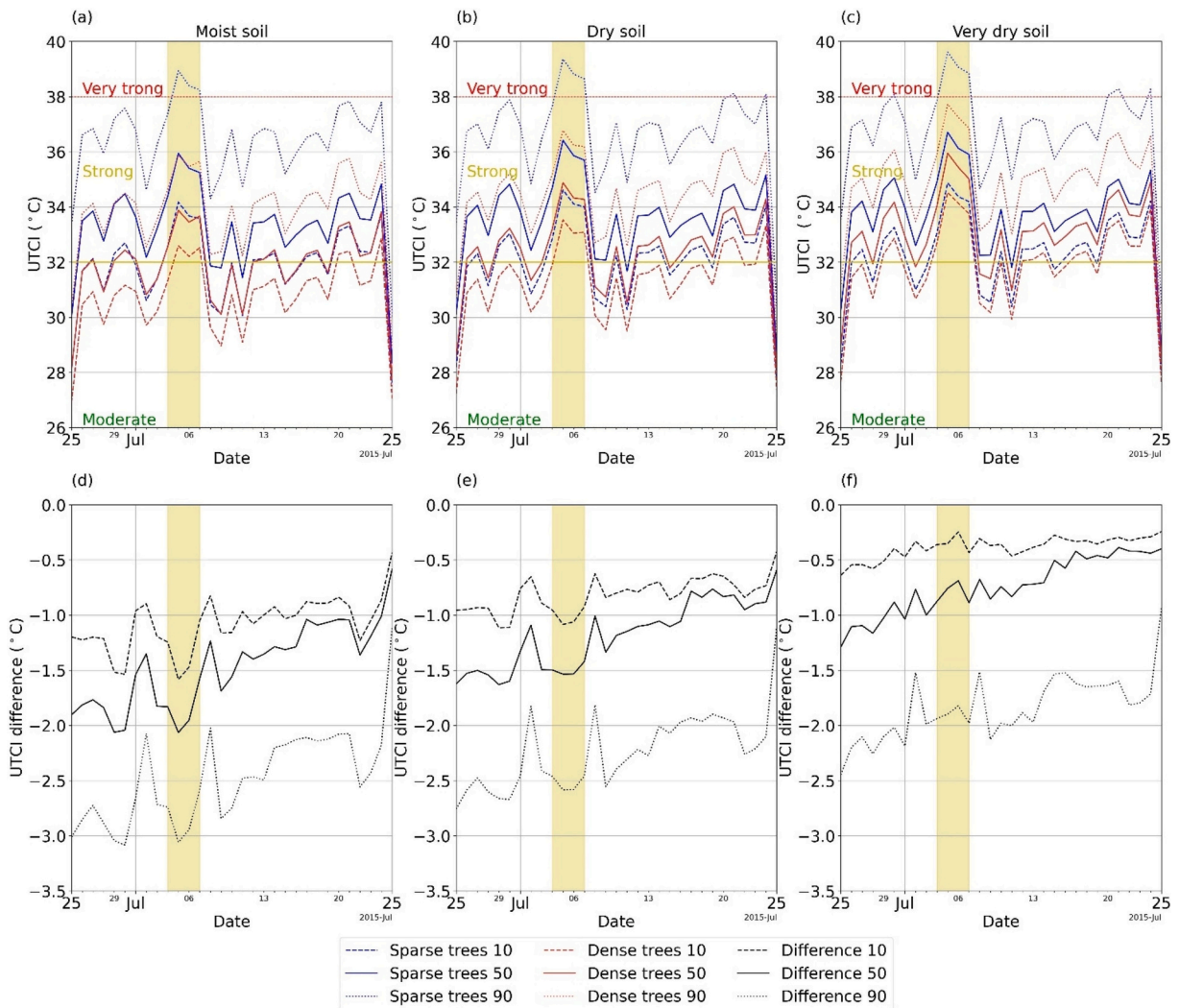


Fig. 9. Average midday/mid-afternoon (between 9 and 15 UTC, 11–17 LT) of the UTCI for the comparison between Sparse trees (blue) and Dense trees (red) neighbourhoods (a) under moist soil, (b) dry soils, and (c) very dry soils, for the 10th, 50th, and 90th percentiles; difference between Dense trees and Sparse trees neighbourhoods (d) under moist soil, (e) dry soil, and (f) very dry soil. The horizontal lines represent the levels of thermal stress for the UTCI. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

sensible heat to the surrounding air, as absorbed radiation is no longer dissipated through latent heat fluxes (Gräf et al., 2021; Meili et al., 2021).

In contrast to the strong moisture sensitivity of air cooling, reductions in T_{MRT} remain consistently substantial across all soil moisture conditions. The simulations demonstrate that shading is the dominant and most resilient mechanism through which street trees reduce pedestrian heat stress during clear-sky days, particularly in high-radiation street hotspots. These results agree with the findings of Gobatti et al. (2025), who found similar proportions between the effects on UTCI of tree shading and evaporative cooling under drought conditions, using the ENVI-met model over the city of Zurich, Switzerland. By reducing direct solar radiation and lowering surface temperatures, canopy cover preserves large reductions in radiation exposure even when transpiration is constrained. This distinction is particularly important because it indicates that the principal thermal adaptation value of street trees in drought-prone climates may lie less in evaporative cooling and more in the persistence of structural shade.

The increased humidity associated with transpiration introduces a secondary but relevant trade-off. In deep urban canyons with limited ventilation, enhanced evapotranspiration can elevate local humidity and partially offset thermal comfort gains during certain periods, particularly when shading benefits decline later in the day. However, the humidifying disservice of trees is generally outweighed by the combined reductions in air temperature and radiant heat load during periods of strongest daytime heat stress. Similarly, although vegetation-induced wind attenuation is often considered an important factor in urban thermal comfort (Krayenhoff et al., 2020), its role appears limited in this compact urban context (see Fig. B.7), where low baseline wind speeds (below 0.1 m s^{-1})

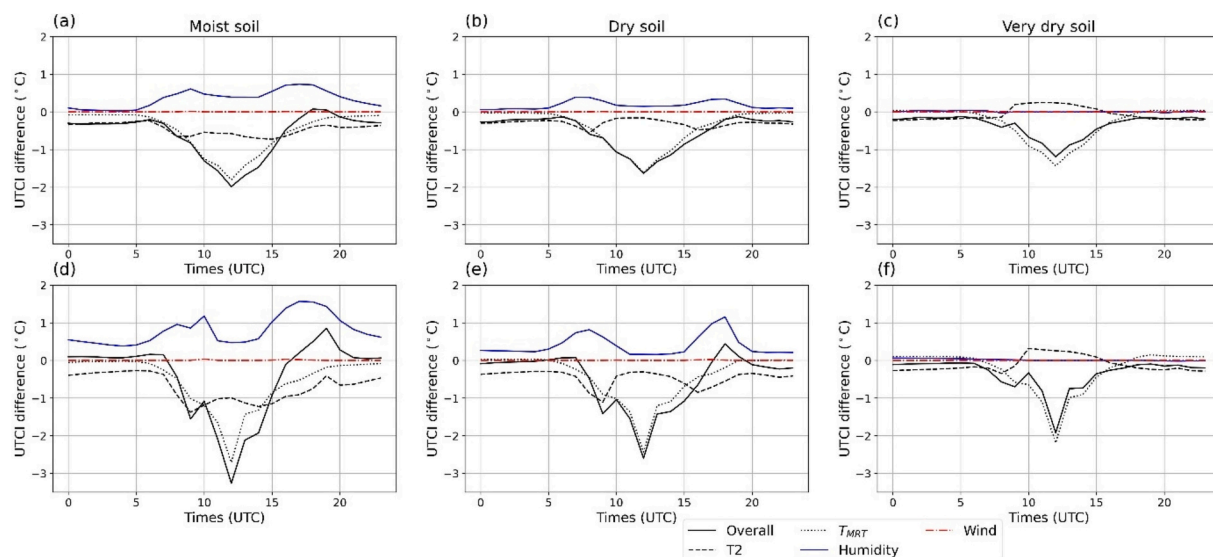


Fig. 10. Mechanistic breakdown of UTCI differences between Dense and Sparse trees neighbourhoods, showing the individual contributions of air temperature, T_{MRT} , humidity, and wind speed, for (a) moist soil outside the heat wave, (b) dry soil outside the heat wave, (c) very dry soil outside the heat wave, (d) moist soil during the heat wave, (e) dry soil during the heat wave, and (f) very dry soil during the heat wave.

reduce the magnitude of aerodynamic effects relative to shading and transpiration.

Overall, the balance of these interacting mechanisms indicates that street trees provide significant net reductions in heat stress across a wide range of summer conditions. Importantly, as soil moisture declines, the dominant cooling pathway shifts from combined transpiration and shading toward predominantly shading-driven mitigation. This helps explain why a substantial proportion of thermal stress reduction is preserved under drought conditions (71–97% during dry soil conditions, and 43–84% during very dry soil conditions) and supports the growing recognition that canopy shade may represent the most-resilient thermal service provided by urban trees (Gobatti et al., 2025).

4.2. Compound effects of heat and water stress on tree-mediated thermal stress reduction

The simulations indicate that the cooling performance of street trees during heat waves is strongly governed by the interaction between atmospheric demand and soil water availability, rather than by temperature extremes alone. Under moist soil conditions, elevated vapor pressure deficits can enhance transpiration (Fig. B.6a) and temporarily strengthen daytime air-cooling, suggesting that well-watered trees may provide amplified thermal benefits during severe heat events. Although extreme heat may also cause stomatal closure (Marchin et al., 2022). However, this response is highly dependent on sufficient soil moisture, as drought progressively constrains stomatal conductance and weakens the positive correlation between tree transpiration and increased evaporative demand.

Transpiration responses vary by species, with some anisohydric species increasing transpiration as an adaptive trait (Barriopedro et al., 2023; Rahman et al., 2024), while other isohydric species close stomata to conserve moisture (Marchin et al., 2022; Rahman et al., 2024). The observed variations between and within tree species to temperature sensitivity contribute to inconsistencies in the observed responses of leaf stomata to high heat stress (Marchin et al., 2022). While this study focused on one species (Krayenhoff et al., 2020), it did not account for species-specific cooling effects (Gillner et al., 2015a). The most common tree species found in Barcelona streets, *Platanus X Hispanica*, is considered a tolerant species to the stressful urban conditions and maintains high transpiration under dry conditions (Gillner et al., 2015b). The study's exclusive focus on one tree species and related model assumptions necessitates a comprehensive investigation of various plant responses in future studies.

Under compounded dry soil conditions and heat stress, the air-cooling capacity of street trees is significantly reduced due to decreased transpiration (Fig. B.6a), but it is still present. This suggests that while vapor pressure deficit increases transpiration, limited soil moisture still restricts stomatal conductance. This contradicts the findings of other studies (Chen et al., 2024), who found that tree transpiration is more restricted by vapor pressure deficits, rather than soil moisture depletion. These interactions highlight limitations in the current plant physiology model (Noilhan and Planton, 1989) used in this BEP-Tree version. Even though certain plant species have been identified to open stomata under compounded heat and drought conditions, potentially leading to increased mortality rates (Marchin et al., 2022).

Street trees consistently reduce human thermal stress through shading, with T_{MRT} reductions remaining stable during heat waves (Fig. 7) and showing no significant differences between heat wave and non-heat wave days. Soil moisture conditions have a limited impact on T_{MRT} reduction by street trees in this study, assuming a constant leaf area density. Yet, prolonged drought or heat waves may affect tree structure and shading capacity, depending on species, health and location (Qu et al., 2024), potentially undermining the effectiveness of street trees in T_{MRT} reductions through shade. The study's assumption may not hold during extended droughts or late-

summer heat waves, when deciduous trees begin leaf senescence (Stratopoulos et al., 2019; Anys and Weiler, 2025). Future models should incorporate dynamic vegetation changes, such as variations in leaf area index over time in response to the drought progression.

During heat waves with moist soils, increased transpiration can raise relative humidity, partially offsetting the cooling benefits during midday and late afternoon. While this is balanced by greater air temperature and T_{MRT} reductions at midday, it leads to increased thermal stress in the evening (Fig. 11d), slowing down the arrival of more comfortable thermal sensations. The retention of humidity may result from reduced ventilation in deep street canyons, where tree canopies disrupt airflow (Oke et al., 2017). This can hinder the dispersion of both humidity and traffic-related air pollutants, potentially impacting human health (Janhäll, 2015; Jin et al., 2014). This effect necessitates a comprehensive understanding of the interplay between street trees, air quality, and thermal stress in compact cities.

The impact of heat waves on the thermal stress reduction by street trees shows high variability, influenced by soil moisture and heat wave progression. The lowest reductions in UTCI are found in the last day of the heat wave, suggesting a potential decline in thermal stress reduction from trees as heat waves persist, potentially due to soil moisture depletion. This trend is not appreciated under dry soil conditions, where the reductions in UTCI are similar within heat wave days, implying that transpiration variability explains the variability in the thermal stress reductions during the heat wave. These results emphasise the more consistent benefits of tree shading on thermal stress reduction, preserving between 69 and 96% of the maximum impact on the human thermal stress under dry soil conditions, and between 20 and 69% under severe drought conditions.

4.3. Model evaluation and sources of uncertainty

This study represents, to our knowledge, one of the first applications of BEP-Tree to evaluate pedestrian-scale T_{MRT} and UTCI in deep urban street canyons using detailed in situ observations. While the model reproduces many key spatial and temporal patterns of thermal stress, discrepancies between simulations and observations require careful interpretation.

Although some model biases may appear relatively large, particularly for localised T_{MRT} extremes beneath tree canopies, these discrepancies are comparable to those reported in recent studies (Sinsel et al., 2022; Aleksandrowicz et al., 2023) using more computationally intensive microscale models such as ENVI-met. Reported evaluations in cities such as Hong Kong (Sinsel et al., 2022) and Tel Aviv (Aleksandrowicz et al., 2023) have reported a similar range of T_{MRT} error (over 13 °C) despite explicit high-resolution representations of urban surfaces and vegetation. This suggests that the uncertainties identified here are not unusual but rather reflect the inherent challenges of accurately simulating highly heterogeneous radiative conditions in complex urban environments.

Several factors likely contribute to model-observation differences. First, atmospheric forcing was derived from WRF simulations rather than direct local observations above the urban canopy, introducing uncertainty into boundary conditions. Second, the comparison involves point-based field observations versus canyon-averaged model outputs, particularly problematic for T_{MRT} due to its strong sensitivity to localised shading, surface temperature contrasts, and pedestrian relative position within the canyon. Finally, BEP-Tree parameterises trees using crown-covered street canyon fractions and distributes tree shadows equally over the canyon width, rather than explicitly resolving individual crowns and the current positions of trees within the streets, which can underestimate highly localised shading effects.

Despite these limitations, BEP-Tree captures the comparative differences between neighbourhoods with contrasting tree densities and reproduces the broader spatial variability of thermal stress within canyons. Since the primary objective of this study is to evaluate relative thermal benefits of street trees at the neighbourhood scale rather than exact point-specific microclimatic conditions, this level of performance provides confidence in the robustness of the broader conclusions.

Nevertheless, these uncertainties highlight the importance of continued model development and evaluation with more comprehensive and targeted observational campaigns, with expanded spatial and temporal monitoring in order to have a complete representation of the spatial heterogeneity within and between streets with diverging tree densities, and over the course of the complete diurnal cycle. Further model developments, such as dynamic seasonal vegetation representations, rather than a prescribed LAI (Meili et al., 2021), and a more complex representation of the modelled response of trees to heat waves, such as different hydric responses (isohydric vs. anisohydric) (Rahman et al., 2024), would strengthen future assessments of urban thermal stress and further improve confidence in neighbourhood-scale urban climate projections.

4.4. Urban planning implications

Based on these findings, the effective urban greening strategies in highly compact cities should prioritise not only increasing tree cover, but also ensuring the long-term functional resilience of street trees under compound heat and drought stress. Because shading remains the most robust mechanism for reducing pedestrian thermal stress, urban planners should prioritise the planting, preservation and maintenance of tree species capable of providing dense shade and retaining foliage during prolonged drought and heat waves. In Mediterranean climates, this may include evergreen broadleaf species or drought-tolerant deciduous species that can sustain canopy structure under increasingly stressful summer conditions.

At the same time, maintaining sufficient soil water availability remains essential for preserving tree health (Haase and Hellwig, 2022), sustaining transpiration, and maximising the provision of additional ecosystem services not contemplated in this study, such as runoff control, air purification, noise reduction and habitat for biodiversity (Baró et al., 2019). Our findings indicate that without adequate water availability, the air-cooling capacity of street trees can be substantially reduced, potentially compromising both thermal comfort benefits and broader ecosystem functioning.

For cities where water scarcity limits natural soil moisture availability, irrigation or water-sensitive urban design may be necessary

to preserve tree performance during extreme heat and drought. Supplemental irrigation can help maintain canopy vitality, delay foliage loss, and sustain cooling services during critical summer periods. However, this presents an important governance challenge, as hydrological droughts often coincide with competing demands for limited water resources, reducing the priority of irrigation for urban green infrastructure.

These constraints emphasise the need for integrated urban climate adaptation strategies that balance water resource management with the preservation of critical green infrastructure. Prioritising street-tree health during periods of climatic stress should be viewed not simply as aesthetic maintenance, but as an investment in public health, urban resilience, and climate adaptation. Ensuring the long-term viability of urban tree systems will be essential for maintaining their capacity to reduce heat stress and enhance resilience in increasingly warming and water-constrained cities.

5. Summary and conclusions

In response to the rising frequency and intensity of heat events in highly compact urban environments, this study highlights the role of street trees as an effective nature-based solution for mitigating thermal stress. By regulating air temperature and providing shade, trees offer critical microclimate benefits. Using a modified BEP-Tree model adapted for highly compact cities, we assessed two Barcelona neighbourhoods with contrasting tree densities to evaluate how street trees influence meteorological factors related to human thermal stress, particularly under typical summer conditions, heat waves, and varying soil moisture levels.

The results show that street trees significantly reduce air temperature and perceived heat stress, especially under moist soil conditions. Denser tree cover led to average midday/mid-afternoon air temperature reductions of 1.2 ± 0.4 °C and mean radiant temperature reductions of up to 12.3 °C in the hottest spot. Even though increased humidity slightly elevated thermal stress, the overall effect of street trees under moist soil conditions resulted in a net UTCI reduction of up to 1.4–3.2 °C. However, dry soil severely limits transpiration and air-cooling effects, reducing thermal benefits from trees and even slightly increasing air temperature in dense tree areas. Nevertheless, shading remains the dominant mechanism for thermal stress mitigation, retaining between 71 and 97% of the cooling impact under dry soil conditions, and 43–84% under very dry conditions.

During heat waves, street trees with moist soil demonstrated enhanced air-cooling capacity and thermal stress reduction due to increased transpiration, reducing air temperatures by up to 1.7 °C and reducing UTCI by 1.6–3.1 °C. The effect of tree shading still preserves between 69 and 96% of the maximum impact of street trees on the human thermal stress under dry soil conditions, and between 20 and 69% under severe drought conditions. However, the effectiveness of trees in reducing thermal stress diminishes as heat waves persist. These findings highlight the critical role of tree shading in mitigating human thermal stress, preserving the majority of their cooling effect even under water-limited conditions. Urban planners should prioritise drought-resistant, evergreen species or deciduous species that retain foliage during heat events and ensure adequate irrigation to sustain tree health and optimize their climate-regulating benefits – particularly in Mediterranean cities facing prolonged heat and water scarcity.

CRedit authorship contribution statement

Ricard Segura-Barrero: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alberto Martilli:** Writing – review & editing, Supervision. **E. Scott Krayenhoff:** Writing – review & editing, Supervision. **Alba Badia:** Writing – review & editing, Supervision. **Gara Villalba:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.uclim.2026.103086>.

Data availability

Data will be made available on request.

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