Summer thermal comfort of pedestrians in diverse urban settings: A mobile study

Original Citation:

Summer thermal comfort of pedestrians in diverse urban settings: A mobile study / Speak A.F.; Salbitano F.. - In: BUILDING AND ENVIRONMENT. - ISSN 0360-1323. - ELETTRONICO. - ..(2021), pp. 0-0. [10.1016/j.buildenv.2021.108600]

Published version:

DOI: 10.1016/j.buildenv.2021.108600

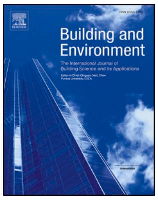
ARTICLE IN PRESS

Building and Environment xxx (xxxx) xxx

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv



Summer thermal comfort of pedestrians in diverse urban settings: A mobile study

Andrew Francis Speak [*], Fabio Salbitano

DAGRI – Department of Agriculture, Food, Environment, and Forest Science and Technology, University of Florence, Florence, Italy

ARTICLE INFO

Keywords:
Urban green spaces
Tree shade
Urban heat island
Climate change
Urban planning

ABSTRACT

Urban planning must consider the outdoor thermal comfort of city dwellers, particularly in cities where climate and the effects of climate change may severely influence human health and wellbeing in increasingly hot summers. The role of the urban forest in ameliorating this problem is decisive. The present study is based on a campaign of meteorological measurements in a large number of sites using a mobile data collection system to allow a human-centred approach. The aim is to quantify the different microclimates and thermal comfort conditions in six classes of urban morphology, discriminating landtypes with or without trees. In the case study of Florence, local physical characteristics of the sites; Sky View Factor (SVF), tree shade, ground surface cover, and canyon effect, can moderate human exposure to potentially uncomfortable thermal conditions during a typical Mediterranean summer. Significant differences in Universal Thermal Comfort Index (UTCI) were observed between treeless piazzas and streets and landtypes with trees or high height to width ratio (narrow alleys). Varying levels of SVF and tree cover in the sites allowed the construction of multivariate models, which revealed that, during common summer afternoon conditions, decreases of SVF by 12.5% or increases of tree cover by 25% can reduce the UTCI by 1°. Additionally, the total site factor, by incorporating temporally integrated sun exposure with the sky view factor, revealed itself a promising variable for future studies to use.

1. Introduction

It is now widely recognised that sustainable urban planning and development must take the outdoor thermal comfort of city dwellers into consideration [1]. When the ambient temperature reaches, or exceeds, the human body temperature of 37 °C, the resulting physiological stress can be detrimental to human health [2]. Increases in heat-related mortality during heatwave events are well-documented [3], with the elderly and city residents disproportionately affected [4]. Extreme air temperature in heatwave events may become exacerbated due to the Urban Heat Island (UHI) effect whereby the energy balance of cities is modified by factors such as the thermal properties of building materials [5], a reduction in the spatial coverage of green areas which provide evapotranspirative cooling [6], and the arrangement of buildings in urban canyons [7,8].

These factors not only cause urban surface and air temperature to be higher than those of nearby rural areas [9] but are also responsible for intra-urban differences in thermal conditions [10,11]. In fact, the complexities of the effect of different urban built forms on the local microclimate has led to a broadening of the UHI concept from a simple urban-rural difference to the appreciation of diverse local climate zones [12]. The outdoor thermal comfort experienced in these different environments can influence not only the health status [13]) but also the behaviour of residents, with some spaces being avoided if they are uncomfortably hot [14]. The liveability and vitality of cities can be greatly improved by a careful consideration of the factors which influence outdoor thermal comfort thus resulting in physical, social, economic, and environmental benefits [15]. These benefits can be incorporated into urban planning and design options which aim to ameliorate the UHI problem and reduce climate change related risks [16].

One of the most important bioclimatic design elements for thermal comfort is greenspace [17]. Trees provide direct shade via interception of solar radiation by the leaf canopy [18,19] which provides a welcome respite for pedestrians [20]; Sun et al., 2021). Additionally, they provide local cooling via evapotranspiration [18] and many studies have demonstrated the impact of various quantities, types and arrangements of urban vegetation on the thermal conditions of public urban spaces (Fan et al., 2015; [21–23]. It is the direct shading factor which most

---

* Corresponding author.
E-mail address: andyspeak33@gmail.com (A.F. Speak).

https://doi.org/10.1016/j.buildenv.2021.108600
Received 31 August 2021; Received in revised form 1 November 2021; Accepted 16 November 2021

Please cite this article as: Andrew Francis Speak, Fabio Salbitano, *Building and Environment*, https://doi.org/10.1016/j.buildenv.2021.108600

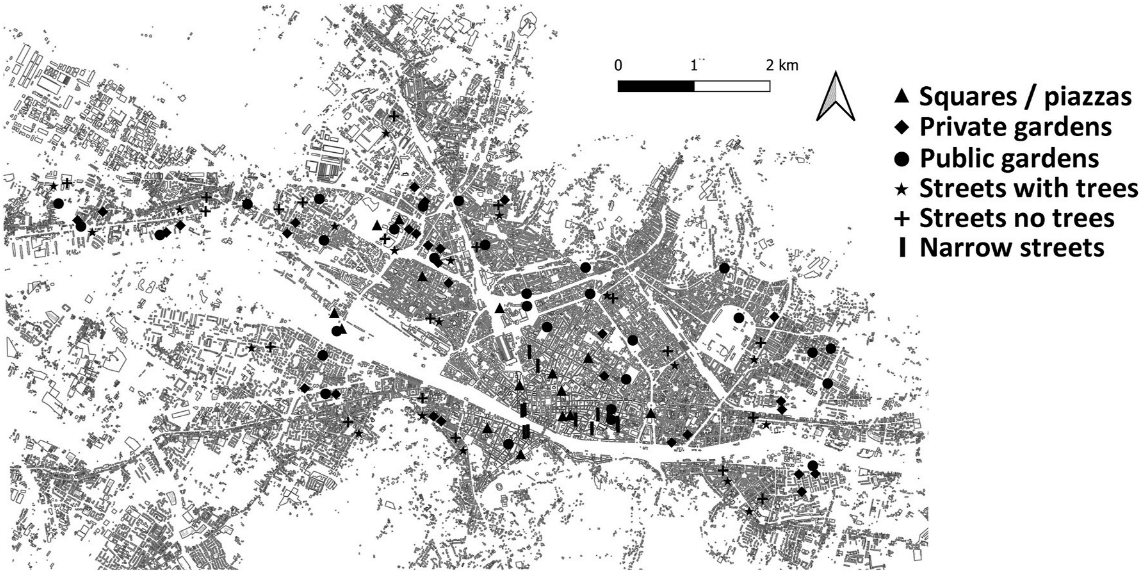


Fig. 1. Distribution of study sites within the city of Florence.

influences the radiation exchange of a person in a certain setting and carries most weight in thermal comfort studies [24,25].

The Sky View Factor (SVF) is a metric which estimates the amount of sun that an area receives via the ratio of visible sky to a hemisphere centred over a fixed point. The mean radiant temperature (MRT) of a location has a significant relationship with SVF, whether the shade comes from trees or buildings [26–28]. Many cities in hot, arid climates were constructed with deep, narrow alleys which reduces the SVF and can reduce summer air temperature by up to 10 °C with respect to a shallow street canyon [29]. The ground surface materials also play a part, and while secondary to shade, may play a significant role in thermal comfort when able to influence surface energy budgets such as the case of irrigated grass [22,30].

Numerous approaches have been used to quantify the spatial variability of thermal comfort within cities [31,32], with the prevailing approach being stationary meteorological stations that measure comfort related variables such as humidity and MRT, which are then used to produce comfort indices such as the Universal Thermal Climate Index (UTCI) [33]). These indices are then mapped to the subjective comfort experienced by interviewing the users of the space by administering standardised questionnaires [20]. These studies often relate the physical characteristics of the locations with the indices, while other studies choose to focus on the human centred perspective, for example using eye level street photos for quantifying tree shade levels (Sun et al., 2021). This human centred approach is important given the high subjectivity of thermal comfort and there is a need to explore further the direct experiences of people as they use the urban spaces. Simply turning a corner into a different street can drastically alter the perceived thermal conditions of a person navigating the city.

Relatively few studies have explored the potential of mobile thermal comfort measuring methods, despite the benefit of improved spatial coverage that they offer, and the ability to address the issue of insufficient fixed measuring points in cities [34]. Tsin et al. [35] attached a meteorological station to a backpack and undertook transects on foot within Vancouver and compared the data to that from fixed stations and remote sensing. The mobile measurements captured more of the infra-urban variability than fixed stations but correlations with land surface temperature were weak and variable. Gallineli et al. [36]; with the CityFeel project, developed a state-of-the-art microclimate monitoring backpack which measured air quality, noise, radiation, temperature, humidity, and wind speed, and took hemispherical images for calculation of the SVF. They found Physiological Equivalent Temperature (PET) varied by location consistently over separate days, with urban morphology being responsible for the variation between locations. Other studies have attached field equipment to bicycles [37,38,34] or carts [39,40] to allow spatial differences in air temperature at the scale of 10^1 m to be detected.

In the present study, we collect microclimate relevant meteorological data from transects using a mobile data collection system within a large number of sites. The aim is to quantify the different microclimates and thermal comfort conditions in six classes of urban morphology. We demonstrate how local physical characteristics of the sites; SVF, tree shade, ground surface cover, and canyon effect, can moderate human exposure to potentially uncomfortable thermal conditions during a typical Mediterranean summer. Different levels of green space in these sites facilitates the quantification of a hypothesised linear effect of tree canopy cover on local cooling. Utilising a mobile station allows an investigation which mimics the actual, dynamic lived experience of urban space, and thus provides results which are translatable and relatable for practitioners and the general public.

2. Methodology

2.1. Site selection

The city of Florence is situated on a plain to the southwest of the Apennine mountains in central Italy. It has a humid Mediterranean climate and is characterised by hot, dry summers. Average high temperatures reach 31.5 °C in the summer, with solar radiation maxima between 1100 and 1400 Wm^{-2} [41]). Variability in green space distribution has been shown to influence intra-urban thermal conditions [10], and rising air temperatures in the summer have been associated with increases in emergency calls for cardiovascular events and psychiatric disorders [42]. The city thus represents a study site where the issue of thermal comfort is very important, not just for residents but for the millions of annual tourists. 18.8% of the land cover is green space resulting in 20.7 m^2 per capita in 2014 (Italian national average is 31.2 m^2 per capita) [43].

The potential area for study was restricted to the city centre and suburbs consisting of commercial and residential areas and excluding industrial zones, agricultural land and low-density residential areas on the periphery (Fig. 1). Six categories of outdoor landtypes were chosen for the study. Three non-green categories: treeless piazzas, two-lane streets and deep, narrow streets (henceforth named alleys), the latter

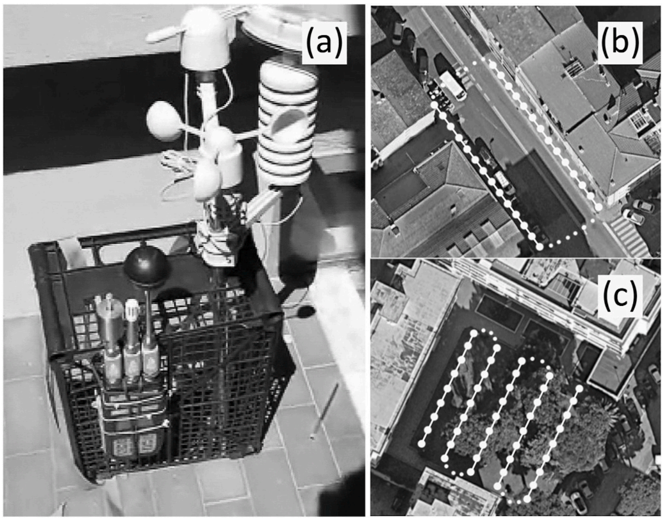


Fig. 2. a) Mobile meteorological monitoring station for measuring wet bulb, dry bulb and globe temperature alongside humidity and wind speed, and schematic diagrams of the walking paths taken in b) streets and c) gardens, parks and piazzas.

being a common feature of the historic city centres of Mediterranean cities. Three green categories: public parks, private gardens (usually belonging to residents of condominiums), and tree-lined two-lane streets. The piazzas were not restricted to city centre historic piazzas, but included also open, treeless areas of parks with grass surfaces. An initial desk study was undertaken to develop a list of potential sites around the city from which sites were chosen randomly.

Florence contains a major river and several minor tributaries within the city, therefore, to reduce potential cooling effect from water bodies, sites were rejected if they were adjacent to these features. The three street categories were sampled by selecting a 30 m long section of the street, and the gardens and piazzas were either studied in their entirety or, in the case of spaces exceeding 0.3 ha in size, a spatial subsection was studied. Permission was always requested to enter private gardens and if permission was denied a new random study site was chosen.

2.2. Data collection

Fieldwork was carried out on 24 days between June 29, 2020 and August 28, 2020 between the times of 11.30 and 17.30. A day was considered suitable for fieldwork if the forecast was for cloudless skies and low winds. A mobile meteorological monitoring station was constructed such that it could be worn as a backpack and carried around the study sites, taking measurements at the relevant body height of 1.5 m. The station primarily consisted of a WBGT (Wet Bulb Globe Temperature) data logger (DeltaOhm HD32.2) with 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. Added to this were sensors for humidity (1–99%, 1%) and wind speed (0–50 ms^{-1}, 0.1 ms^{-1}) (PCE Instruments FWS-20), and all equipment were attached to an open lattice plastic crate of depth 30 cm, to minimise obstruction of air movements and to minimise any influence of human body temperature on the sensors.

The researcher, wearing the mounted station, walked very slowly (approx. 1 km h^{-1}) for 30 min around the whole study site in order to minimise the creation of air movements related to normal walking speed, retracing steps if the area was covered within the time period (Fig. 2b and c). For the street study sites the researcher walked up and down the pavements, crossing the road after the completion of one side, repeating as necessary within the 30 min time period. A 5 min adjustment period was included at each site before data logging started and the log interval was 15 s. All data were then averaged for the 30 min period, which overcomes issues with sensor lag [44]. This is particularly relevant for the globe thermometer which can take a couple of minutes to equilibrate to sudden changes in radiation flux, so the average provides an estimate of the integrated thermal conditions within the space.

A Nikon D300s 12.3 Mp digital camera equipped with a hemispherical 180° lens (AF DX Fisheye Nikkor) was used to take upward photographs at a height of 1 m, oriented north in the centre of the study site, pre-calculated as the centroid using QGIS (version 3.12.1). The images were later processed and analysed using the Winscanopy Pro software [43]version) which allows the calculation of the canopy openness, which corresponds to the SVF, here represented as a percentage. The total site factor (TSF) was also calculated which is a ratio to quantify the incident radiation that penetrates below canopy during the growing season calculated by average daily radiation received under canopy divided by that received over canopy.

The height and diameter at breast height (DBH) of all the trees in the green sites were measured using a vertex IV laser hypsometer (Haglöf Inc.) and a DBH measuring tape, respectively. Additional measures included the average of the crown width in two dimensions and the trees were also identified to species level. The tree density was calculated as trees per hectare. A visual estimate of the percentage floor cover by grass, bare soil and impermeable paving was made to evaluate the potential influence of evapotranspiring surfaces within the site.

Geospatial data were downloaded from the province of Tuscany's online portal [45]). A surface elevation model was used to calculate the height to width (HW) ratio of the streets. This was also calculated for the piazzas and parks/gardens, where possible, by taking the average width of the site and the average heights of surrounding buildings. This was not possible for all sites, for instance piazzas in parks, so a value of 0.1 was given to these open spaces. An orthophotograph from July 2019 with a high resolution of 20 cm was used to estimate percentage tree canopy cover in the green sites by a manual pixel counting method.

Multispectral Sentinel 2 data were acquired from the Copernicus hub with a search criterion of less than 15% cloud cover. The data were from June 23, 2019 at 10:10 and had a resolution of 10 m. The Normalised Difference Vegetation Index (NDVI) was calculated using QGIS which created a vegetation layer for the city. This layer was further processed by selecting only pixels with a NDVI greater than 0.4, which represents moderate to high vegetation density [46]. Finally, the amount of vegetation within a 250 m radius of each site was calculated.

2.3. Index calculation

We chose to use WBGT and the UTCI to estimate the thermal comfort conditions at the study sites, with most analyses using UTCI due to the clearer stress category scale for comparative interpretation of results. We chose WBGT because it is easy to calculate and requires few variables, therefore it is easily transferable to other studies. UTCI was chosen for its sensitivity to changes in ambient stimuli and the fact it represents the state of the art of thermal indices [47]. WBGT in external environments is calculated by:

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

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 nonacclimatised people.

The UTCI uses a multi-node model for human heat balance in conjunction with measured microclimatological and clothing level (CLO) data inputs alongside metabolic rates [48,33]. The indices were calculated with the free software BioKlima 2.6 (http://www.igipz.pan.pl/Bioklima-zgik.html). UTCI categories of 9–26 °C (no thermal stress), 26–32 °C (moderate stress), 32–38 °C (strong stress) and 38–46 °C (very strong stress) were used in the analysis. The default settings from the Rayman model [25] of a 35-year-old male of height 1.80 m, weight 75 kg, CLO level 0.4 and activity level of 80 W (light activity) were used as parameters. Mean radiant temperature (MRT), which is used in the calculations, was estimated from measured globe thermometer temperature using equation (1) [49]:

$$MRT = \left[\left((Tg + 273.15)^4 + \left(1.1{*}10^8{*}\ Va^{0.6}\right)\right) \div \left(\left(\varepsilon{*}\ D^{0.4}\right){*}(Tg - Ta)\right)\right]^{1/4} - 273.15 \qquad (2)$$

where Ta and Tg are in ^{o}C, Va is wind speed in m s^{-1}, D is globe diameter in mm and ϵ is globe emissivity. In low wind conditions (0–6 ms^{-1}), using globe thermometers to estimate MRT is an acceptable method, used in several studies [19,50], especially when data are averaged to smooth the effect of sensor lag.

2.4. Data analysis

Sites were visited at different times of the afternoon, therefore an adjustment to the data was necessary to make them directly comparable. Independent climate data of air temperature, humidity, wind speed and solar radiation were obtained from Florence University meteorological station with a time period of 15 min [41]. An initial check was undertaken to ensure the station and WBGT measuring device data were correlated by leaving the device in a suburb of Florence (approx. 3 km from the station) between 11.30 and 17.30 to match the field measurement period, on two days. One day in full sun and one in full shade.

For each study day the station air temperature at the midpoint of each site visit time period was registered and an adjustment factor derived which transforms the temperature at the midpoint into that recorded at 14:00, chosen because it is a central time within the range of study times. These adjustment factors were then applied to the dry bulb and globe temperatures for that day. The adjusted site data are thus rendered more comparable as they approximate data taken at the same time of day.

All data analyses were carried out using R version 4.0.2 [51]. The effect of the different site landtypes was assessed using Kruskal Wallis chi-square with Benjamini-Hochberg post-hoc tests.

Multiple regression models were constructed which assess the relationship between site characteristics (tree cover, SVF, HW ratio, ground surface cover, TSF, vegetation percentage in 250 m radius) and meteorological variables (humidity, air temperature and wind speed from both mobile and fixed stations, and solar radiation and pressure from the fixed station) with UTCI as the dependent variable. The relative importance of all the predictor variables was first determined (as a relative percentage) using the 'relaimpo' package which assesses the contribution of predictors to the R^2 averaged over orderings [52]). A stepwise regression approach was used to determine the best models using Akaike Information Criterion (AIC) and testing the effect of site landtype and a binary tree vs no tree site category within mixed models. These models were then further refined by assessing the theoretical sense of the model, significance of variable inclusion (p values) and collinearity of variables determined using Variance Inflation Factors (VIF). The best models were used to visualise the effect of varying tree canopy cover and SVF on UTCI keeping any other variables constant.

3. Results

The weather conditions on the study days were very similar with average maximum solar radiation 1134 W m^{-2} (StDev 68), maximum air temperature 32.2 °C (StDev 2.1), relative humidity 37.2% (StDev 6.2) and wind velocity 2.2 ms^{-1} (StDev 1.2). The correlations of the WBGT data logger with the university stationary meteorological station were all high and significant, indicating the suitability of using the station data to standardise the field measurements. Specifically, for the full sun trial the correlations had an R of 0.77 ($p < 0.001$) for Ta and 0.87 ($p < 0.001$) for Tg, and for the shade trial, 0.94 ($p < 0.001$) for both Ta and Tg. Tw was observed to remain constant in both sun and shade therefore no adjustment was made to the study Tw data. The adjustment factors ranged from 0.92 to 1.12 with a mean of 1.01.

A total of 126 sites were visited with sizes ranging from 0.05 to 0.29

Table 1
– Key features of the different landtypes.

	Piazzas N = 15	Alleys N = 12	Streets without trees N = 20	Streets with trees N = 20	Public gardens N = 30	Private gardens N = 29
H/W ratio	0.48 ± 0.25	3.11 ± 0.61	1.06 ± 0.53	0.75 ± 0.32	0.31 ± 0.17	0.45 ± 0.20
Sky View Factor	0.64 ± 0.15	0.09 ± 0.03	0.49 ± 0.15	0.34 ± 0.16	0.33 ± 0.17	0.25 ± 0.15
Vegetation in 250 m radius %	16.0 ± 20.2	3.6 ± 3.5	17.5 ± 7.8	19.8 ± 8.6	23.4 ± 14.4	26.6 ± 11.0
Live grass %	1.3 ± 2.9	0.0	0.0	0.5 ± 2.2	14.0 ± 17.9	44.5 ± 32.9
Dead grass %	21.7 ± 37.4	0.0	0.0	0.5 ± 1.5	28.0 ± 29.8	35.3 ± 31.2
Bare soil %	3.7 ± 7.2	0.0	0.0	2.8 ± 3.8	20.8 ± 25.8	13.3 ± 21.3
Paved %	73.3 ± 45.8	100.0	100.0	96.3 ± 5.6	37.7 ± 37.4	5.0 ± 15.1

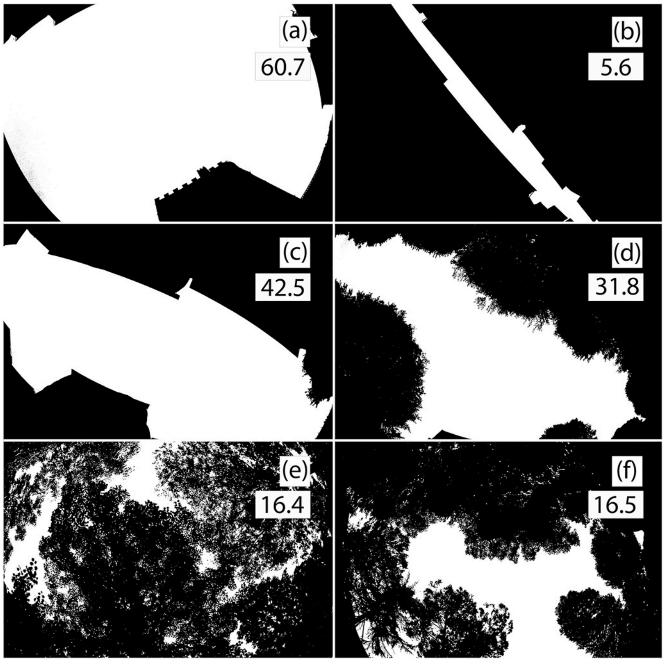


Fig. 3. Processed hemispherical images from each site landtype used in calculating sky view factor and total site factor. A) Piazza, b) alley, c) street without trees, d) street with trees, e) public garden, f) private garden.

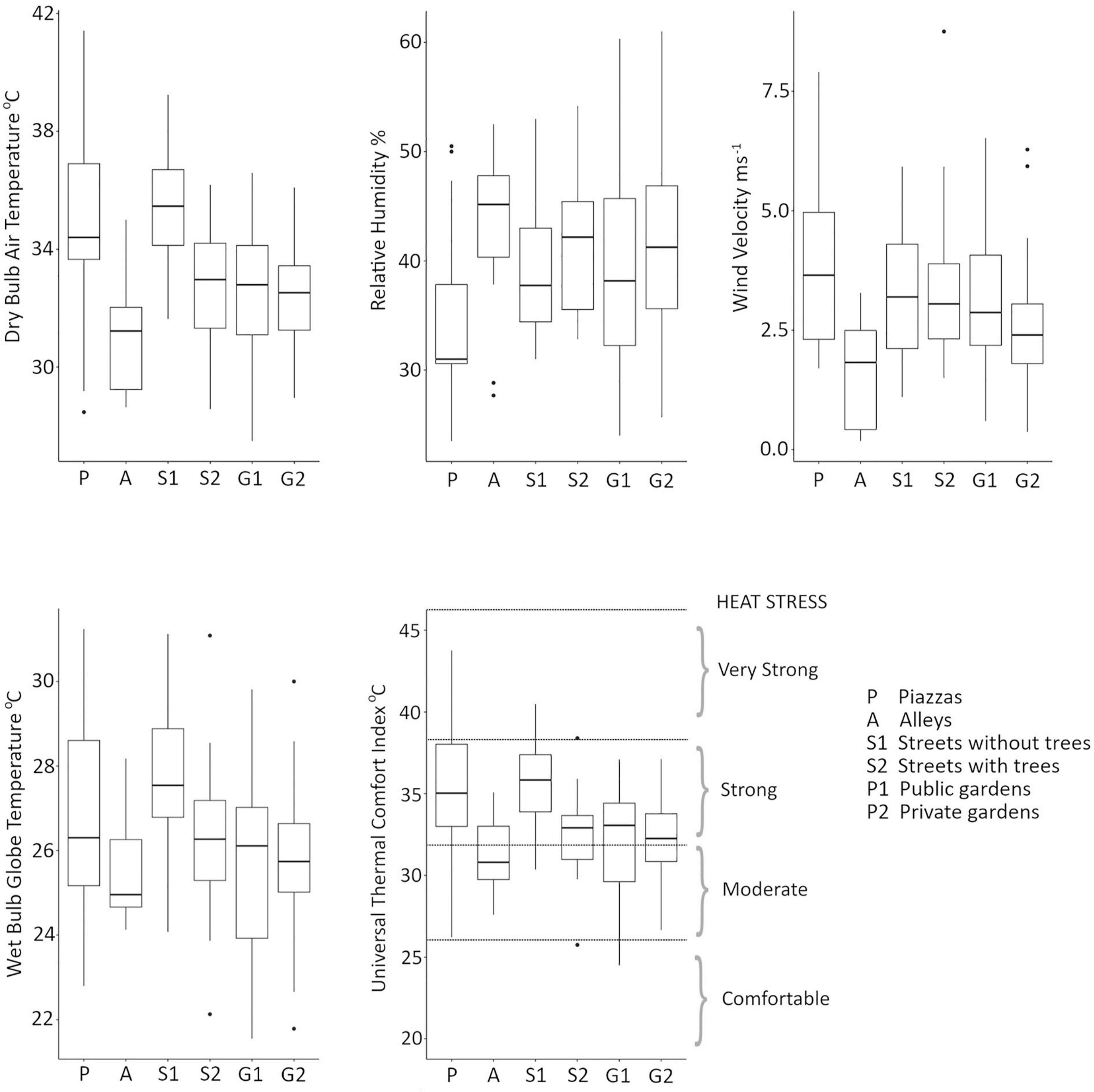


Fig. 4. Boxplots to show the difference in selected meteorological variables and thermal comfort indicators between the site types.

ha (mean 0.13). The alleys were between 70 and 340 m^2 in area and were oriented at least 20° from 0° (north – south orientation).

3.1. Landtype differences

The different site types varied considerably in physical characteristics (Table 1). Alleys consisted of deep urban canyons evidenced by a high H/W ratio and low SVF (Fig. 3b). Streets with trees were generally wider than streets without trees due to the space needed for planting, and the most open spaces were the gardens and piazzas (Fig. 3). The presence of trees in green spaces lowered the SVF in comparison to treeless streets and piazzas. The lack of vegetation in the city centre is reflected in the lower values for vegetation in a 250 m radius for the alleys, a uniquely city centre feature. Most of the piazzas were paved and streets with trees generally had low amounts of permeable ground cover existing solely in the tree pits. Public parks suffered more from a lack of irrigation, reflected in the quality of the grass cover, and contained more paved areas than private gardens.

Table 2
– Key features of the green landtypes, range in brackets.

	Streets with trees	Public gardens	Private gardens
Tree cover %	56.7 ± 23.7 (6.6–92.1)	58.7 ± 24.7 (15.6–99.0)	63.4 ± 19.5 (13.7–93.7)
Height m	13.3 ± 4.7 (3.6–24.5)	12.3 ± 4.7 (4.0–22.0)	13.0 ± 4.4 (4.4–21.0)
DBH m	43.5 ± 14.5 (8.1–65.2)	38.2 ± 13.9 (12.3–66.1)	36.4 ± 10.0 (12.2–60.1)
Crown width m	6.6 ± 2.0 (1.3–10.4)	6.8 ± 2.5 (2.6–11.8)	6.0 ± 1.8 (1.9–10.8)
Trees per hectare	94.3 ± 39.4 (48–118)	112.6 ± 42.7 (53–233.3)	169.4 ± 74.3 (76.1–395.8)
Species richness	1.5 ± 0.5 (1–2)	4.5 ± 2.3 (1–9)	6.1 ± 2.2 (1–11)

Table 3
Correlations of physical site characteristics for the green landtypes with meteorological variables and thermal comfort indices.

	Dry bulb air temperature	Globe temperature	Humidity	WBGT	UTCI
Tree cover %	−0.30**	−0.54***	−0.14	−0.37***	−0.32**
Diameter at Breast Height m	−0.34**	−0.51***	−0.09	−0.32**	−0.36***
Height m	−0.30**	−0.45***	−0.05	−0.26*	−0.35**
Crown Width m	−0.23*	−0.42***	−0.07	−0.22	−0.24*
Trees per hectare	−0.02	−0.04	−0.14	−0.09	−0.01
Sky View Factor	0.13	0.35*	0.12	0.24*	0.14
Total Site Factor	0.21	0.41***	0.13	0.27*	0.25*
Species	−0.16	0.27*	0.13	0.10	0.24*
Using all data:					
Sky View Factor	0.39***	0.59***	−0.11	0.33***	0.32***
Total Site Factor	0.43***	0.62***	−0.11	0.34***	0.39***

Fig. 4 illustrates the main differences in micrometeorological conditions between the site types. Air temperatures were generally a couple of degrees higher in the piazzas and treeless streets, lowest in the alleys, and very similar in the green spaces. Humidity levels tended to be higher in the alleys and lowest in the piazzas, with the reverse pattern for wind speeds. The trends for the calculated thermal comfort indices are very similar, with the majority (89%) of sites falling in the moderate to strong UTCI heat class. Only sites from the piazza and treeless streets categories registered UTCI values linked to very strong heat stress, and only sites from public parks and treelined streets with comfortable values. The differences were highly significant (Kruskal Wallis $\chi^2 = 27.5$, $p < 0.001$) with a post-hoc test revealing pair-wise differences between treeless streets and all the green site types plus alleys, and between piazzas and the two garden site types plus alleys.

3.2. Landtypes and cooling

Table 2 reveals that the three green landtypes were very similar in tree cover percentage, and the physical dimensions of the trees. Tree planting density and species richness were much higher in the gardens than the monospecific rows of street trees, with private gardens being the most densely planted and species rich. The top five species, constituting 51% of the measured trees and encountered in all three green landtypes were, *Celtis australis*, *Tilia x europaea*, *Platanus x acerifolia*, *Quercus ilex* and *Pinus pinea.*

The correlations (Table 3) suggest significant negative relationships exist between tree cover and the three tree dimensions and air temperature, globe temperature and the indices, with the strongest relationship for Tg. Increasing tree cover and size did not significantly affect the humidity at the sites. Low correlations were noted between the measures of solar penetration (SVF and TSF) and Tg and the indices, but these improve considerably when the data from sites without trees are included. Species richness seems to have an effect on Tg and UTCI but it is weak and the direction of the relationship is positive. When these relationships are modelled with linear regressions (Fig. 5) the models fail to explain much of the variance observed, with very low R^2 values. There is a negative linear relationship between HW ratio and UTCI for sites without trees, and the presence of trees generally lowers the UTCI in comparison with sites without trees at HW ratios less than 1 (Fig. 5f).

There was no correlation between UTCI and the amount of ground covered by live grass ($r = -0.15$, $p = 0.09$), dry grass ($r = -0.06$, $p = 0.49$), bare soil ($r = -0.03$. $p = 0.71$) or paving ($r = 0.14$, $p = 0.11$) for all the landtypes. This did not change when only the green landtypes were considered. Nonetheless grass and paving cover variables were included in the multivariate modelling.

3.3. Multivariate models

The mixed effects models showed that very little of the variance was explained by either of the random effects of site land type or sites with trees versus no trees. Therefore, the optimum linear multiple regression model was sought using the best combination of variables, without the random effects. Table 4 shows that the variables of ground cover, species richness, solar radiation and percent vegetation in a 250 m radius contributed little to the models, while Ta, Va and site openness variables contributed the most.

Models were created which included weather data from the fixed station with some site characteristic variables in order to make the models applicable to situations where in situ meteorological data may not be available. Tmrt was not included, even though it is the best predictor for UTCI, due to the difficulties associated with measuring it, thus making the models useable with commonly accessible urban meteorological data. The best model using data from all the sites to predict UTCI consisted of fixed station air temperature and humidity, mobile station wind speed, and SVF (R^2adj $= 0.57$, $p < 0.001$, AIC $=$ 565.9). The best model using data from the sites with trees only consisted of fixed station air temperature and humidity, mobile station wind speed and tree cover (R^2adj $= 0.74$, $p < 0.001$, AIC $= 287.6$). VIF were below 2 for all variables in both models indicating no potential issues of collinearity. Both models and all predictor variables were significant at $p < 0.001$. Given the higher relative importance of mobile station air temperature (Table 4), its replacement of fixed station air temperature in the models improved the performance of the all-data SVF model (R^2adj $= 0.65$, AIC $= 540.2$). However, it was decided to use the more generally applicable fixed station data for replicability.

The two models were used to simulate how the physical parameters influence UTCI when wind speed is kept at 2 m s^{-1}, at three different summer air temperatures and two different humidity levels (Fig. 6). A sensitivity analysis, altering each predictor variable by 20%, showed the dependent variable of UTCI was most sensitive to changes in air temperature (alterations of ~18% compared to alterations of 1–4% with the other variables).

4. Discussion

The results of this study indicate clear differences in the summer meteorological variables measured in six categories of outdoor urban environment. Average differences in air temperature of over 2 °C were observed between treeless streets and piazzas and the three landtypes with trees, demonstrating the ability of tree shade and evapotranspiration to cool the local environment. The subsequent differences in the calculated UTCI between these spaces were significant and provide further evidence for the complex spatial patterns of thermal comfort within local microclimate zones of cities related to the location and type of infrastructural elements.

The physical greenspace characteristics varied little between the three green landtype categories, however, private gardens were more likely to include a wider variety of species and provide irrigation for the vegetation. This did not appear to increase the cooling capability of these spaces over public gardens and, in fact, there was some indication of a positive relationship between species richness and MRT. This was unexpected, as the currently accepted theory is that an increase in diversity would increase cooling by creating a heterogenous, multi-layered canopy which intercepts more radiation [53]. The private gardens varied in their structure, from purely ornamental to functional park-like spaces for residents of the condominiums, therefore any cooling influence of species richness may have been obscured by the

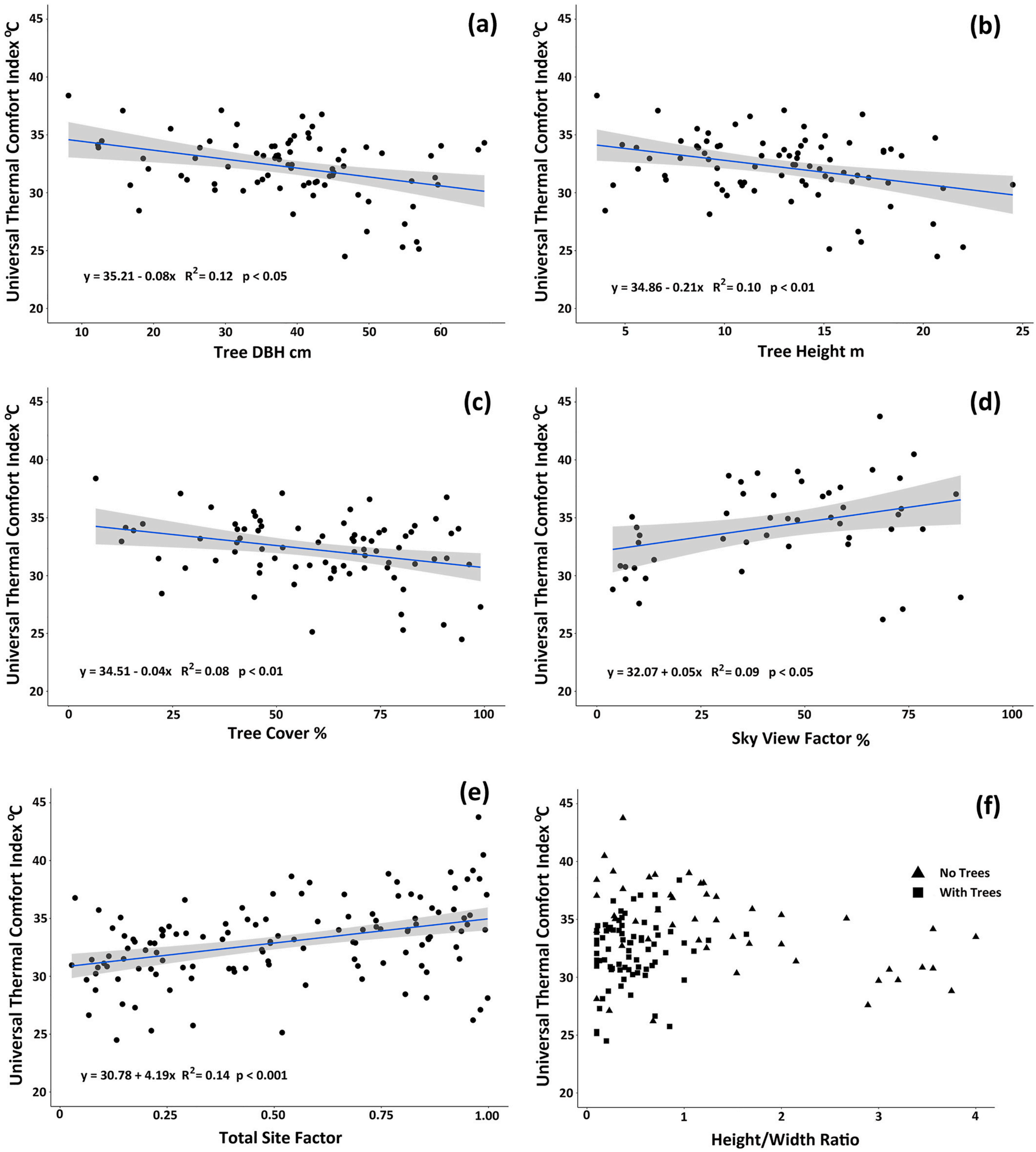


Fig. 5. Variation of the thermal index UTCI by a) average tree diameter, b) average tree height, c) tree canopy cover, d) sky view factor, e) total site factor, and f) Height/width ratio. a) to c) represent data from green sites only, d) from non-green sites only and e) to f) using all data. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

diversity of sites and planting arrangements. The similarity in ambient conditions between private and public gardens is more than likely due to the similarities in tree height and canopy cover.

The tree morphology variables of height, DBH and crown width all showed significant correlations with cooling, as they are the underlying structures contributing, directly or indirectly, to the total canopy cover of a site. This result reaffirms the need for well-established urban forests with large, healthy trees in order to maximise the ecosystem services provided in cities [54]). Newly planted trees with small crowns with low leaf density will provide little cooling and may take decades before they provide the cooling effects observed in this study. While not significant, the areas with trees registered lower average wind speeds and higher humidity than piazzas and treeless streets (Fig. 4), an effect of trees concurrent with other studies [55].

Table 4
Relative importance of the model predictor variables for UTCI.

Variable	All data
Air temperature (mobile station)	44.5
Air temperature (fixed station)	10.2
Wind speed (mobile station)	5.1
Total site factor	3.5
Sky view factor	2.5
Height	2.4
DBH	2.4
Tree cover	2.2
Humidity (mobile station)	2.0
Height/Width ratio	1.8
Crown width	1.8
Pressure	1.5
Humidity (fixed station)	1.5
Wind speed (fixed station)	1.4
Species, Paving cover, Grass cover, Trees per hectare, Solar radiation, Vegetation 250 m radius	<1

The potential cooling effect of ground surfaces on comfort relevant indices was not apparent within this study. The change of surface cover from paving or bare soil to grass can certainly have a strong effect on surface temperature, especially in combination with tree shade [23] but the translation of these to perceivable thermal comfort effects is less conclusive [56]. The differences in MRT, important for comfort, between a shaded location and one in full sun far outweigh any influence on MRT from the surface covering and the present study was not able to discern an effect from the ground surface covering on comfort. This is potentially a consequence of the long, hot periods without precipitation in Florence which reduces grass areas to bare soil and dead grass, which then act more like concrete surfaces thermally. We must conclude, like other studies, that shade is the most important element for comfort [40] and future research is needed to quantify the impact of ground surface materials.

There was no apparent influence of the quantity of vegetation in a 250 m radius of the sites, in contrast to a previous study in Florence [57] which found a 10% increase in green in that radius could reduce the number of hours of summer discomfort by 30. They investigated a longer, seasonal time scale using air temperature and humidity from fixed stations. The shorter timescales and inclusion of MRT, which varies greatly on very small spatial scales within cities, would perhaps not capture this wider scale effect. In fact, this contrast highlights the different scales upon which intra urban differences in comfort indices operate, with a single tree influencing the surface energy budget directly beneath it, up to a park acting as a cool island with impacts on the surrounding neighbourhood [58,59].

The importance of SVF for localised cooling was demonstrated clearly in this study by the inclusion of narrow streets (alleys) with HW ratios over 2 leading to low SVF. This structure, combined with orientations away from the north-south axis, prevents solar radiative forcing and subsequent re-irradiation of long wave energy from building and floor surfaces. This resulted in alleys having the lowest average UTCI values of all the sites, despite the higher humidity and low penetration of cooling breezes in these spaces. The use of deep urban canyons is a well-established adaptation to hot climates, exemplified by the medinas of north Africa, but they are often colder in winter due to low solar access [29]) and they are unlikely to be considered in modern urban planning.

Based on the correlations, the strongest relationship appeared with TSF. This is probably due to the fact that TSF is a measure of not just the SVF but also takes into consideration the path of the sun during summer and thus finetunes SVF to include actual solar radiation. It may thus better estimate the time-integrated solar radiation a space receives over the course of a day and future outdoor thermal comfort studies might benefit from the inclusion of this metric instead of SVF. However, its calculation is not trivial without dedicated software like Winscanopy.

Few studies to date have produced general rules linking greenspace quantity to local thermal comfort. The large number of sites with varying amounts of tree cover and SVF has allowed the production of multivariate models capable of demonstrating a simple linear relationship between these two elements and the comfort index UTCI. The models are promising, with high R^2 values and variable significance.

There is a clear influence of SVF on thermal comfort, in line with past studies [60,24,26,28]. A SVF of 0.63, common in city squares and piazzas was predicted to determine the boundary between 'very strong' and 'extreme' heat stress at 50% humidity and 40 °C air temperature, and a SVF of 0.28 demarcated 'strong' and 'very strong' (50% humidity and 35 °C) (Fig. 5). In terms of the model, an increase in SVF of 0.13 increased the UTCI by 1 °C approximately. A study in Hong Kong found

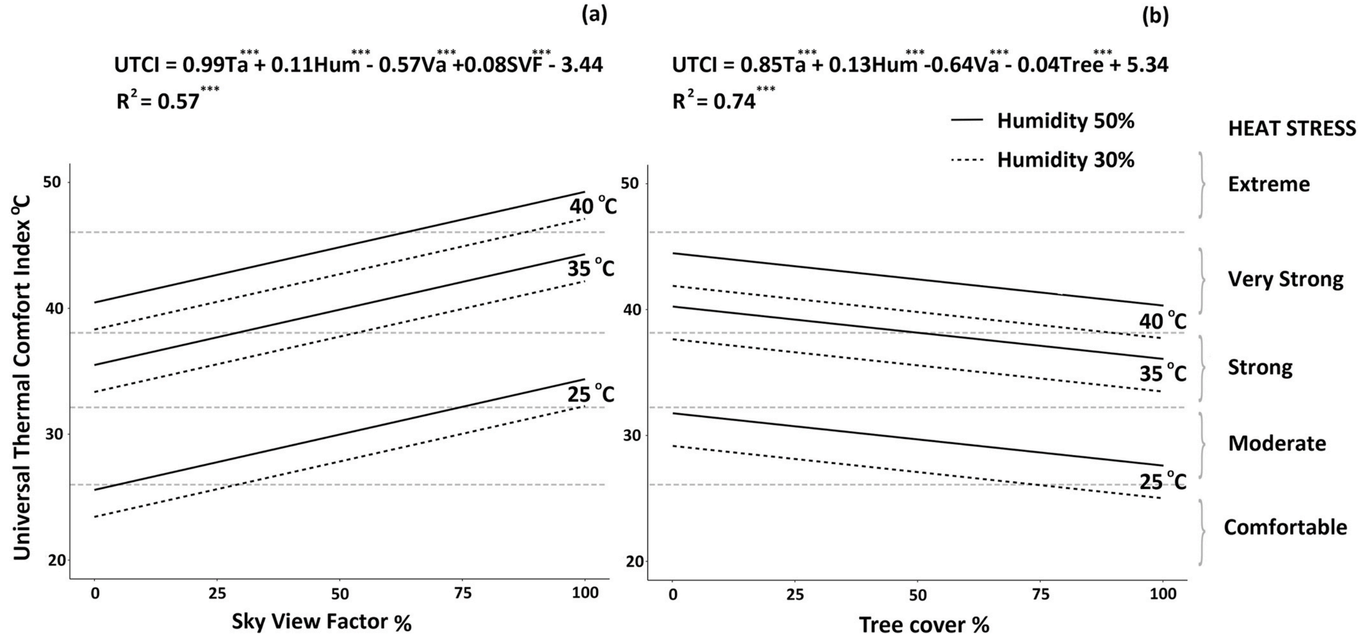


Fig. 6. Simulations of the effect of physical site characteristics on UTCI when keeping climate variables constant for a) sky view factor (SVF) and b) tree cover (Tree, using only the green site data). Ta = air temperature, Hum = humidity, Va = wind speed, *** = $p < 0.001$.

an increase in the 100 m neighbourhood average SVF of 0.1 increased the measurable UHI effect by 0.7 °C [60], though comparisons are made with caution as UTCI is different than UHI effect [61]. showed a 10% reduction in SVF can lead to a lowering of Tmrt and Physiological Equivalent Temperature (PET) by 3.8 °C and 1.4 °C respectively.

In the case of the tree cover model, a cover of 54% was able to reduce the stress category from 'very strong' to 'strong' at 50% humidity and 35 °C. Maximum temperatures in the city between 2014 and 2019 were greater than 31 °C on 82 days per year on average (25 days above 36 °C, and 3 days above 40 °C) [41]. The severity of these frequent hot periods may thus be ameliorated by achievable levels of tree cover. The UTCI was able to be reduced by 1° for every 25% increase in tree cover approximately. This is not too distant from the 0.8 °C cooling predicted by a 10% increase in the ratio of green to built in a model simulation [62]. A meta-analysis of observational studies of urban greenery showed that parks are on average 1 °C cooler than non-vegetated sites [63].

The summer in which field work took place was typical of recent summers in Florence in terms of maximum temperatures [41] and it must be noted that a number of field sites in piazzas and treeless streets recorded thermal stress levels within the 'very strong' category for UTCI, indicating these spaces may be avoided or used unwillingly in such a typical summer. These areas classed as strong heat stress will only become more abundant during the more frequent heat wave events predicted for the future. In contrast, several sites in parks and streets with trees registered 'comfortable' thermal conditions and reinforce the need for urban planning to consider green infrastructure as an important component of the urban fabric. This conclusion should stress careful consideration of thermal comfort in current and future urban planning, design and adaptive management [54]).

4.1. Study limitations

While the mobile data collection method has allowed an in-depth localised analysis of a high number of different field sites within the city, the sensor lag (approx. 2 min) of the globe thermometer may have led to an underestimation of the true MRT in sites with a mixture of sun and shade. The averaging of data over 30 min should compensate this. For instance, while collecting data in a site with dappled shade, the inability of the sensor to adjust from going from sun into shade would be matched by the reverse trend when re-entering the sun so the sensor is recording the average ambient conditions.

The use of a thermal comfort index such as UTCI has its uses but it must be remembered that the actual reactions and preferences of people using these spaces will vary greatly depending on several factors such as gender, previous experiences, expectations, and purpose of visit [20]).

The data represent thermal comfort during hot, summer days with full sun. Future studies could benefit from also studying how these different landtypes differ at night, especially as the inability to cool down on 'tropical nights' (when the air temperature does not go below 20 °C) is a major factor in heat-related illness. It would be interesting also to clarify the effect of species richness and three-dimensional tree canopy structure on the thermal comfort experienced.

5. Conclusion

A mobile method of monitoring thermal climate variables relevant to pedestrians was employed in a large number of sites during typical summer weather in the city of Florence. Varying levels of SVF and tree cover in the sites allowed the construction of multivariate models which revealed that decreases of SVF by 12.5% and increases of tree cover by 25% can reduce the UTCI by 1°. Such quantitative relationships may prove to be a useful tool for practitioners aiming to improve the thermal comfort of outdoor spaces. The only sites reaching comfortable UTCI categories were streets with trees and public gardens.

The mobile methodology has proved useful for investigating a large number of sites from the point of view of the pedestrians that use those spaces, and future studies could benefit from application and modification of this approach. Additionally, the total site factor, by incorporating temporally integrated sun exposure with the sky view factor, revealed itself to be a promising variable for future studies to use.

The effects of species richness, ground cover and amount of vegetation in a 250 m radius neighbourhood were inconclusive, but the approach and the time and spatial scales of the study were not directed to capture these effects.

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.

Acknowledgements

The authors would like to thank Lucia Mondanelli and Bianca Rompato for their invaluable assistance with data collection. The research was carried out under the project "Establishing Urban FORest based solutions In Changing Cities" (EUFORICC), supported by the Ministry of Education, University and Research (MIUR) of Italy (PRIN 20173RRN2S)

References

[1] Nature Editorial, Cities must protect people from extreme heat, Nature 595 (2021) 331–332.

[2] G.C. Donaldson, R.S. Kovats, W.R. Keatinge, R.J. Mcmichael, Heat- and cold-related mortality and morbidity and climate change, in: R.L. Maynard (Ed.), Health Effects of Climate Change in the UK, Department of Health, London, 2001.

[3] R.S. Kovats, S. Hajat, Heat stress and public health: a critical review, Annu. Rev. Publ. Health 29 (2008) 41–55.

[4] S. Conti, P. Meli, G. Minelli, R. Solimini, V. Toccaceli, M. Vichi, C. Beltrano, L. Perini, Epidemiologic study of mortality during the Summer 2003 heat wave in Italy, Environ. Res. 98 (2005) 390–399.

[5] S. Wonorahardjo, I.M. Suthaja, Y. Mardiyati, H. Andoni, T. Dixon, R.A. Achsani, S. Steven, Characterising thermal behaviour of buildings and its effect on urban heat island in tropical areas, Int. J. Energy Environ. Eng. 11 (2020) 129–142.

[6] Z. Tan, K.K. Lau, E. Ng, Urban tree design approaches for mitigating daytime urban heat island effects in a high-density urban environment, Energy Build. 114 (2016) 265–274.

[7] H.E. Landsberg, The Urban Climate, in: International Geographic Series, 28, Academic Press, NewYork, 1981.

[8] M.W. Yahia, E. Johansson, Landscape interventions in improving thermal comfort in the hot dry city of Damascus, Syria—the example of residential spaces with detached buildings, Landsc. Urban Plann. 125 (2014) 1–16.

[9] L. Gartland, Heat Islands: Understanding and Mitigating Heat in Urban Areas, Routledge, London, 2010.

[10] M. Petralli, L. Massetti, S. Orlandini, Five years of thermal intra-urban monitoring in Florence (Italy) and application of climatological indices, Theor. Appl. Climatol. 104 (2010) 349–356.

[11] S. Top, D. Milošević, S. Caluwaerts, R. Hamdi, S. Savić, Intra-urban differences of outdoor thermal comfort in Ghent on seasonal level and during record-breaking 2019 heat wave, Build. Environ. 185 (2020), 107103.

[12] I.D. Stewart, T.R. Oke, Local climate zones for urban temperature studies, Bull. Am. Meteorol. Soc. 93 (2012) 1879–1900.

[13] C. Heaviside, H. Macintyre, S. Vardoulakis, The urban heat island: implications for health in a changing environment, Current Environmental Health Reports 4 (3) (2017) 296–305.

[14] J.K. Vanos, J.S. Warland, T.J. Gillespie, N.A. Kenny, Review of the physiology of human thermal comfort while exercising in urban landscapes and implications for bioclimatic design, Int. J. Biometeorol. 54 (2010) 319–334.

[15] L. Chen, E. Ng, Outdoor thermal comfort and outdoor activities: a review of research in the past decade, Cities 29 (2012) 118–125.

[16] L. Kleerekoper, M. van Esch, T.B. Salcedo, How to make a city climate-proof, addressing the urban heat island effect, Resour. Conserv. Recycl. 64 (2012) 30–38.

[17] J.N. Georgi, D. Dimitriou, The contribution of urban green spaces to the improvement of environment in cities: case study of Chania, Greece, Build. Environ. 45 (2010) 1401–1414.

[18] M.A. Rahman, A. Moser, T. Rotzer, S. Pauleit, Comparing the transpirational and shading effects of two contrasting urban tree species, Urban Ecosyst. 22 (2019) 683–697.

[19] R. Sanusi, D. Johnstone, P. May, S.J. Livesley, Microclimate benefits that different street trees provide to sidewalk pedestrians relate to differences in Plant Area Index, Landsc. Urban Plann. 157 (2017) 502–511.

[20] K. Pantavou, G. Theoharatos, M. Santamouris, D. Asimakopoulos, Outdoor thermal sensation of pedestrians in a Mediterranean climate and a comparison with UTCI Building and Environment 66 (2013) 82–95.

[21] A. Hami, B. Abdi, D. Zarehaghi, S. Bin Maulan, Assessing the thermal comfort effects of green spaces: a systematic review of methods, parameters, and plants' attributes, Sustainable Cities and Society 49 (2019).

[22] H. Lee, H. Mayer, L. Chen, Contribution of trees and grasslands to the mitigation of human heat stress in a residential district of Freiburg, Southwest Germany, Landsc. Urban Plann. 148 (2016) 37–50, https://doi.org/10.1016/j.landurbplan.2015.12.004.

[23] A.F. Speak, L. Montagnani, C. Wellstein, S. Zerbe, The influence of tree traits on urban ground surface shade cooling, Landsc. Urban Plann. 197 (2020), 103748.

[24] J. Holst, H. Mayer, Impacts of street design parameters on human-biometeorological variables, Meteorol. Z. 20 (2011) 541–552.

[25] A. Matzarakis, F. Rutz, H. Mayer, Modelling radiation fluxes in simple and complex environments – application of the RayMan model, Int. J. Biometerology 51 (4) (2007) 323–334.

[26] A. Lai, M. Maing, E. Ng, Observational studies of mean radiant temperature across different outdoor spaces under shaded conditions in densely built environment, Build. Environ. 114 (2017) 397–409.

[27] H. Lee, J. Holst, H. Mayer, Modification of human-biometeorologically significant radiant flux densities by shading as local method to mitigate heat stress in summer within urban street canyons, Adv. Meteorol. (2013) 13, https://doi.org/10.1155/2013/312572, 2013, article ID 312572.

[28] T.P. Lin, A. Matzarakis, R.L. Hwang, Shading effect on long-term outdoor thermal comfort, Build. Environ. 45 (1) (2010) 213–221.

[29] E. Johansson, Influence of urban geometry on outdoor thermal comfort in a hot dry climate: a study in Fez, Morocco, Build. Environ. 41 (2006) 1326–1338.

[30] A. Middel, E.S. Krayenhoff, Micrometeorological determinants of pedestrian thermal exposure during record-breaking heat in Tempe, Arizona: introducing the MaRTy observational platform, Sci. Total Environ. 687 (2019) 137–151.

[31] E. Johansson, S. Thorsson, R. Emmanuel, E. Krüger, Instruments and methods in outdoor thermal comfort studies—the need for standardization Urban Climate 10 (2014) 346–366.

[32] J. Spagnolo, R. de Dear, A field study of thermal comfort in outdoor and semi-outdoor environments in subtropical Sydney Australia, Build. Environ. 38 (2003) 721–738.

[33] G. Jendritzky, R. de Dear, G. Havenith, UTCI—why another thermal index? Int. J. Biometeorol. 56 (3) (2012) 421–428.

[34] H. Yokoyama, R. Ooka, H. Kikumoto, Study of mobile measurements for detailed temperature distribution in a high-density urban area in Tokyo, Urban Climate 24 (2018) 517–528.

[35] P.K. Tsin, A. Knudby, E.S. Krayenhoff, H.C. Ho, M. Brauer, S.B. Henderson, Microscale mobile monitoring of urban air temperature, Urban Climate 18 (2016) 58–72.

[36] P. Gallinelli, R. Camponovo, V. Guillot, CityFeel – micro climate monitoring for climate mitigation and urban design, Energy Procedia 122 (2017) 391–396.

[37] E. Melhuish, M. Pedder, Observing an urban heat island by bicycle, Weather 53 (1998) 121–128.

[38] N.B. Rajkovich, L. Larsen, A bicycle-based field measurement system for the study of thermal exposure in Cuyahoga County, Ohio, USA, Int. J. Environ. Res. Publ. Health 13 (2016) 159.

[39] B.G. Heusinkveld, L. van Hove, C. Jacobs, G. Steeneveld, J. Elbers, E. Moors, A. Holtslag, Use of a Mobile Platform for Assessing Urban Heat Stress in Rotterdam, in: Proceedings of the 7th Conference on Biometeorology Albert-Ludwigs-University of Freiburg, Freiburg Germany, 12–14 April 2010, 2010, p. 14.

[40] L. Klok, N. Rood, J. Kluck, L. Kleerekoper, Assessment of thermally comfortable urban spaces in Amsterdam during hot summer days, Int. J. Biometeorol. 63 (2018) 129–141.

[41] Regione Toscana, Historical Archive of Meteorological Station Data, 2021. http://www.sir.toscana.it/consistenza-rete. (Accessed 29 January 2020).

[42] M. Petralli, M. Morabito, L. Cecchi, A. Crisci, S. Orlandini, Urban morbidity in summer: ambulance dispatch data, periodicity and weather, Cent. Eur. J. Med. 7 (2012) 775–782.

[43] ISTAT, Istituto Natzionale di Statistica. Comunicato Stampa – Verde Urbano, 2020. https://www. Sustain. Cities Soc.istat.it/it/archivio/186267. (Accessed 12 December 2020).

[44] K. Häb, B.L. Ruddell, A. Middel, Sensor lag correction for mobile urban microclimate measurements, Urban Climate 14 (2015) 622–635.

[45] Geoscopio, Regione Toscana – SITA: Cartoteca, 2021. http://www502.regione.toscana.it/geoscopio/cartoteca.html. (Accessed 29 January 2021).

[46] J. Weier, D. Herring, Measuring Vegetation (NDVI & EVI), NASA Earth Observatory, Washington DC, 2000.

[47] K. Błażejczyk, Y. Epstein, G. Jendritzky, H. Staiger, B. Tinz, Comparison of UTCI to selected thermal indices, Int. J. Biometeorol. 56 (2012) 515–535.

[48] K. Błażejczyk, G. Jendritzky, P. Bröde, D. Fiala, G. Havenith, Y. Epstein, A. Psikuta, B. Kampmann, An introduction to the universal thermal climate index (UTCI), Geogr. Pol. 86 (1) (2013) 5–10.

[49] J. van Hoof, Forty years of Fanger's model of thermal comfort: comfort for all? Indoor Air 18 (3) (2008) 182–201.

[50] S. Thorsson, F. Lindberg, I. Eliasson, B. Holmer, Different methods for estimating the mean radiant temperature in an outdoor setting, Int J. Climtology 27 (2007) 1983–1993.

[51] R Core Team, R: A Language and Environment for Statistical Computing, R Foundation for Statistical Computing, Vienna, Austria, 2020. URL, https://www.R-project.org/.

[52] A. Chevan, M. Sutherland, Hierarchical partitioning, Am. Statistician 45 (1991) 90–96.

[53] X. Wang, M. Dallimer, C.E. Scott, W. Shi, J. Gao, Tree species richness and diversity predicts the magnitude of urban heat island mitigation effects of greenspaces, Sci. Total Environ. 770 (2021), 145211.

[54] FAO, Guidelines on urban and peri-urban forestry, in: F. Salbitano, S. Borelli, M. Conigliaro, Y. Chen (Eds.), FAO Forestry Paper No.¬178, Food and Agriculture Organization of the United Nations, Rome, 2016.

[55] M. Park, A. Hagishima, J. Tanimoto, K. Narita, Effect of urban vegetation on outdoor thermal environment: field measurement at a model scale, Build. Environ. 56 (2012) 38–46.

[56] D. Armson, P. Stringer, A.R. Ennos, The effect of tree shade and grass on surface and globe temperatures in an urban area, Urban For. Urban Green. 11 (2012) 245–255.

[57] M. Petralli, G. Brandani, M. Napoli, A. Messeri, L. Massetti, Thermal comfort and green areas in Florence, Italian Journal of Agrometeorology 2 (2015) 39–48.

[58] T.R. Oke, J.M. Crowther, K.G. Mcnaughton, J.L. Monteith, B. Gardiner, The micrometeorology of the urban forest [and discussion], Phil. Trans. Biol. Sci. 324 (1223) (1989) 335–349.

[59] F. Yang, L. Chen, Cooling Effects of Urban Greenery at Three Scales, in: High-Rise Urban Form and Microclimate. The Urban Book Series, Springer, Singapore, 2020.

[60] L. Chen, E. Ng, X. An, C. Ren, M. Lee, U. Wang, Z. He, Sky view factor analysis of street canyons and its implications for daytime intra-urban air temperature differentials in high-rise, high-density urban areas of Hong Kong: a GIS-based simulation approach, Int. J. Climatol. 32 (1) (2012) 121–136.

[61] H. Lee, H. Mayer, D. Schindler, Importance of 3-D radiant flux densities for outdoor human thermal comfort on clear-sky summer days in Freiburg, Southwest Germany, Meteorologische Zietschrift 23 (3) (2014) 315–330, https://doi.org/10.1127/0941-2948/2014/0536.

[62] A. Dimoudi, M. Nikolopoulou, Vegetation in the urban environment: microclimatic analysis and benefits, Energy Build. 35 (1) (2003) 69–76, 2003.

[63] D.E. Bowler, L. Buyung-Ali, T.M. Knight, A.S. Pullin, Urban greening to cool towns and cities: a systematic review of the empirical evidence, Landsc.Urban Plan. 97 (3) (2010) 147–155.