



Heat stress in social housing districts: tree cover–built form interaction

RESEARCH

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ABSTRACT

As global warming increases, understanding the vulnerability of urban areas to extreme heat becomes crucial. Social housing districts, due to their urban form and demographic composition, are identified as high-risk areas for heat stress. This study investigates the impact of trees on mitigating outdoor heat stress in social housing districts, focusing on the Mediterranean region, particularly the metropolitan area of Barcelona, Spain. Using mean radiant temperature (MRT) as a key parameter, simulations were conducted to assess the influence of trees on heat stress in two districts differing in building types: linear blocks versus towers. The results show that the absence of trees makes towers more vulnerable to heat stress, as they lack long-term shaded spaces, such as the corridors in the linear blocks. In contrast, when trees are considered, tree-induced shading significantly decreases MRT and shifts its distribution pattern so that both urban fabrics exhibit similar performances, achieving the same percentage of open space with moderate heat stress (22%). These findings underscore the importance of a performance-based design approach, emphasising the need to consider both urban form and tree cover for effective heat stress mitigation in social housing districts.

POLICY RELEVANCE

Shade planning plays a key role in shaping thermal comfort outcomes under heat-stress conditions. Urban fabrics with high open space ratios, typical of the European post-war modernist social housing boom, are especially vulnerable to this issue, underscoring the importance of integrating vegetation as a key component of green infrastructure and a critical microclimatic resource. This work emphasises the need for planning frameworks that recognise trees not only as design elements but also as essential urban infrastructure. By leveraging workflows compatible with geographical information system (GIS)-based tools used by urban practitioners, the study supports both the design and the management of green infrastructure through actionable, context-sensitive, heat-mitigation strategies. By enabling the identification of critical shade providers and assessing their performance under different morphologies, such tools can guide adaptive strategies, from tree placement to irrigation prioritisation, enhancing the resilience of urban environments to rising heat stress.

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Human-induced global warming is causing climate change, which is resulting in an increased frequency of extreme weather events across the globe (Calvin et al. 2023). This trend is predicted to intensify over the coming years, leading to severe impacts on people and ecosystems (Maragno et al. 2020). In this context, the mitigation of the effects of extreme heat events in urban areas has become a growing concern due to their significant negative impacts on public health and wellbeing (Hatvani-Kovacs et al. 2018). A significant gradient of thermal conditions exists in the urban fabric at both the mesoscale and local level, according to spatial and physical characteristics (high resolution is needed).

Most climate projections identify the Mediterranean region as a hotspot for climate change impacts, where more pronounced warming and drying trends are expected compared with broader global climate patterns, due to its geographical and climatic characteristics (Cos et al. 2022). As climate change progresses, heat-related issues in this region are projected to intensify, with severe consequences for urban areas, where the urban heat island effect exacerbates heat. Given its geographical and climatic characteristics, Mediterranean cities are particularly relevant for studying urban heat stress. The evolution and shaping of Mediterranean cities result from extraordinarily complex interactions among science, social culture, technology, economy and human needs. These interactions produce a combination of diverse urban fabrics, each with distinct spatial and physical characteristics (Busquets 2005; Yang et al. 2019). It is well documented that these characteristics determine local environmental conditions, human comfort, and the energy performance of buildings and neighbourhoods.

Identifying the most vulnerable areas in cities becomes crucial for counteracting heat stress in open spaces and prioritising climate-sensitive urban regeneration (Ho et al. 2025; Sola-Caraballo et al. 2025). In this context, social housing districts are of particular interest due to a combination of specific vulnerabilities. These districts, often characterised by open urban forms, are especially prone to heat stress due to limited protection against excessive solar radiation during the warm season compared with the historic city and 19th-century city textures (Maragno et al. 2020; Sola-Caraballo et al. 2024). Additionally, social housing districts are usually home to marginalised and fragile communities, making them even higher risk areas (UNDRR 2017).

Understanding the relationship between built form and outdoor thermal comfort under different spatial configurations becomes essential for providing actionable insights and design guidelines to improve thermal conditions in public spaces. Urban morphology, surface materials and vegetation cover significantly influence microclimates and outdoor thermal comfort (Lau et al. 2015; Lindberg & Grimmond 2011). These elements modulate the urban microclimate by altering shadow patterns, evapotranspiration, and the urban fabric's thermal and radiative properties (e.g. emissivity, albedo). Consequently, they modify shortwave radiation incident on the human body and the longwave radiative exchange with the environment (Emmanuel & Fernando 2007; Erell et al. 2011; Evola et al. 2021; Mayer et al. 2008; Salvati et al. 2022). It has been consistently demonstrated that trees, in particular, serve as potent agents in the mitigation of diurnal outdoor heat stress. Their efficacy is primarily attributable to the processes of evapotranspiration and the provision of cooling shade. Their extensive canopies function as efficient barriers, substantially reducing solar radiation exposure on the human body (Lee et al. 2020; Palme et al. 2020; Thorsson et al. 2014).

Among the various factors affecting thermal comfort, mean radiant temperature (MRT), which quantifies radiative heat exchange, has been identified as the most influential parameter in thermal stress in outdoor environments (Kántor & Unger 2011).

The MRT reflecting the dynamic interaction of urban elements with radiation fluxes and providing a reliable measure of outdoor thermal comfort remains widely recognised as a key determinant of outdoor thermal perception, despite the availability of other advanced indices (Gál & Kántor 2020; Lindberg et al. 2008; Matzarakis et al. 2007, 2010; Staiger & Matzarakis 2020; Thorsson et al. 2007). Indeed, research demonstrates a strong correlation between MRT and both

universal thermal climate index (UTCI) and physiologically equivalent temperature (PET) values (Mahdavinejad et al. 2024).

Some of the causes of a high MRT in urban environments are the absorption and re-radiation of heat from urban components made of concrete, asphalt and metal, among others, as well as the lack of green and blue infrastructure (Koch et al. 2020).

Assessing outdoor thermal comfort is inherently complex, as it involves both objective environmental parameters and subjective human physiological and psychological responses. Key meteorological variables include air temperature, humidity, wind speed and radiation fluxes. Among these, radiative and convective exchanges between the human body and the environment are particularly significant, making MRT a crucial, though difficult-to-measure *in situ*, indicator for thermal perception (Thorsson et al. 2007; Vanos et al. 2021).

MRT is defined as the uniform temperature of a theoretical enclosure that produces the same radiant energy exchange as the actual outdoor environment, effectively capturing the interplay of short- and longwave radiation fluxes (Lindberg et al. 2008). While advanced indices such as PET and UTCI integrate meteorological inputs to provide a comprehensive measure of the thermal environment experienced by humans, MRT remains a recognised key determinant (Kántor & Unger 2011; Lindberg et al. 2008; Staiger & Matzarakis 2020; Thorsson et al. 2007), showing strong correlation with these indices (Mahdavinejad et al. 2024).

Experimental evaluation of MRT is particularly challenging, as it is one of the most difficult variables to assess (Banfi et al. 2022; Johansson et al. 2014). To overcome these limitations, spatial computation of MRT over uniform gridded surfaces or using three-dimensional (3D) models has become increasingly prominent, using several robust tools, including SOLar LongWave Environmental Irradiance Geometry (SOLWEIG) (Briegel et al. 2023; Lau et al. 2015; Lindberg et al. 2008; Mutani & Beltramo 2022) ENVI-met (Bruse & Fleer 1998; Emmanuel & Fernando 2007) and Ladybug Tools suite (Roudsari et al. 2013). ENVI-met presents challenges in terms of 3D modelling limitations, the need for site-specific meteorological data, extensive computational time and modelling constraints (Aleksandrowicz et al. 2020). Ladybug, while versatile, may demand substantial computational resources for complex district-scale analysis and associated extensive datasets (Evola et al. 2020). SOLWEIG, an open-source geographical information system (GIS)-based tool currently available through the urban multi-scale environmental predictor (UMEP), has demonstrated high accuracy in predicting observed radiation fluxes and MRT, producing high-resolution and large-scale simulations of radiation fluxes and MRT in complex urban environments (Lindberg et al. 2008). For all the reasons above, UMEP is selected as the primary tool for high-resolution MRT mapping at the district scale in this study.

The aim of this research is to assess analytically and spatially the impact of trees on heat stress in the open space of social housing districts depending on their urban form. For this purpose, the role of trees is compared in two neighbourhoods with different urban forms, using the spatial distribution of MRT as a proxy to describe heat stress at high resolution. The results would provide a framework for performance-based climate-sensitive design solutions.

This study analyses the MRT distribution in public spaces of social housing districts as a proxy for heat stress at the neighbourhood level. The methodology comprised three key steps. First, case study selection and data collection were conducted (Section 2.1). Second, urban energy models were developed using UMEP (Lindberg et al. 2018) for simulations (Section 2.2). Third, MRT simulations were performed under two scenarios: with and without trees (Section 2.3). Results were analysed spatially and quantitatively to reveal the interplay between urban morphology and tree shading (Section 3). To discuss the implications for heat-mitigation strategies (Section 4), MRT impacts on thermal sensation were assessed using the UTCI, and diurnal variations were investigated. Finally, conclusions address trees' cooling efficacy across urban morphologies and the methodological value for planning (Section 5).

2. METHOD

2.1 SELECTION OF THE CASE STUDY

This study focuses on two case studies located in District VI of L'Hospitalet de Llobregat, the second-largest city in the Barcelona metropolitan area. L'Hospitalet is characterised by a Mediterranean climate (Csa: Köppen classification), with an annual mean temperature of 16.1°C and a mean relative humidity of 69%. The city experiences mild winters and warm to hot summers, with monthly mean temperatures ranging from 9.2 to 24.4°C. However, during summer, maximum daily temperatures frequently exceed 28.5°C (Table 1), with an increasing recurrence of heat episodes surpassing 30°C. Furthermore, recent climatological studies have documented a significant increase in the frequency, severity and duration of heatwaves in the region since 1970 (Serra et al. 2024), a trend that is projected to persist and further exacerbate outdoor thermal discomfort in this urban area.

MONTH	AVERAGE MAXIMUM TEMPERATURE (°C)	MEAN TEMPERATURE (°C)	AVERAGE MINIMUM TEMPERATURE (°C)	RELATIVE HUMIDITY (%)	DAILY GLOBAL HORIZONTAL RADIATION (kWh/m²)
January	13.6	9.2	4.7	70%	2.2
February	14.3	9.9	5.4	70%	3.1
March	16.1	11.8	7.4	70%	4.3
April	18.0	13.7	9.4	69%	5.7
May	21.1	16.9	12.8	70%	6.5
June	24.9	20.9	16.8	68%	7.1
July	28.0	23.9	19.8	67%	7.3
August	28.5	24.4	20.2	68%	6.1
September	26.0	21.7	17.4	70%	4.8
October	22.1	17.8	13.5	73%	3.3
November	17.3	13.0	8.6	71%	2.3
December	14.3	10.0	5.7	69%	1.9
Year	20.4	16.1	11.8	70%	4.6

Table 1: L'Hospitalet de Llobregat monthly data of average maximum temperature, mean temperature, average minimum temperature, relative humidity and daily global horizontal radiation.

Source: AEMET (2024).

The two selected case studies, Bellvitge (constructed in 1964) and Gornal (constructed in 1972), are contiguous social housing developments separated by a railway infrastructure (Figure 1). These neighbourhoods were originally designed to accommodate the influx of migrants in the 1960s and to relocate residents from informal settlements. Many of the original inhabitants remain in these areas, contributing to a high ageing index, with 26.1% of the district's population over 64 years old. This demographic characteristic exacerbates climate vulnerability, as older adults are particularly susceptible to heat stress due to pre-existing health conditions and prolonged heat exposure resulting from reduced mobility. Both neighbourhoods have been officially classified as socio-economically vulnerable and included in the Spanish Catalogue of Vulnerable Neighbourhoods (Ministerio de Transportes Movilidad y Agenda Urbana 2023). Additionally, they exhibit high *indice de vulnerabilidad al cambio climatico* (IVAC) values, a local measure of climate change vulnerability (Area Metropolitana de Barcelona (AMB) 2022).

The focus on districts such as Bellvitge and Gornal is essential due to their significant influence on urban vulnerability and citizen's wellbeing. These neighbourhoods not only exemplify challenges common to ageing social housing estates throughout Europe but also constitute a significant proportion of the continent's existing housing stock, thereby presenting major regeneration challenges for architecture and urban design professionals. Bellvitge and Gornal exemplify the core characteristics of the Spain social housing scheme '*Polígonos de Viviendas*', developed to

support low-income segments of the population through welfare-driven policies and mitigate the negative effects of private suburban expansions. Similar housing models emerged concurrently across Europe, including France's *Grands Ensembles*, the UK's housing estates, Italy's *Piani di Edilizia Economica e Popolare*, etc. These schemes, which were conceived as modern-city experimental master plans across Europe, are deeply rooted in the architectural culture of Western Europe. However, despite their well-intended origins, many of these places have proved vulnerable when faced with practical realities.

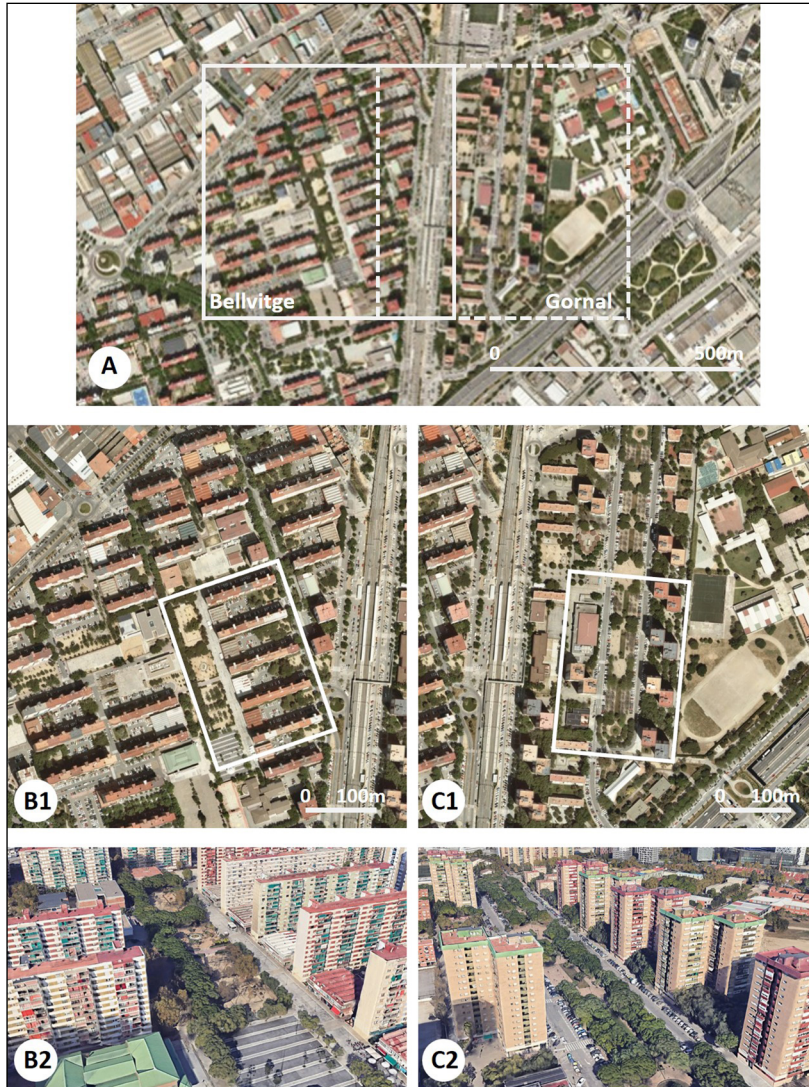


Figure 1: (A) Locations of the case studies and energy simulation domains (500 × 500 m each): sites of interest (4 ha each) for the simulations in Bellvitge (B1) and Gornal (C1); and aerial views of Bellvitge (B2) and Gornal (C2).

Note: Bellvitge's urban form consists of 14-storey linear blocks (96 m long × 9–10 m wide), each containing dual 75 m² apartments per floor, arranged in a parallel alignment with 40 m spacing. Interspersed low-rise buildings provide commercial and community services. In contrast, Gornal features 18-storey residential towers with four 100 m² apartments per floor around a central core, complemented by vibrant ground-floor commercial spaces.

Source: Google Earth.

The experimental design approach of these districts manifests in their distinct spatial and physical characteristics, as defined by specific ranges of urban form indicators (Figure 2 and Table 2). Similar to many other cases, Bellvitge and Gornal follow an urban form model based on zoning principles. This model is characterised by a precise pattern of high-rise structures (↑L, number of floors), low building intensity (↓FSI; floor space index), reduced compactness (↓GSI, ground space index) and elevated open space ratios (↑OSR). Another prominent feature of these social housing districts is the oversized and often undefined nature of public spaces in terms of land use and ownership, and substantial green areas with relatively uniform tree density.

While both case studies demonstrate comparable urban metrics (Table 2), they differ significantly in their spatial configuration, building typologies and open space organisation. Bellvitge primarily consists of linear blocks forming elongated street-like outdoor spaces, resulting in clearly defined corridors and structured pedestrian environments. In contrast, Gornal is characterised by a higher concentration of residential towers, which generate large but relatively undefined open spaces.

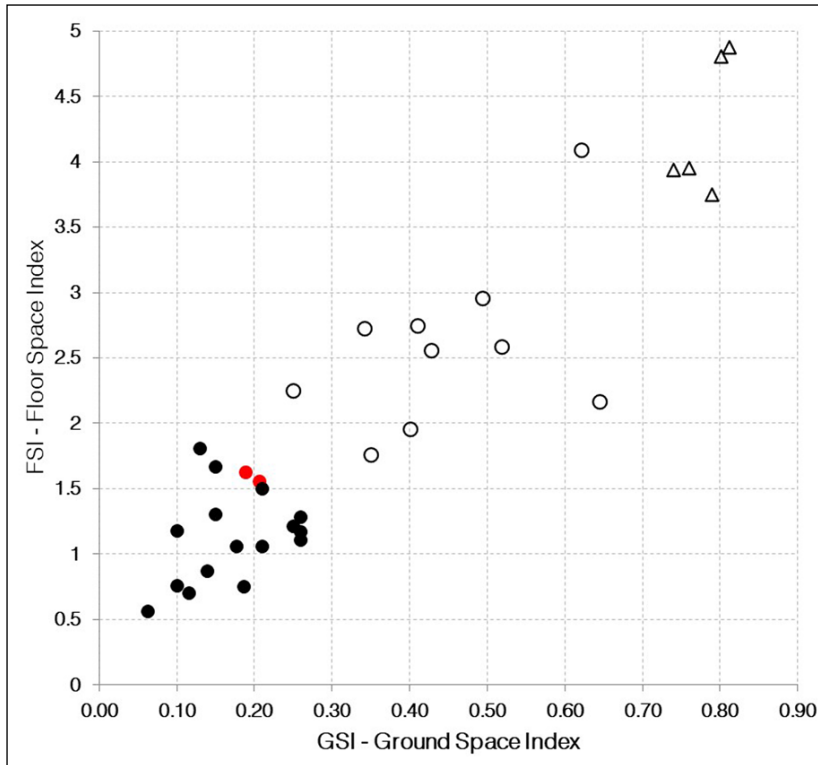


Figure 2: Urban form metrics for case studies (red dots) compared with other European social housing districts (black dots), compact urban fabrics (white dots) and historical urban fabrics (triangles).

These morphological distinctions hold particular significance for outdoor thermal comfort assessment, as they influence exposure to direct solar radiation and the availability of shaded areas, providing an interesting starting point to assess the effects of vegetation.

	$A \text{ (m}^2\text{)}$	$C \text{ (m}^2\text{)}$	$F \text{ (m}^2\text{)}$	$V \text{ (m}^3\text{)}$	L	GSI	FSI	OSR	TREE DENSITY (unit/ha)	GREEN SPACE INDEX	PERVIOUS SURFACE FRACTION
DEFINITION	DISTRICT REFERENCE AREA	BUILDING FOOTPRINT	GROSS FLOOR AREA	BUILT VOLUME	$\frac{F}{C}$	$\frac{C}{A}$	$\frac{F}{A}$	$\frac{F}{A-C}$	$\frac{\text{trees}}{A}$	$\frac{\text{green area}}{A}$	$\frac{\text{pervious area}}{A}$
Bellvitge	40,232	8,282	62,753	191,213	7.58	0.21	1.56	1.96	67	0.076	0.192
Gornal	40,232	7,573	65,639	203,267	8.67	0.19	1.63	2.01	83	0.103	0.013

In the cases of Bellvitge and Gornal, both have a high open space ratio ($\uparrow$ OSR), with a value close to 2, meaning that for every 1 m² of built floor area on a site, there are 2 m² of open, unbuilt space. Such large open spaces can reduce heat if properly planned and maintained (e.g. shading devices, trees, grass), but increase radiant heat otherwise (e.g. paved surfaces), underscoring the need for optimised urban design from a climate-centric perspective.

Bellvitge and Gornal exhibit a relatively similar presence of green areas (green space index = 0.1–0.08). The tree density in Gornal (83 trees/ha) is 24% higher than in Bellvitge (67 trees/ha), but Bellvitge has a higher pervious-to-impervious surface ratio, which may influence its microclimatic behaviour. The study area (delineated by the white square in Figure 1) contains 2261 trees across public open spaces—according to the latest municipal inventory—representing 91 distinct species. Table 3 summarises the predominant ones and their key characteristics.

The selection of Bellvitge and Gornal as case studies is particularly relevant due to their contrasting urban morphologies and shared vulnerability to heat stress. Their characteristics allow for an in-depth exploration of how urban form and tree cover influence outdoor thermal conditions in social housing districts across the Mediterranean region.

Table 2: Urban form metrics of the case studies.

Note: FSI = floor space index; GSI = ground space index; OSR = open space ratios.

SCIENTIFIC NAME	COUNT	%	LEAF TYPE	SIZE CLASS	MATURE HEIGHT (m)
<i>Pinus pinea</i>	284	12.6%	Evergreen	High	12–20
<i>Ulmus pumila</i>	255	11.3%	Deciduous	Medium	10–15
<i>Platanus hispanica</i>	161	7.1%	Deciduous	High	20–30
<i>Jacaranda mimosifolia</i>	150	6.6%	Semi-deciduous	Medium-high	10–15
<i>Tipuana tipu</i>	150	6.6%	Deciduous	High	12–18
<i>Celtis australis</i>	129	5.7%	Deciduous	Medium-high	15–20
<i>Styphnolobium japonicum</i>	111	4.9%	Deciduous	Medium	10–15
Others	1,021	45.1%	–	–	–
Total	2,261	100%			

Table 3: Tree species within the investigated urban areas of Bellvitge and Gornal.

Source: Ajuntament de l'Hospitalet de Llobregat (2024): municipal tree inventory.

2.2 MODEL DEVELOPMENT

UMEP uses its own meteorological data file format. In this case, the Barcelona typical meteorological year (TMY) EnergyPlus Weather (EPW) file was used to generate the appropriate format. To conduct the simulations, several types of raster files are necessary as input to calculate MRT:

- Digital elevation model (DEM): this raster file contains terrain elevation. The DEM for each neighbourhood was downloaded from the Barcelona Metropolitan Area (AMB) database (AMB 2024).
- Digital surface model (DSM): this raster file includes terrain elevation, as well as the footprint and height of buildings. It was generated using the UMEP DSM Creator tool, based on a polygonal vector layer with building information from the AMB database and the DEM raster file.
- Canopy digital surface model (CDSM) and trunk digital surface model (TDSM): these raster files provide vegetation-related information. The CDSM and TDSM were created using the UMEP Tree Generator tool, which utilised a point vector layer detailing the location and dimensions of trees (tree type, total height, trunk height and diameter) developed by the authors based on the data from the L'Hospitalet de Llobregat Municipality (Ajuntament de l'Hospitalet de Llobregat 2024) and Google Earth.
- Land cover types: this raster file categorises land cover types such as grass, water, buildings, paved surfaces, evergreen trees, deciduous trees and bare soil. It was produced using the rasterise with attributes tool in QGIS, utilising a polygon vector layer with the land cover categories and the DEM raster file.

The remaining raster files required for the simulations were generated using UMEP tools. These included the aspect (orientation) and height of the walls and the Sky View Factor raster file, for which two versions were created for each neighbourhood, one including trees and one without.

2.3 MRT SIMULATION AND ANALYSIS

Urban heat stress in both neighbourhoods is analysed through simulations of MRT using UMEP version 3.20.9, an open-source QGIS plugin. MRT calculations in UMEP are based on the SOLWEIG model v2022a, which can compute spatial variations of solar (K) and longwave (L) radiation fluxes from six directions in complex 3D environments. SOLWEIG considers the sky, buildings, ground and vegetation components separately (Figure 3).

High-resolution (1 px = 1 m²) MRT maps were generated through pixel-by-pixel simulations of the open spaces under study in two scenarios: with and without trees. The emissivity and albedo values used in the model were as follows. For horizontal surfaces: asphalt = 0.95 and 0.18; grass = 0.94 and 0.16; and bare soil = 0.94 and 0.25. For vertical surfaces (walls), values of 0.90 and 0.50

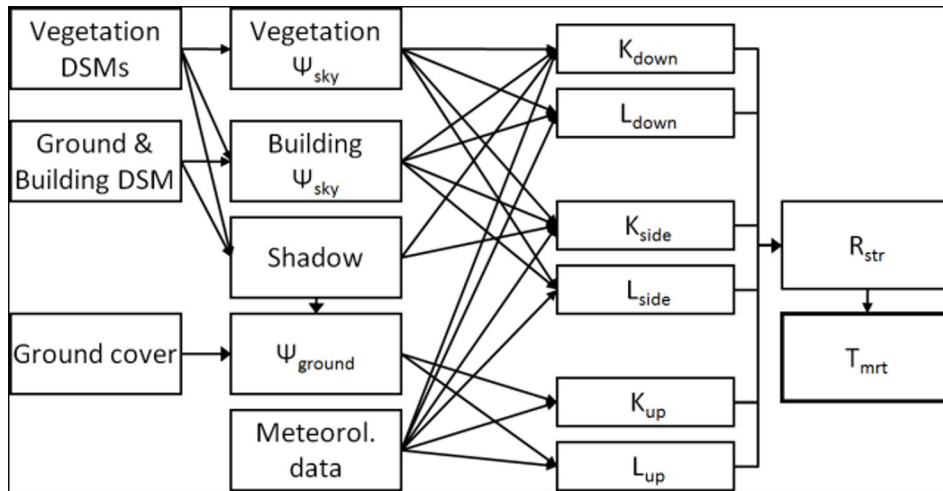


Figure 3: Overview of the SOLar LongWave Environmental Irradiance Geometry (SOLWEIG) model.

Note: DSM = digital surface model.

Source: Lindberg et al. (2019).

were applied, respectively, along with a vegetation light transmissivity of 3%. A single emissivity and albedo value was applied uniformly to all vertical surfaces in the model. While SOLWEIG allows these properties to be specified for vertical surfaces, it only permits one global value for each across the entire model. Given this limitation (and considering the high degree of homogeneity in building materials, facade colours and glazing ratios in the study area), the use of averages was considered an appropriate and representative simplification.

The simulations focused on a 500×500 m ($250,000 \text{ m}^2$) study area characterised by a morphologically uniform urban fabric. The simulation period selected for this study was the warmest summer week from the TMY EPW file used. Figure 4 provides a summary of the weather conditions during this week (3–9 August). The results analysis focused on the central hours of the day, from 10:00 to 16:00 local time (coordinated universal time (UTC)+2). Within the study area, a specific 4-ha region of interest (black square in Figure 5) was selected for a more in-depth quantitative analysis of MRT data, utilising zonal statistics, raster layer histograms and the GRASS r.quantile tools of QGIS. Finally, the heat stress category was calculated using the UTCI based on the simulation results.

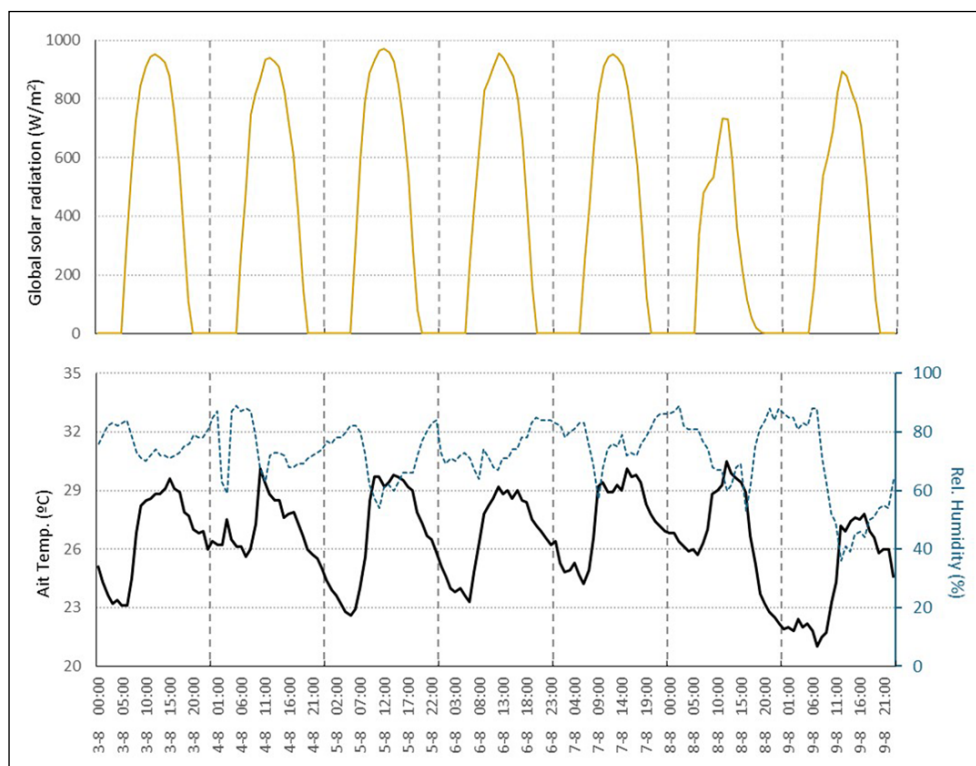


Figure 4: Climatic data used for simulations (3–9 August).

Source: Typical meteorological year (TMY) EnergyPlus Weather (EPW) from Climate. OneBuilding.Org (2024).

3. RESULTS

The simulation results indicate that, in the absence of trees, MRTs range between similar values in both areas (Table 4). However, the range was slightly wider in Bellvitge (39.3–71.9°C) compared with Gornal (41.0–71.9°C). On average, the MRTs were also similar, but slightly higher in Gornal (57.4°C) than in Bellvitge (55.2°C).

When the effect of trees is considered, a decrease in MRT is observed due to the expansion of the shaded area in both neighbourhoods. Trees cause the average MRTs of the studied areas to decline by 5.3°C in Bellvitge and by 8.8°C in Gornal compared with the no-trees scenario. Additionally, minimum MRTs decrease by 4 and 6°C, respectively (Table 4). In quantitative terms, the two neighbourhoods behave similarly when trees are accounted for, though Gornal is slightly cooler (−0.3°C in MRT_{max} , MRT_{min} , and −1.4°C in MRT_{ave}).

MRT RANGE (°C)	BELLVITGE		GORNAL	
	WITHOUT TREES	WITH TREES	WITHOUT TREES	WITH TREES
Maximum	71.98	71.57	71.91	71.22
Average	55.23	49.95	57.44	48.57
Minimum	39.35	35.30	41.03	35.03

Much more significant differences emerge between the two neighbourhoods when analysing the spatial distribution of MRTs using the maps in Figure 5. The no-trees scenario (Figure 5, top) demonstrates that differences in the urban form itself lead to uneven MRT patterns between studied cases. In Bellvitge, the presence of linear blocks creates shaded corridors along the north side of buildings, which remain significantly cooler (MRTs around 39–40°C).

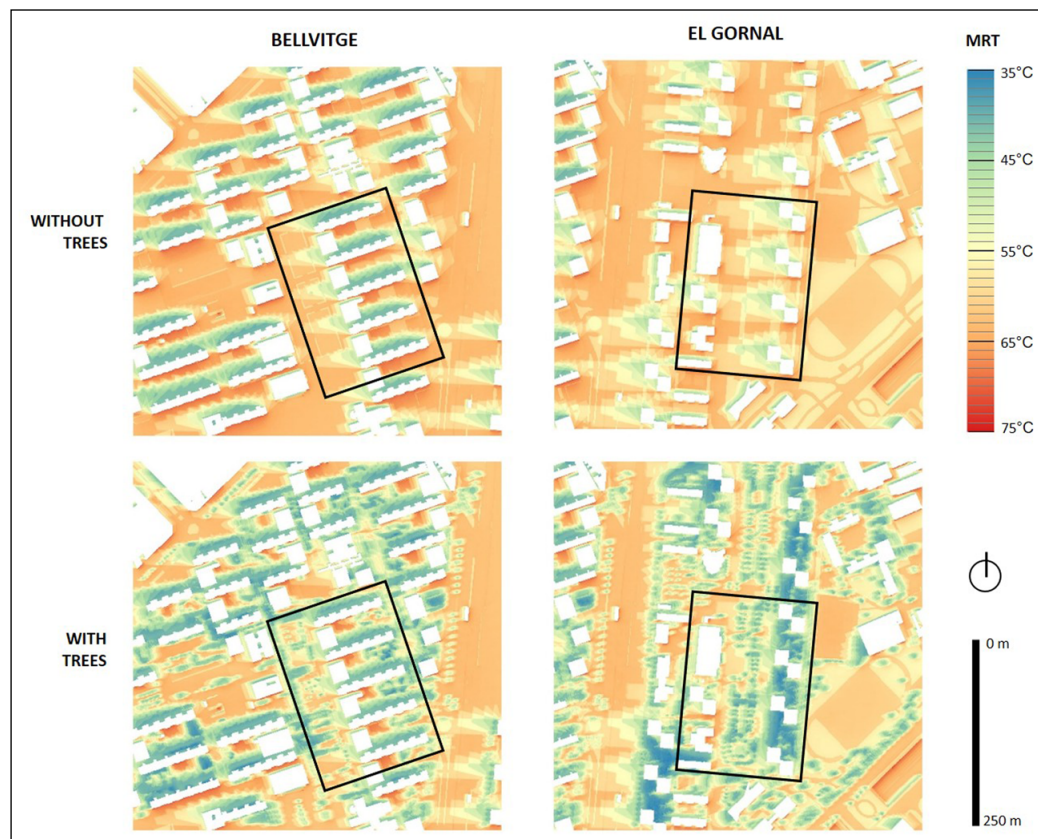


Table 4: Summary of the key mean radiant temperatures (MRT) of the study areas.

Figure 5: Maps of the average mean radiant temperatures (MRTs) obtained for Bellvitge and Gornal districts during the simulation period (3–9 August, 08:00–14:00 UTC) with and without trees.

Source: Lopez-Ordóñez et al. (2024).

These areas contrast with the zones near the south side of buildings, which are much warmer (MRTs up to 72°C) due to both the high levels of direct radiation and reflected radiation from building surfaces. In Gornal, tower buildings create a less defined shadow pattern, resulting in open spaces with higher and more uniform MRTs compared with Bellvitge. Furthermore, the coolest areas are located on the north-west side of the tower blocks and exhibit MRTs that generally remain > 41°C.

Simulations including trees reveal significant changes in MRT distribution patterns for both neighbourhoods (Figure 5, bottom). Tree shadows create cooler areas along the park avenues and between buildings, with MRTs typically ranging between 35 and 45°C. The vegetation benefits are more pronounced in the tower-type neighbourhood (Gornal) than in the linear-block neighbourhood (Bellvitge), where the urban form itself creates cool shaded zones. The inclusion of trees in urban fabric such as Gornal enables the creation of new shaded corridors between towers, spaces that would otherwise receive minimal building-shade protection.

To better quantify trees' impact on each neighbourhood's radiant environment, histograms and a table describing the percentage of open space by MRT, with and without trees, were created (Figure 6 and Table 5).

Without trees, the data reveal a non-symmetric bimodal distribution in Bellvitge, suggesting the presence of two different behaviours. The smaller cluster (MRTs between 39 and 46°C) is associated with shaded areas that constitute 15% of open space. The larger cluster (46–72°C) is linked to sunlit zones, comprising 85% of the open space; peaking at the 62–64°C interval where nearly one-quarter (22%) of open space falls. When considering tree effect, the distribution becomes noticeably right-skewed, suggesting that trees help maintain cooler conditions in most of the open space, reducing the prevalence of extreme MRTs.

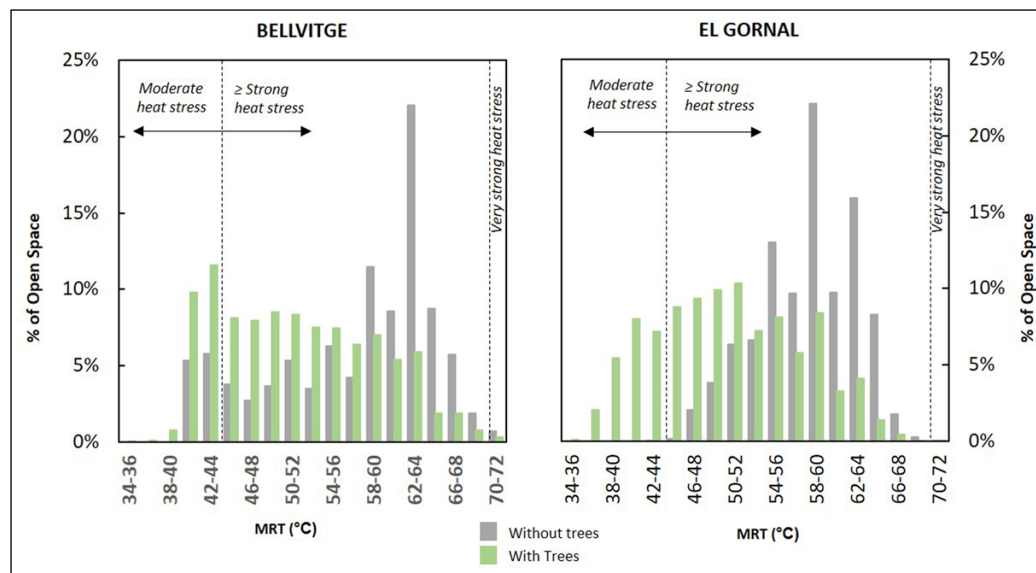


Figure 6: Percentage of open space according to its mean radiant temperature (MRT) for Bellvitge and Gornal districts during the simulation period (3–9 August, 08:00–14:00 UTC) with and without trees.

Source: Lopez-Ordonez et al. (2024).

For Gornal, MRT data in the no-trees scenario exhibit a symmetric unimodal distribution, with most values concentrated between 46 and 68°C. The results indicate that 80% of the open space experiences MRTs > 54°C, with nearly one-quarter (22%) falling within the 58–60°C range (the distribution's peak). The distribution's shape and range suggest sun-exposed open spaces dominate, with no persistent shaded areas present. When trees are included, the dataset shifts toward lower MRTs: 68% of the open space presents MRT < 54°C, and almost one-third of them have MRT < 46°C, a value associated with long-term shaded spaces. Particularly significant is the appearance of areas with temperatures < 40°C, 'cool spots' which accounts for almost 8% of the neighbourhood area.

MRT RANGE (°C)	BELLVITGE				GORNAL			
	WITHOUT TREES	%	WITH TREES	%	WITHOUT TREES	%	WITH TREES	%
35–40	2	0.006	313	0.97	0	0	2,558	7.71
40–45	4,358	13.53	8,135	25.26	22	0.07	6,524	19.67
45–50	2,569	7.98	6,815	21.16	2,060	6.21	7,987	24.08
50–55	3,993	12.40	6,353	19.73	5,972	18	7,325	22.08
55–60	6,121	19.01	5,516	17.13	13,586	40.96	5,858	17.66
60–65	11,428	35.49	3,851	11.96	10,231	30.85	2,649	7.99
65–70	3,491	10.84	1,105	3.43	1,283	3.87	267	0.80
70–75	239	0.74	113	0.35	15	0.05	1	0.003

Table 5: Summary of key mean radiant temperatures (MRTs) of the study area.

Note: Yellow = moderate, pink = strong and purple = very strong heat stress levels.

4. DISCUSSION

4.1 TEMPORAL VARIATION OF MRT VALUES

The analyses in this paper are based on MRTs during the central hours of the day (10:00–16:00 local time; 08:00–14:00 UTC). While this approach provides a general understanding of the thermal impacts of urban morphology and vegetation, it does not capture their dynamic variations throughout the diurnal cycle. To discuss this aspect, Figure 7 presents hourly MRT distributions (including maximum, minimum and quartile values), which reveal significant temporal variations between both neighbourhoods.

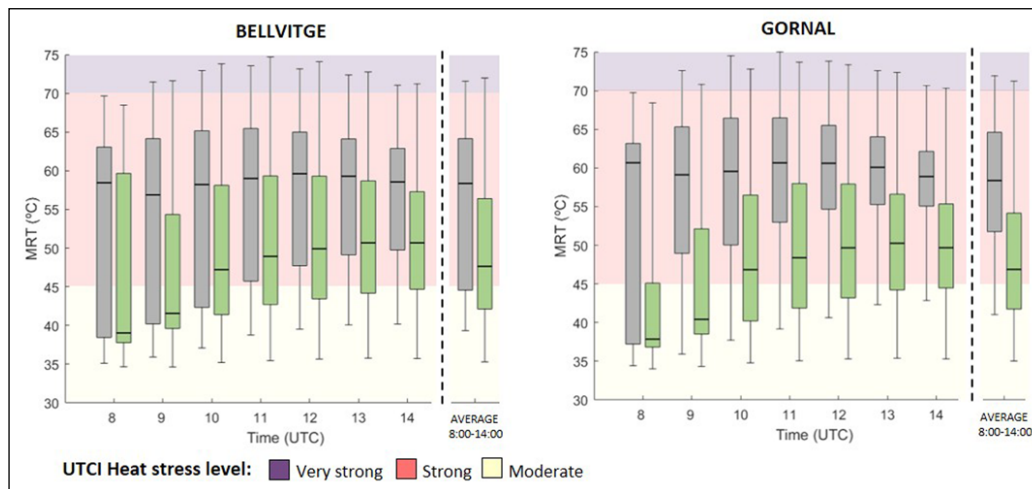


Figure 7: Hourly evolution of the mean radiant temperature (MRT) distribution (maximum, minimum and quartiles) compared with the average distribution of MRT throughout the simulation period for Bellvitge and Gornal districts with and without trees.

In the treeless scenario, median MRTs remain consistently high throughout the day, peaking around midday (11:00 UTC in Gornal and 12:00 UTC in Bellvitge) in synchronisation with maximum solar radiation. In contrast, the vegetated scenario exhibits consistently lower median MRTs that increase more gradually, with peak temperatures delayed by approximately 2 h. To illustrate the mechanisms underlying these contrasting thermal dynamics, Figure 8 presents the hourly evolution of MRT distribution for the Gornal case.

As shown, the presence of trees introduces a pronounced diurnal variation in MRT due to their dynamic shading effects throughout the day. In the morning, when the sun is low, trees cast long shadows across the urban spaces. These shadows significantly reduce exposure to direct solar radiation, and by extension, prevent surfaces from early overheating, leading to much lower average MRTs compared with the no-tree scenario. As the day progresses and the solar angle increases, the shadows cast by the trees become shorter and shorter until midday, and hence, less effective at covering large surface areas. Consequently, average MRTs rise throughout the day,

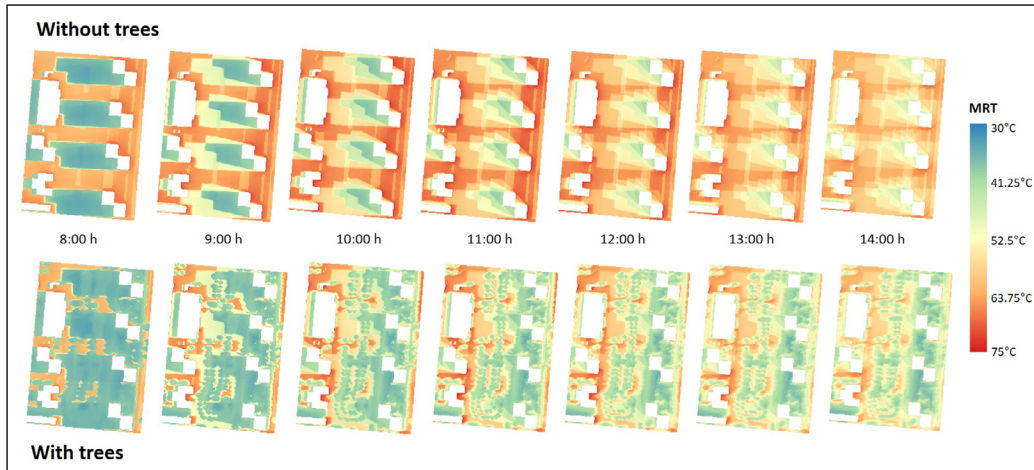


Figure 8: Hourly evolution of the mean radiant temperature (MRT) maps for the Gornal case, with and without trees (UTC time).

producing a typical daily temperature curve: low in the morning, peaking in the early afternoon, 1 h after the maximum horizontal irradiance and matching the peak of surface temperatures.

In contrast, the no-tree scenario displays relatively uniform average MRTs throughout the day. Although there is some shading variability due to the hourly movement of shadows cast by tower buildings (08:00–14:00 UTC), surfaces remain exposed to direct sunlight for extended periods. As a result, even shaded areas retain accumulated heat, and MRT remains high. The absence of trees, combined with thermal inertia and limited shading heterogeneity, leads to consistently elevated and homogeneous thermal conditions.

Overall, trees not only reduce peak thermal stress but also modulate the timing of urban heat. During the study period, trees lowered median MRT by 10.7°C (Bellvitge) and 11.5°C (Gornal), with cooling effectiveness varying diurnally. The most substantial changes occur in the early morning (08:00 UTC), where trees reduce median MRT by 19.4°C in Bellvitge and 22.8°C in Gornal. These impacts diminish by early afternoon to 7.9 and 9.2°C, respectively. These results demonstrate a clear diurnal pattern in vegetation benefits, with morning reductions being particularly crucial as they coincide with intense pedestrian activity periods (e.g. commercial establishments typically open at 10:00 local time/08:00 UTC).

The observed 2-h delay in peak MRT under vegetated conditions carries important implications for urban thermal management. By shifting heat accumulation to less sensitive hours, trees not only reduce extreme temperatures but also temporally redistribute thermal stress, offering enhanced comfort during high-usage periods. While averaged values provide useful insights, these findings underscore that temporal resolution is critical for fully understanding mitigation strategies. The identification of morning as the period of maximum cooling efficacy, coupled with the observed phase shift in peak temperatures, suggests that urban greenery's benefits extend beyond simple temperature reduction to include temporal modulation of thermal extremes. Future work could integrate additional metrics (e.g. hourly extremes or rate of change) to further disentangle these dynamics.

4.2 CRITICAL MRT THRESHOLD

Since thermal perception depends on multiple climatic variables beyond MRT, this section examines the relationship between MRT and heat stress levels using the UTCI as an outdoor thermal comfort metric. The analysis employed average simulation conditions ($T_{\text{air}} = 28.7^{\circ}\text{C}$, relative humidity = 65% and $V_{\text{air}} = 3 \text{ m/s}$). Results shown in Figure 9 demonstrate that the observed MRT ranges in both study areas consistently correspond to UTCI values exceeding comfort thresholds, ranging between moderate to very strong heat stress conditions during the study period.

Based on the MRT–UTCI correlation, two critical MRT thresholds were identified at 45 and 70°C. These represent transition points from moderate to strong and very strong heat stress perception (indicated by the dashed lines in Figure 6). Simulations revealed that only shaded areas—whether

by trees or buildings—consistently maintained MRTs below the 45°C threshold. In contrast, zones > 70°C were restricted to unshaded areas with high reflected solar radiation gains (from building surfaces). These findings underscore solar radiation as the predominant driver of extreme heat stress conditions and highlight the crucial role of shading in mitigating radiative heat, a key consideration for urban design.

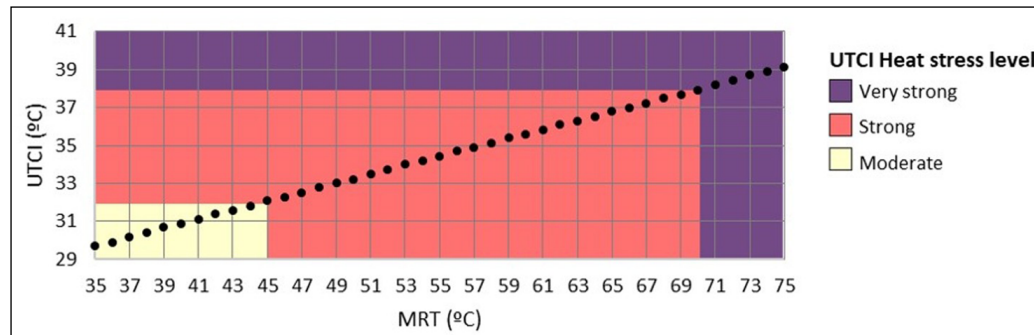


Figure 9: Correlation between mean radiant temperature (MRT) and universal thermal climate index (UTCI) values.

The established MRT thresholds were applied to quantify heat stress levels (moderate, strong and very strong) across open spaces in both case studies (Figure 10). Analysis revealed that in the absence of trees, most of the open space in both neighbourhoods falls within the category of strong heat stress (85.7% for Bellvitge versus 99.9% in Gornal). In contrast, when trees are considered, shaded areas substantially increase in both neighbourhoods, leading to significantly MRT reductions and consequent heat stress mitigation. Thanks to trees, both cases achieve virtually the same percentage of open spaces classified as having moderate heat stress (~27%), underscoring the compensatory role of vegetation in mitigating heat stress.

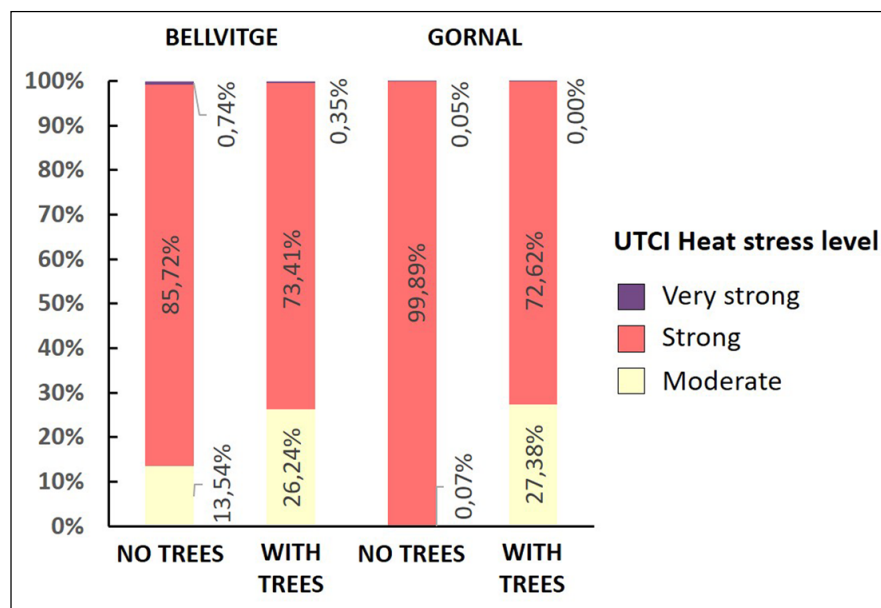


Figure 10: Distribution of open space area by thermal comfort perception level according to the universal thermal climate index (UTCI) scale (based on the average results during the simulation period 3–9 August, 08:00–14:00 UTC).

The analysis reveals significantly greater thermal comfort improvements from tree coverage in Gornal compared with Bellvitge when using the no-tree scenario as a reference. Although Gornal exhibits higher tree density (83 versus 67 trees/ha), this quantitative difference alone cannot account for the substantial variation in observed benefits: vegetation enhances comfort conditions by 27.3% in Gornal compared with just 12.7% in Bellvitge. Particularly notable is the emergence of ‘cool spots’ in Gornal—areas with MRTs of 35–40°C covering approximately 8% of the total surface area (Table 5)—which are absent in Bellvitge. These divergences can be attributed to several factors: the generally smaller tree size in Bellvitge, and the suboptimal placement of some trees in already shaded building areas.

These findings underscore the critical importance of shadow-related design considerations for maximising vegetation's cooling potential. While our simulations incorporated individual tree parameters (height, canopy dimensions) for all specimens, software limitations necessitated assuming constant light transmissivity across species. Future studies should assess the sensitivity of results to this factor, accounting for parameter variations due to seasonal dynamics and environmental influences such as water scarcity.

The location-specific nature of the proposed MRT threshold—derived from UTCI heat stress levels and influenced by local meteorological variables (air temperature, humidity, wind speed)—limits its direct transferability to other climatic contexts. However, the methodological framework presented here, combining GIS-based workflows with MRT thresholds, offers transferable value for urban practitioners implementing green infrastructure solutions. As Figure 11 demonstrates, this approach enables the following:

- Hotspot identification through energy simulations of non-vegetated urban models.
- Strategic tree selection by overlaying hotspot maps with urban tree inventories to differentiate critical shade providers (targeting highly irradiated areas) from redundant ones (in building-shaded zones).
- Performance evaluation based on the analysis of vegetated urban models to quantify species-specific cooling effectiveness, enabling microclimatic service rankings.

This systematic process may extend the concept of ‘critical infrastructure’—traditionally applied to non-living structures such as electric or transport networks—to urban trees as essential components for thermal comfort during heat stress. Such classification could inform adaptive management strategies, including prioritised irrigation during water scarcity (increasingly prevalent under climate change), ensuring optimal resource allocation where ecosystem services are most impactful.

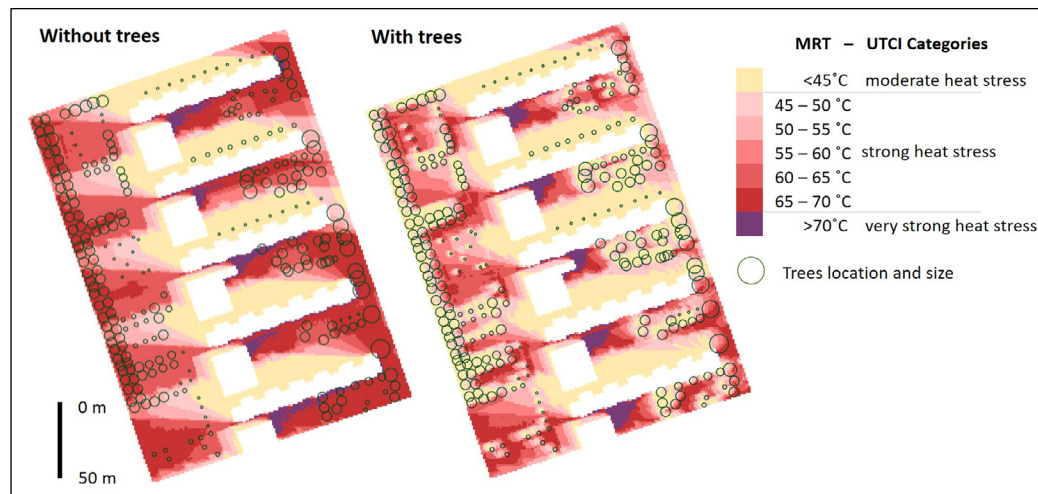


Figure 11: Application of mean radiant temperature (MRT) thresholds for urban green infrastructure planning to mitigate heat stress: example based on the Bellvitge case study (11:00 UTC).

Note: (left) The map depicts results without trees and allows for detecting hotspots and identifying critical shade providers (e.g. those out of yellow areas). (right) The map depicts results with trees and helps ranking trees based on their rank cooling effectiveness.

Though the interplay between vegetation, building energy consumption and urban microclimate falls beyond the scope of the present study, it is worth noting that energy simulations of existing buildings necessitate careful modelling of urban vegetation, akin to other urban obstructions, in order to yield reliable results. The presence of urban tree cover provides shading to building facades—particularly at lower storey levels—which modifies solar gains through the building envelope throughout the year (Calcerano & Martinelli 2016; Garcia-Nevado et al. 2021; Palme et al. 2021).

With specific reference to the warm season investigated herein, which in the Mediterranean context is projected to increase energy consumption for building cooling due to climate change, urban trees can counteract such increases. Nevertheless, the inverse effects during the cold

season must also be considered, depending on the type of tree species present in the urban space (i.e. deciduous or evergreen).

These findings highlight the need for further research examining how tree-mediated heat-mitigation strategies—through both shading and air temperature regulation—influence indoor thermal comfort and building energy consumption patterns.

5. CONCLUSIONS

Introducing a performance-based design approach to mitigate heat stress in open spaces is paramount, particularly in social housing districts where urban form alone provides limited solar obstruction during hot seasons. This study examines two prototypical Mediterranean social housing neighbourhoods, the linear-block morphology in Bellvitge and the tower-block configuration in Gornal, to develop a framework for heat stress mitigation in open spaces, relying on the assessment of mean radiant temperature (MRT). The analysis demonstrates that in Mediterranean climates, trees emerge as essential components of climate-adaptive design.

Key findings about the trees' effect from these representative cases reveal the following:

- *Thermal modulation effect*
Beyond absolute temperature reductions, vegetation introduced a phase shift in diurnal heat patterns, delaying peak MRT by 2 h to less critical periods, a particularly valuable effect in Mediterranean summers when thermal stress persists into evening hours.
- *Morphological dependencies*
The high-rise, low-density tower-block neighbourhood exhibited greater thermal reliance on strategic tree placement compared with linear-block configurations, where buildings provided inherent shading benefits.
- *Spatial compensation*
Despite initial disparities, both neighbourhoods achieved approximately 27% of open space within the moderate heat stress levels thanks to trees. This evidence shows that proper tree design can compensate for morphological deficiencies, enabling comparable outdoor comfort levels across divergent urban forms.
- *Threshold management*
While trees alone may not achieve full thermal comfort, they create urban heat havens: areas with reduced heat stress compared with their surroundings. This partial mitigation proves critical for vulnerable populations during extreme heat events when complete comfort is unattainable.

This study introduces a methodological framework that integrates geographical information system (GIS)-based workflows with MRT thresholds, leveraging thermal analysis of both purely morphological and vegetated urban models. By employing tools and workflows familiar to planning professionals, this approach aims to support data-driven decision-making across all stages of green infrastructure planning, from design to maintenance. These insights inform climate-adaptive strategies, such as targeted planting and irrigation, to maximise resource allocation where ecosystem services yield the highest impact, thereby enhancing urban resilience against rising heat stress. Future research should explore species-specific performance under climate change scenarios to refine the framework's long-term adaptability.

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COMPETING INTERESTS

The authors have no competing interests to declare.

DATA ACCESSIBILITY

Data are available on request.

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