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Coupling remote sensing data and local meteorological measurements to predict thermal stress and its potential mitigation by urban forests

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A R T I C L E I N F O

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A B S T R A C T

Urban areas face complex challenges including air pollution, land use changes, and rising temperatures driven by Urban Heat Island (UHI) effects. UHIs heighten heat stress risks, impacting human health and well-being. Urban green spaces, particularly urban forests, are key ecosystems to address these challenges by providing cooling effects and enhancing thermal comfort. In this context, monitoring the role of trees in mitigating the temperature is crucial. Remote sensing optical data may represent a powerful tool for this aim, but available sensors generally provide temperature at a very low spatial resolution that is not effective in the urban context. The primary aims of this study are to (i) develop and test a model for assessing thermal comfort in urban settings with an enhanced spatial resolution and (ii) investigate how urban green spaces contribute to increasing thermal comfort. Remote sensing Landsat 8 and Sentinel 2 data were combined to increase the spatial resolution of land surface temperature maps from 30 m to 10 m. The model was validated with ground data. Air temperature, global temperature, and thermal comfort maps were then created for the city of Florence. The results show significantly lower thermal comfort in areas lacking vegetation cover, while tree-lined streets and green spaces exhibit higher thermal comfort. Even vegetation traits such as height and fresh-wood volume positively correlate with thermal comfort, emphasizing the cooling effects of urban trees and their role in mitigating heat stress. This study promotes data and methods accessibility and replicability and supports evidence-based decision-making, highlighting the role of green spaces in mitigating heat stress and climate changes issues.

1. Introduction

Cities today are facing unprecedented and severe challenges (Mugnozza, 2023) such as deleterious changes in air quality, changes in land use and water flow with erosion risk and loss of water quality, modification and destruction of habitats with a huge loss of biodiversity, rising temperatures, and the amplification of the heat accumulation phenomenon induced by the Urban Heat Island (UHI) effect (Mugnozza, 2023; Yang et al., 2016). Where UHI are urbanized areas that experience higher temperatures than surrounding rural areas due to heat-trapping effects from land use, built environment and sealed surfaces, heat-absorbing materials, reduced greenery, limited ventilation, and heat emissions from human activities (United States Environmental Protection Agency, IPCC, 2022). UHI can lead to average differences in mean temperature of dense urban areas vs. rural or vegetated land cover ranging from 1° to 8° C (Chen et al., 2006; Imhoff et al., 2010; Oke et al., 2017; Tam et al., 2015). Ongoing climate change further amplifies the UHI effects and decreases human thermal comfort (Rötzer et al. 2021). Thermal comfort is the subjective condition of satisfaction with the thermal environment (ANSI/ASHRAE, 2004). A direct relationship exists between UHI, thermal comfort, heat-related diseases, and fatalities. Indeed, considering the summer of 2003 alone, heat waves and related issues caused more than 70,000 deaths in Europe (Robine et al., 2008). Accordingly, thermal discomfort is one of the most significant reasons for human cardiovascular and respiratory diseases (Grigorieva and Lukyanets, 2021; Uejio et al., 2016).

Heat-related mortality is expected to increase as the climate warms and urban areas continue to grow. The need to assess heat stress is

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increasing since it can affect individual productivity, health, and tolerance to other environmental hazards (Margolis, 2021; Zander et al., 2015). Heat stress occurs when the body can't cool itself through sweating and heat dissipation, leading to an increase in core temperature. This condition arises from prolonged exposure to high temperatures and can be exacerbated by high humidity, direct sun exposure, and physical exertion in hot conditions (Larrañaga, 2021). Heat stress conditions outdoors are strictly linked to environmental parameters such as air temperature, humidity, wind speed, and solar radiation, that play significant roles in the onset of heat stress. Urban environments can intensify these factors due to the UHI. The body normally maintains a stable internal temperature through thermoregulatory mechanisms. Heat stress disrupts these mechanisms, potentially leading to serious health consequences such as heat exhaustion or heat stroke (Kovats and Hajat, 2008; Romanello et al. 2021). In the quantitative evaluation of heat stress and thermal comfort, the Wet Bulb Globe Temperature (WGBT) index, introduced by Yaglou and Mynard in 1957, was recognised as ISO 7243 standard in 1989 (ISO, 1989). Despite the recent development of more than 100 novel heat stress indices, the WBGT index is still considered one of the most reliable (Teimori et al., 2020).

Enhancing the liveability of our cities, both now and in the future, can be achieved by addressing factors that influence and improve thermal comfort. The ultimate goal is to mitigate UHI effects and minimize the risks of heat stress through adaptive urban planning and design. In this context, the pattern and functions of urban green spaces are assumed to be a crucial factor (Grimm et al., 2008; Kong et al., 2014; Semenzato and Bortolini, 2023), particularly referring to the urban forest component (Hwang et al. 2023). Urban forests, namely the totality of urban and periurban trees, shrubs, lawns, and pervious soil, provide a wide range of ecosystem services (ES) important for human well-being, such as urban temperature mitigation (Bottalico et al., 2017, Francini et al., 2024a). Furthermore, among various natural elements, trees are recognized as the principal and most efficient in regulating microclimates and enhancing conditions for outdoor thermal comfort (Lee et al., 2016). The microclimatic influence of trees is achieved through various interconnected processes that contribute to thermal regulation in urban environments. One key mechanism is the reduction of solar heat gains on building surfaces such as windows, walls, and roofs, as tree canopies provide effective direct shading by leaf canopy interception (Rocha et al., 2022a). Additionally, by lowering surface temperatures through shade, trees limit the long-wave radiation exchange between buildings and the sky, thereby mitigating heat accumulation. Another crucial effect is the decrease in conductive and convective heat transfer, as trees help lower ambient air temperatures through the process of evapotranspiration, which reduces overall heat absorption by buildings (Dimoudi and Nikolopoulou, 2003). Furthermore, trees enhance latent cooling by increasing atmospheric moisture levels via evapotranspiration; plants help maintain air humidity by minimizing water loss, blocking direct sunlight, slowing wind speed, and reducing evaporation, improving thermal comfort and reducing cooling energy demands during warmer periods. A single tree approximately 21 m tall can release around 400 litres of water per day (Federer, 1976). Additionally, vegetation influences wind patterns, reducing or redirecting airflow (Hong et al., 2012). Properly placed greenery around buildings can significantly lower wind speeds (Onder and Dursun, 2011). The influence of tree quantity, disposition, and type in enhancing the thermal conditions of urban areas is widely accepted (Acero and Herranz-Pascual, 2015; Hami et al., 2019). Tree canopy coverage characterized by dense, contiguous crowns, as opposed to sparse and separated, has a more pronounced influence in mitigating temperatures and enhancing thermal comfort (Zhang et al., 2018). The functional arrangements of urban green spaces, urban forests, and green and blue infrastructure components are reported as key for mitigating heat stress conditions (Cornu et al., 2024; Gunawardena et al., 2017). Moreover, the efficacy of various tree species in this regard is contingent upon their crown morphology, wherein species with wider canopies, facilitating greater shading, demonstrate a superior capacity for ameliorating thermal discomfort during hotter seasons (El-Bardisy et al., 2016). The positioning and arrangement of urban features like buildings and vegetation significantly impact outdoor thermal comfort. Particularly, the placement of marginal trees plays a crucial role in altering wind patterns and regulating airflow (El-Bardisy et al., 2016). Additionally, the location of trees influences the absorption of short-wave radiation, with trees exposed to direct sunlight exerting greater cooling effects on the environment compared to those shaded by buildings (Wu and Chen, 2017).

Streets and piazzas without trees showed air temperatures approximately two degrees higher than land types with trees (Speak and Salbitano, 2022), and multi-layer vegetation-covered (tree-shrub-grass) determines the largest cooling effect of the area, up to 8.9 °C (Li et al., 2020). High incoming radiation can be better managed by tree species with greater leaf area, where diffuse-porous trees can reduce canopy air temperature by 2.8 °C and increase absolute humidity by 2.6 g/m^3 , compared to a 1.9 °C temperature reduction and 1.9 g/m^3 humidity increase in ring-porous trees (Rahman et al., 2020). Different tree traits such as leaf colour and shape, crown shape, diameter, and width play a key role in the cooling of urban areas (Hwang et al., 2023). Generally, small-leaved species maintain lower crown temperatures than large-leaved ones (Leuzinger et al., 2010); trees provide a higher cooling effect with a greater crown diameter than crown height; it is also demonstrated that a wide, umbrella crown shape has a higher cooling effect than a columnar shape (Speak et al., 2020).

The value of urban green spaces in thermal comfort mitigation defines the necessity to integrate the planning and design of urban environments with traits of adaptative and resilient cities. The measurement methods adopted so far are mainly fixed or portable weather stations. While they allow us to obtain very detailed and accurate data, they are extremely expensive, both from an economic and time point of view. Also, large study areas include often very heterogeneous networks of stations, which complicates the harmonization process and information comparability (Gál and Kántor, 2020). Critically, weather stations provide point data for very specific areas, while a more exhaustive coverage of our cities would be needed for proper planning and decision-making.

Remote sensing is known to be a relevant source of information for large-scale monitoring of Land Surface Temperature (LST). LST, obtained through remote sensing, is widely studied for various purposes, such as mapping, monitoring, and characterising urban landscapes (Mushore et al., 2022). Additionally, it is employed to estimate the rapid development of an urban area, to determine the composition of different urban classes (Cruz et al., 2019), to study the intra-urban spatial distributions of LST patterns, and to investigate surface heat island intensity, among other applications (Cotlier and Jimenez, 2022; Sankalp and Sahoo, 2022). Some studies have employed airborne laser scanning data to determine LST, (Bartesaghi-Koc et al., 2018) while numerous others have used Landsat data (Danai, 2019). However, ground temperature is not the sole determinant of thermal stress conditions and it is crucial to assess the relationships between LST and perceived atmospheric temperature to spatially characterize potential thermal stress.

Landsat provides LST data at 30 m, but urban monitoring requires data at a finer resolution. Urban spaces are often characterized by very small and fragmented patches that are challenging to analyse using 30-meters resolution data. Accordingly, a recent study demonstrated that correlations between mobile air temperature measurements, collected on foot using a temperature sensor, and satellite-derived LST were weak and highly variable in the urban context ($r^2 = 0.04 – 0.38$) (Tsin et al., 2016). In this sense, increasing the spatial resolution of LST products via the integration of Landsat and Sentinel-2 data represents a powerful opportunity. While there are studies combining MODIS and Landsat LST data (Bisquert et al., 2016; Cotlier and Jimenez, 2022), combining MODIS LST and Sentinel-2 data (Sanchez et al., 2020) and studies combining Sentinel-3 LST and Sentinel-2 data (Sanchez et al., 2020), almost any study focuses on upscaling Landsat LST data by using

Sentinel-2 data (Marchese et al., 2019).

In summary, more spatially detailed and accurate temperature data and a more exhaustive understanding of the correlation between LST and thermal comfort are needed, as well as a more in-depth knowledge of the role of urban green areas in mitigating temperature and in addressing climate change issues. In detail, the gap existing in predicting thermal comfort by combining ground data and remote sensing data is a challenge, such as the description about how vegetation traits affect these variables.

In this regard, this study addresses the following aims:

1. To increase the spatial resolution of LST from remote sensing data, ensuring a high spatial resolution that is both useful and necessary for applications in urban environments. Specifically, the enhancement of spatial resolution is intended to improve the comparability between remotely sensed LST and ground-based measurements, thereby allowing for a more accurate representation of local-scale thermal variability.
2. To propose the use of LST as a proxy for identifying areas of potential thermal discomfort within urban environments, by investigating the relationship between LST and the Wet Bulb Globe Temperature (WBGT). This analysis aims to assess the reliability of LST as a proxy of thermal stress and its potential use in mapping and monitoring zones of urban thermal discomfort.
3. To analyse the relationship between the predicted thermal comfort and vegetation structural traits, including tree height, basal area (BA), volume (V), crown width, and height to the crown base. This objective seeks to identify which vegetation characteristics most effectively contribute to improving outdoor thermal comfort conditions.

2. Materials and methods

2.1. Study area and reference data

The study considered the urban area of Florence, Italy, where a fieldwork survey collecting meteorological data was conducted in the summer of 2020 (Speak and Salbitano, 2022). The survey covered 126 sites located in the city center and suburbs consisting of commercial and residential areas. Industrial zones, agricultural land, and low-density residential areas on the periphery were excluded from this study. The 126 sites were divided into six categories of outdoor space: three "non-green" categories consisting of treeless squares (including also open, treeless areas of parks with grass surfaces), two-lane streets and old town alleys, and three "green" categories consisting of public parks and gardens, private gardens and tree-lined two-lane streets. Very small areas (< 0.05 ha) measured in the field were removed from this study because they were not compatible with the pixel size of 10 m of remote sensing products. The resulting number of sites in our reference dataset was 120 and the category "Old-town alleys" was excluded in this step (Fig. 1).

In each site, thermal variables were measured using a mobile station consisting of a WBGT data logger (DeltaOhm HD32.2) with a dry bulb (range −40 – 100 °C, resolution 0.1 °C), wet bulb (4–80 °C, 0.1 °C) and 50 mm diameter globe temperature (−30 – 120 °C, 0.1 °C) probes. Sensors for humidity (1–99 %, 1 %) and wind speed (0–50 ms^{-1}, 0.1 ms^{-1}) (PCE Instruments FWS-20) were added. All the measurements were carried out between 11.30 am and 5.30 pm with cloudless sky and low wind conditions. The measured climatic parameters allowed the calculation of the WBGT index for each site ($WBGT_{outdoor}$, Eq. 1), useful for quantifying thermal comfort.

$$WBGT_{outdoor} = 0.7*Tw + 0.2*Tg + 0.1*Ta \tag{1}$$

where Tw, Tg, and Ta are the wet bulb, globe, and dry bulb temperature, respectively. According to ISO 7243, the stress limit at light activity is a WBGT of 30 °C for acclimatised and 29 °C for unacclimatised people (Speak and Salbitano, 2022). Acclimatisation is the process by which a living organism becomes adapted to a change of climatic environment (Gosling et al., 2014)

In all "green sites" the trees were identified to species level and, the height and the diameter at breast height (DBH) of all the trees were measured using a vertex IV laser hypsometer (Haglöf Inc.) and a DBH measuring tape, respectively. The average of the crown width in two dimensions was also recorded. The amount of vegetation within each site was then calculated within a 250 m radius by acquiring Multispectral Sentinel-2 data from Copernicus, calculating the Normalised

Fig. 1. The 120 sites considered in the study divided in categories.

Difference Vegetation Index (NDVI) in QGIS, and processing this layer by selecting only pixels with an NDVI greater than 0.4 (moderate to high vegetation density).

2.2. Landsat and Sentinel-2 remotely sensed data

The Landsat program is a long-standing collaboration between NASA and the United States Geological Survey (USGS) that acquires satellite imagery of the Earth (Payra, Sharma, and Verma, 2023). Landsat satellites operate in a Sun-synchronous pattern and provide imagery with 16 days of revisitation time and 30 m of spatial resolution (Wulder et al.. 2019). Sentinel-2 (S2) is a European Space Agency (ESA) imaging mission integrated within the Copernicus Programme, a component of the European Union's Earth observation initiative (Drusch et al.. 2018). S2 serves as a crucial asset for monitoring the Earth's surface, offering diverse applications including agricultural and forest monitoring, disaster management, and land cover/use classification (Phiri et al.. 2020). S2 ensures a revisit period of 5 days at the equator under cloud-free conditions, extending to 3–5 days at mid-latitudes, and a spatial resolution of up to 10 m depending on the band. Sentinel-2 and Landsat data are open access and freely available and were processed and downloaded using Google Earth Engine (Gorelick et al., 2017), a cloud computing platform that offers unprecedented opportunities for analysing remote sensing data over large areas (Francini et al.. 2023a, 2023b).

2.3. LST modelling

Maps of LST allow the identification and monitoring of UHIs over time, as well as quantifying the contribution made by vegetation and trees in mitigating temperature. The Landsat satellite mission provides LST data at a spatial resolution of 30 m. However, this detail is insufficient in urban environments, where green areas are often present in scattered and small-sized areas. To overcome this limitation, we have leveraged the Sentinel-2 satellite mission, which however does not acquire temperature data. In this study, we used the Random Forests machine learning algorithm (Breiman, 2001), to predict the temperature acquired by the Landsat satellite mission using Sentinel-2 images. This provides a product with higher spatial and temporal resolution.

More specifically, the procedure consists of the following steps:

I. Selection of all Sentinel-2 images and Landsat 8 with a cloud cover of less than 70 % (White et al., 2014) and acquired between June 1, 2020, and August 31, 2020.
II. Production of a Landsat 8 summer composite (Francini et al., 2023a, 2023b; Kennedy et al., 2014) with a spatial resolution of 30 m, indicating the median temperature for each pixel.
III. Production of a Sentinel-2 summer composite with a spatial resolution of 10 m, indicating the median values of reflectance for the four available Sentinel-2 bands at 10 m spatial resolution: blue (B2), red (B3), green (B4), and near-infrared (B8) (Francini et al., 2024b).
IV. Simple random sampling and selection of 20,000 Sentinel-2 pixels followed by the construction of a training database consisting of 20,000 examples for which the four Sentinel-2 bands (dependent variables) and the Landsat 8 LST (independent variable) are available.
V. Training of the Random Forests algorithm (Breiman, 2001) implemented within Google Earth Engine (https://developers.google.com/earth-engine/apidocs/ee-classifier-smilerandomforest).
VI. Application of the model to each Sentinel-2 image (see point 1) to estimate the temperature based on the four bands.
VII. Maps of air temperature, globe temperature, and WBGT, were created on the basis of a linear regression conducted using ground data, for which all of these three variables were available in addition to LST.

2.4. Model Validation

The performance of the model predicting LST at 10 meters resolution was assessed by randomly selecting 1000 pixels within the study area, but excluding from the pool of available pixels the 20,000 pixels that were used to train the model. This ensures that the data used to validate the model is "never-seen-before", i.e., totally independent from that used to train the model (Francini et al., 2023a, 2023b).

Then, for the randomly selected 1000 pixels, the LST predicted using S2 is compared with the LST acquired by Landsat 8. More in detail, a scatter plot is constructed and the Pearson Correlation Coefficient and the Root Mean Square errors are calculated.

In addition, a linear regression analysis was conducted to explore the relationship between LST and the ground reference dataset (Speak and Salbitano, 2022) and specifically, (i) the air temperature, (ii) the globe temperature, and (iii) the WBGT index. The significance of the regression model as a whole was assessed using the F-test, and the goodness of fit was evaluated using the coefficient of determination (R-squared). The model validation was performed by comparing predicted maps with ground data acquired on the same day. This limitation reduced the number of sites to 22.

2.5. The vegetation effect

Analysis of variance (one-way ANOVA) at the 0.05 level of significance was performed on the WBGT data to assess the effect of the presence/absence of vegetation in all six site categories on the predicted thermal comfort index. The applicability of ANOVA is confirmed by Levene's test and we applied the Tukey Test as a post hoc test. The relationship between the derived WGBT and vegetation parameters was explored using the Pearson method.

The fresh-wood volume (V) of each tree was calculated using two general equations - one for broadleaves (Eq. 2) and one for conifers (Eq. 3) - (McPherson et al., 2016). In the end, also the relationship between V and WBGT was investigated. Statistical analysis was performed using ggplot2 package in R version 4.2.3 and OriginPro8 program (OriginLab Corporation, Northampton, UK).

$$\text{Urban Gen Broadleaf Volume} = 0.0002835 \times DBH^{2.310647} \quad (2)$$

$$\text{Urban Gen conifer Volume} = 0.0000698 \times DBH^{2.578027} \quad (3)$$

3. Results

The automated process of combining Landsat 8 and Sentinel 2 imagery via Random Forests enabled the creation of an LST image of the entire urban area of Florence for the summer of 2020 with a spatial resolution of 10 m (Fig. 2). The performance assessment procedure (Figure A.1) revealed an R^2 of 0,52, a root mean square error of 2,56 °C and a root mean square error percentage of 6,17 %.

Such LST map was significantly positively correlated with all the meteorological variables collected in the field: air temperature ($n = 22$, $r = 0.74$, $R^2 = 0.55$, $p < 0.001$), globe temperature ($n = 22$, $r = 0.83$, $R^2 = 0.69$, $p < 0.001$), and WBGT index ($n = 22$, $r = 0.74$; $R^2 = 0.55$, $p < 0.001$) (Fig. 3). Specific regression equations are in Table 1.

Using the LST predicted map we were able to estimate WBGT at 10 m resolution, once more for the entirety of the Florence urban area (Fig. 4).

The mean WBGT is significantly higher in streets without trees than in tree-lined streets (+1.44 °C), private gardens (+2.42 °C), and public parks (+2.06 °C) (Fig. 5). Furthermore, piazzas show a higher mean WBGT value than streets with trees (+1.37°C), private gardens (+2.35 °C) and public gardens and parks (1.99 °C). Ultimately, the WBGT is

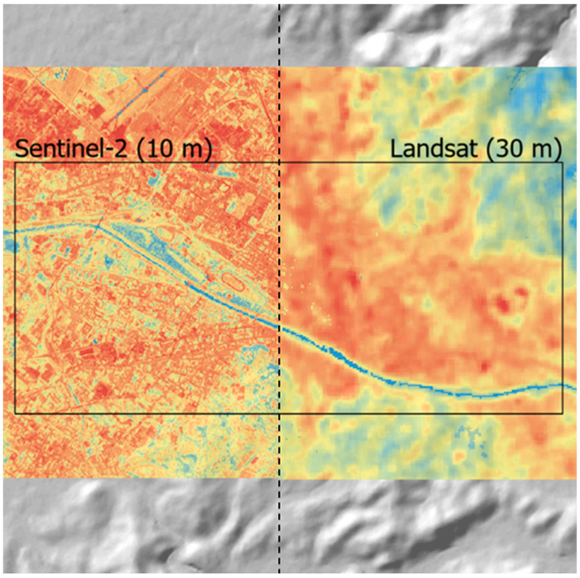

Fig. 2. Comparison between Landsat LST (30 m resolution) and the LST predicted using S2 data (10 m resolution).

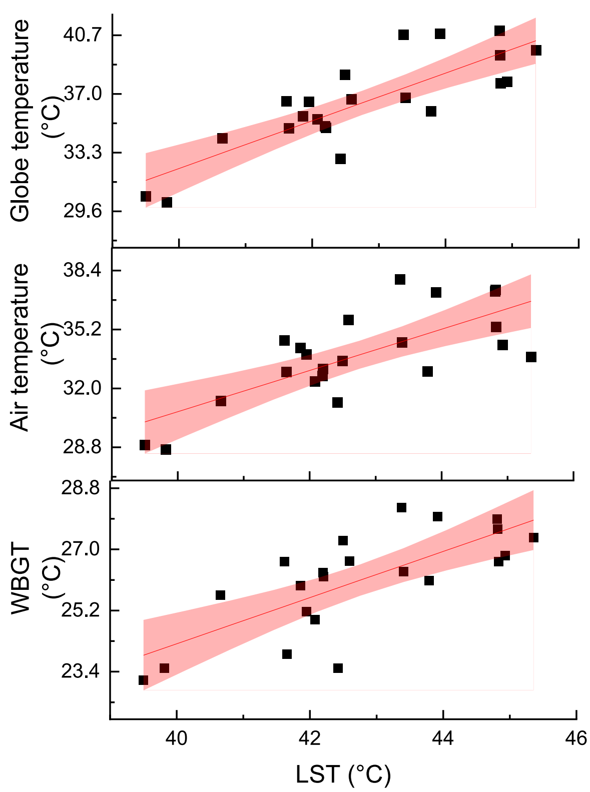

Fig. 3. Linear regression between predicted LST and measured globe temperature, air temperature, and WBGT index.

higher in streets with trees than in private (+0.97 °C) and public (0.61 °C) gardens and parks (Fig. 5).

WBGT derived from the model showed negative correlations (i) with tree height in public parks and gardens ($R = -0.7$, $p < 0.001$) and streets with trees ($R = -0.8$, $p < 0.05$), (ii) with the crown width ($R = -0.7$, $p < 0.001$; $R = -0.8$, $p < 0.001$) in public parks and gardens and streets with trees, (iii) with the crown height in public parks and gardens ($R = -0.7$, $p < 0.001$) and streets with trees ($R = -0.8$, $p < 0.001$) and (iv) with trees' volume (R=-0.4, $p < 0.05$; R= −0.5, $p < 0.01$; R= −0.5, $p < 0.5$) in private gardens, public parks and street with trees (Fig. 6). Equations derived from significant correlations are showed in Table 2.

Table 1
Equations and statistics from linear regression between predicted LST and measured globe temperature, air temperature, and WBGT index.

	Air T	Globe T	WBGT index
Equation	y = a + b*x	y = a + b*x	y = a + b*x
Intercept	−14.04654	−27.85215	−2.94195
Slope	1.11953	1.50368	0.67911
Residual Sum of Squares	58.32406	58.32511	21.3808
Pearson's r	0.74019	0.82833	0.74082
R-Square (COD)	0.54788	0.68614	0.54881
Adj. R-Square	0.52528	0.67044	0.52625

4. Discussions

This study aimed to address the issues associated with the monitoring and quantification of thermal comfort in urban areas by exploiting remote sensing data and enriching the knowledge about the role of green areas and trees in mitigating temperature and in addressing challenges associated with global warming. Specifically, this study seeks to: (1) increase the spatial resolution of land surface temperature (LST) from remote sensing data from 30 m to 10 m, (2) Propose the use of LST as a proxy indicator to identify areas of potential thermal discomfort within urban environments (Goldblatt et al., 2021), and (3) analyze the relationship between thermal comfort and key vegetation characteristics, including tree volume, height, basal area, crown width, and height to crown.

First, achieving higher spatial resolution in LST measurements is essential in urban areas, which are characterized by a mosaic of varied land uses and structural layouts. Standard LST resolutions, such as those from Landsat (30 m), often miss these variations, particularly in smaller green spaces or densely built neighborhoods. This study enhances the spatial resolution to 10 m by coupling Landsat 8 and Sentinel-2 data, making it feasible to capture the fine-grained temperature variations within urban microclimates. Higher-resolution LST maps allow for the identification of local heat spots and more effective cooling interventions, aligning with increasing demands in urban planning for data that can guide targeted action on heat reduction strategies (Gál and Kántor, 2020). The 10-meter spatial resolution dataset we generated helps overcome limitations associated with lower-resolution data that miss critical urban microclimatic features. This enhanced resolution enables a clearer understanding of small-scale temperature variations, especially in cities like Florence, where narrow streets, piazzas, and dispersed vegetation create complex thermal environments. This improvement is important as it equips urban planners with accurate, location-specific data needed for localized cooling strategies in high-temperature zones and complements efforts for better spatial monitoring of UHIs globally (Bartesaghi-Koc et al., 2018).

Second, thermal comfort in outdoor urban spaces is influenced by complex interactions among temperature, humidity, solar radiation, and wind speed. Using the Wet Bulb Globe Temperature (WBGT) index as a metric, this study combines remote sensing LST data with ground-based measurements to create predictive maps of thermal comfort. Unlike standalone LST metrics, the WBGT considers atmospheric conditions, enhancing the model's relevance for real-world human comfort predictions. This integration supports urban planners in identifying zones with high heat stress risk and allows for climate-responsive design interventions that improve public health and livability, especially during heat waves (Uejio et al., 2016). The integration of satellite-derived LST with ground measurements of air and globe temperatures and humidity allows to provision of more actionable and reliable predictions of thermal comfort than LST alone, accommodating the variances in temperature perception among urban residents. In doing so, it also establishes a replicable model for other urban areas where UHI effects are

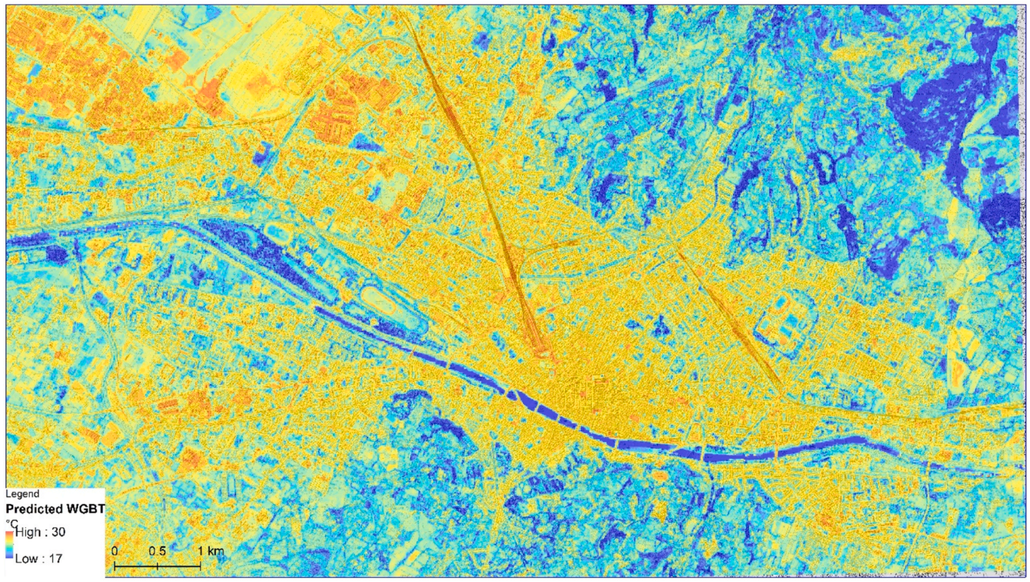

Fig. 4. Predicted average WGBT index map for summer 2020.

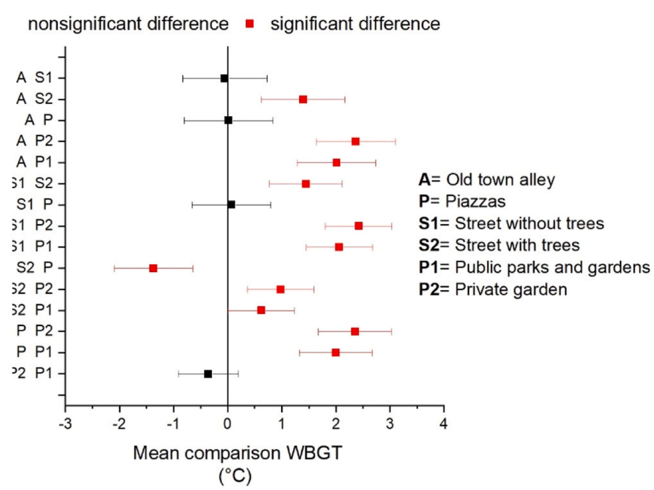

Fig. 5. Mean comparison of WBGT for each site resulting from One-way ANOVA test. Red bars represent significant differences between the means (p value < 0.05).

intensifying, enabling both researchers and policymakers to better identify and manage zones with severe thermal discomfort (Gorelick et al., 2017). A limitation of this study is the lack of analysis of WBGT pattern variations across diurnal cycles and between extreme and average thermal conditions. Prioritizing higher spatial resolution over temporal frequency reflects a necessary trade-off imposed by the limitations of current satellite technology (Logan et al., 2020; Reiners et al., 2024). This also helps minimize biases arising from spatial mismatches between satellite imagery and in situ data. As example, while geosynchronous satellites can provide multiple observations per day, their maximum downscaled spatial resolution (~70 m) is generally insufficient for precise integration with ground-based measurements, which was essential for this study's objectives. In parallel, they have limited coverage because they must remain stationary relative to one point on the planet's rotation axis.

Third, by examining parameters like height, basal area, crown width, and overall volume, we gain insight into the qualities that make certain trees and configurations more effective in cooling urban spaces. Understanding these attributes enables planners to select tree species and plant configurations that maximize cooling efficiency. Furthermore, this aim underscores the role of green infrastructure in enhancing urban resilience, supporting findings that urban vegetation is a critical factor in reducing UHI effects and promoting thermal comfort (Rocha et al., 2022b; Speak et al., 2020). We assessed thermal comfort across different urban vegetation types and linked cooling effects to specific tree characteristics. Notably, we found that tree height, crown width, and overall volume significantly correlate with WBGT reductions, highlighting the importance of morphology in urban cooling strategies. These findings add to existing research by quantifying the impact of tree structural parameters on thermal comfort and further emphasizing the value of maintaining large, dense-canopy species in urban environments to maximize cooling benefits (Hami et al., 2019; Rahman et al., 2020).

The results underscore the substantial cooling effect of vegetation in reducing WBGT, which was consistently lower in green spaces compared to treeless areas. Specifically, tree-lined streets showed WBGT levels that were 1.44 °C lower than those of streets without trees, and private gardens exhibited WBGT values 2.42 °C lower than treeless areas (Fig. 5). These differences confirm the findings of prior studies on the effectiveness of urban vegetation in reducing ambient temperature and thermal discomfort through shading and evapotranspiration (Cornu et al., 2024; Speak et al., 2022).

Further, our analysis of tree characteristics revealed that height, crown width, and volume were inversely correlated with WBGT – thus positively correlated with thermal comfort - with taller and denser canopies providing the most pronounced cooling effects (Fig. 6). These results support existing research indicating that larger trees offer superior shade and cooling, enhancing thermal comfort in open spaces (Lee et al., 2016; Wu and Chen, 2017). Interestingly, the impact of vegetation on WBGT differed by location type; while trees in public parks achieved greater cooling than those in streets, the benefit was moderated by factors like ground material and proximity to traffic, which increase local heat retention (Shashua-Bar and Hoffman, 2000).

The findings of this study also highlight specific areas where targeted cooling interventions could be applied. For instance, the consistently higher WBGT values in piazzas compared to tree-lined streets point to a need for increased vegetation or alternative cooling measures in high-use public spaces. This reflects a growing body of evidence advocating for nature-based solutions in urban planning to counterbalance UHI effects and improve resilience in climate-sensitive areas (Hwang et al., 2023).

While our outcomes highlight the effectiveness of green spaces in

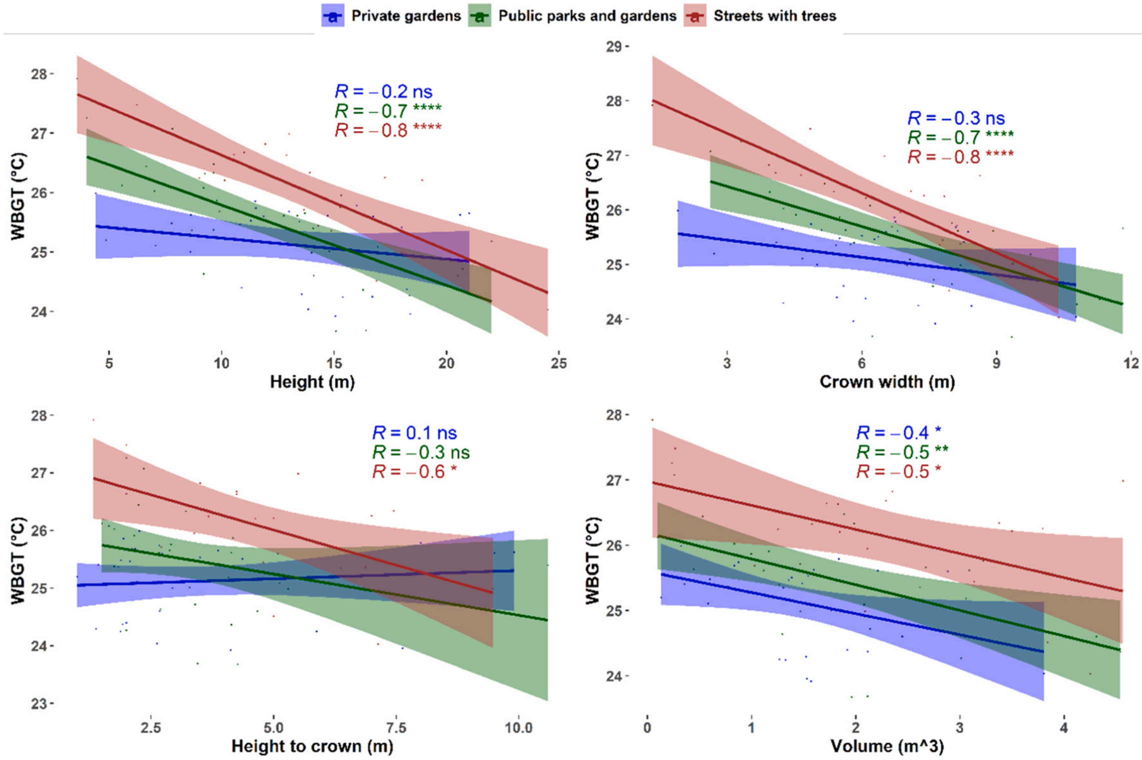

Fig. 6. Correlation analysis between WBGT and total height, crown width, height to crown, and volume for each green site's category. The P-value statistically significant correlation analysis was conducted. Where **** indicates a very high significant correlation; *** indicates high significance, ** indicates medium significance, * indicates low significance, and ns indicates that the variables were not statistically significantly correlated.

Table 2
Equations derived from significant correlations in Fig. 6.

Vegetation parameter	Site category	Equation
Height	Public parks and gardens	y = 27.1–0135x
	Streets with trees	y = 28.2–0.16x
Crown width	Public parks and gardens	y = 27.2–0.245x
	Streets with trees	y = 28.2–0.364x
Height to crown	Streets with trees	y = 27.2–0.244x
Volume	Public parks and gardens	y = 26.2–0.394x
	Streets with trees	y = 27–0.368x

urban cooling, certain limitations should be noted. The 10-meter resolution maps we generated cannot fully represent the extreme thermal conditions found in very narrow alleys or urban canyons, where airflow and radiation vary substantially due to building density. Indeed, such areas require even finer-scale monitoring to accurately assess their unique microclimates (Ali-Toudert, 2021). Future advancements in higher-resolution satellite technology or the inclusion of mobile ground sensors could provide the necessary granularity for effective climate monitoring in these spaces (Tsin et al., 2016). In addition, LST was considered in this study as the primary proxy for assessing thermal comfort. Although informative, it does not fully capture the multifactorial nature of urban thermal environments. Therefore, future research should consider a multi-factor modelling approach that integrates additional environmental variables to enhance the accuracy and robustness of thermal comfort assessments. For example, humidity could be derived from atmospheric reanalysis datasets; however, a spatial resolution comparable to Sentinel-2 is required to ensure data consistency. Wind speed could be inferred from urban morphology metrics, including the Sky View Factor, building height, or surface roughness length. At the same time, radiation effects could be estimated through shadow analysis or geometric modelling based on street orientation and solar altitude. The implementation of these improvements would nonetheless require a new set of ground-based measurements, different from those used in the present study, to provide adequate validation for the additional parameters. Incorporating such complementary datasets in future research would enable the development of more comprehensive and realistic models of urban thermal comfort.

This study's methodology and findings are highly relevant under current climate change scenarios, 14 where the frequency and intensity of heat waves are expected to increase, particularly in the Mediterranean and other temperate urban zones. With global temperature rise projections, the need for precise, high-resolution thermal data is more pressing than ever to guide urban resilience strategies. Our findings support the strategic selection of tree species and canopy structures that maximize cooling effects, thereby contributing to adaptive urban design practices that mitigate the impacts of rising temperatures (Romanello et al., 2021; Kovats and Hajat, 2008).

Furthermore, as cities worldwide commit to resilience and sustainability targets, incorporating high-resolution WBGT and LST data into urban planning can help prioritize interventions in areas with the greatest need. This aligns with broader efforts to promote nature-based solutions that enhance human well-being, reduce health risks, and ensure equitable access to cooler, more livable public spaces in warming cities. Our model offers an accessible and replicable tool for urban policymakers to assess and address thermal stress, particularly as the availability of open-access satellite data expands, furthering the utility and global relevance of this research (Margolis, 2021; Francini et al., 2023a, 2023b).

By mapping spatial variations in LST with fine granularity, planners can identify urban "hot spots" at both macro (city-wide) and micro (neighborhood or block) levels. This aligns with previous studies (e.g., Morabito et al., 2016) that demonstrated how built-up density correlates with LST, and how LST maps can be used to locate priority areas for mitigation efforts such as tree planting or reflective surface treatments. The resulting LST/WBGT maps support the spatial targeting of NbS, such as vegetative corridors and water-sensitive urban design, to optimize cooling effects where they are most needed. As Đorđević (2023) suggests, mapping LST in conjunction with NDVI and imperviousness can help simulate and prioritize blue-green infrastructure interventions to enhance evapotranspiration and reduce heat accumulation.

Urban heat vulnerability data derived from LST maps can be operationalized into zoning overlays. These overlays can guide urban form regulations (e.g., building material selection, minimum vegetation cover, or setback requirements), as also discussed in the work by Echevarría Icaza et al., 2016), which promotes the integration of urban heat indicators like albedo and vegetation into dynamic planning tools and zoning types. LST-based thermal models can serve as spatial decision-support tools for simulating the thermal impacts of alternative urban development scenarios. This capability empowers planners to evaluate trade-offs and synergies between thermal comfort and other planning objectives (e.g., density, mobility, equity), fostering climate-sensitive spatial planning. Visualizations of thermal discomfort based on WBGT/LST mapping can also be leveraged in participatory processes, helping both stakeholders and citizens grasp the tangible effects of heat stress and support adaptive planning responses.

5. Conclusions

The remote sensing model coupling LST and WBGT data in terms of predicting heat stress conditions holds promise for spatializing risks and vulnerabilities to heat-related thermal discomfort and so can support tools based on nature-based solutions to reduce causes of illness and discomfort while enhancing resilience to heat waves and climate change impacts in urban areas. By fostering greater accessibility and replicability, the model facilitates evidence-based decision-making and promotes equitable adaptation strategies to safeguard human health and productivity in a warming world. This study confirms that the presence of well-established green spaces with morphological characteristics that provide ample shade reduces the risk of heat stress and improves thermal comfort for citizens. What makes it innovative is the use of model-derived data, which have yielded results consistent with previous studies based on field-collected data. This demonstrates the reliability and validity of using this model to assess the thermal comfort index and the impact of green spaces on urban microclimate and the well-being of city residents. Specifically, the following three main conclusions can be drawn from this study.

First, our results emphasized the significance of enhancing land surface temperature (LST) resolution from 30 meters to 10 meters, which allows for more accurate assessments of urban microclimates and facilitates targeted interventions to mitigate urban heat island effects and improve climate resilience. Accordingly, the predicted LST map was significantly positively correlated with all the meteorological variables collected in the field: air temperature ($r = 0.74$, $R^2 = 0.55$, $p < 0.001$), globe temperature ($r = 0.83$, $R^2 = 0.69$, $p < 0.001$), and WBGT ($r = 0.74$; $R^2 = 0.55$, $p < 0.001$) (Fig. 2).

Second, the integration of satellite-derived LST data with ground-based measurements to predict thermal comfort using the Wet Bulb Globe Temperature (WBGT) index provides urban planners with actionable insights for identifying heat stress zones and implementing climate-responsive designs to improve public health.

Third, our findings reinforce the importance of specific tree structural traits, such as height, crown width, and volume, in contributing to cooling effects in urban areas. This research underscores the value of selecting appropriate tree species and configurations to enhance urban green infrastructure, thereby promoting thermal comfort and mitigating the impacts of climate change in cities.

Author agreement statement

We the undersigned declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We understand that the Corresponding Author is the sole contact for the Editorial process. He/she is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs.

CRediT authorship contribution statement

Claudia Cocozza: Writing – original draft, Supervision, Conceptualization. **Gherardo Chirici:** Writing – review & editing, Supervision, Conceptualization. **Andrew Speak:** Writing – review & editing, Data curation. **Fabio Salbitano:** Writing – review & editing, Supervision, Conceptualization. **Livia Passarino:** Writing – review & editing, Visualization, Data curation. **Saverio Francini:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Lucia Mondanelli:** Writing – review & editing, Writing – original draft, Methodology, Investigation, 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

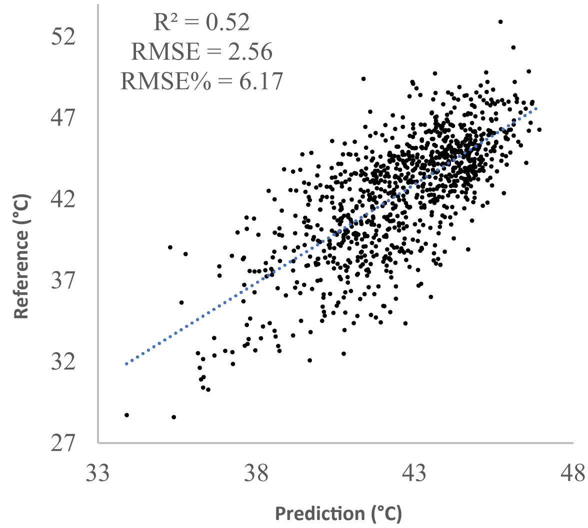

Figure A1. Performance assessment of the LST prediction model

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