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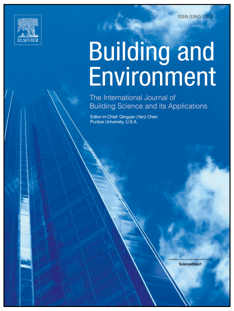
Original
Effect of tree cover and tree species on microclimate and pedestrian comfort in a residential district in Iran / Teshnehdel, S.; Akbari, H.; Di Giuseppe, E.; Brown, R. D.. - In: BUILDING AND ENVIRONMENT. - ISSN 0360-1323. - ELETTRONICO. - 178:(2020). [10.1016/j.buildenv.2020.106899]

Availability:
This version is available at: 11566/285007 since: 2024-04-22T12:11:46Z

Publisher:

Published
DOI:10.1016/j.buildenv.2020.106899



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PII: S0360-1323(20)30258-4

DOI: https://doi.org/10.1016/j.buildenv.2020.106899

Reference: BAE 106899

To appear in: *Building and Environment*

Received Date: 12 January 2020

Revised Date: 8 April 2020

Accepted Date: 10 April 2020

Please cite this article as: Teshnehdel S, Akbari H, Di Giuseppe E, Brown RD, Effect of tree cover and tree species on microclimate and pedestrian comfort in a residential district in Iran, *Building and Environment* (2020), doi: https://doi.org/10.1016/j.buildenv.2020.106899.

Effect of tree cover and tree species on microclimate and pedestrian comfort in a residential district in Iran

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Abstract

According to the challenge of global warming, trees play an effective role in reducing heat islands and improving thermal comfort. In this study, the impact of urban greening on microclimate and pedestrian comfort is studied using ENVI met v4 for a residential district in Tabriz, Iran. In-situ measurements of air temperature and relative humidity have been preliminary performed on ten points in the studied site and collected data used to successfully validate the model. Four scenarios with different trees species and patterns were simulated during typical summer and winter days, to assess benefits and disadvantages during different seasons, in terms of air temperature (Ta) and relative humidity (RH), mean radiant temperature (Tmrt) and physiologically equivalent temperature (PET). Result showed that the best scenario provides great summer cooling without compromising winter comfort. In summer Ta and Tmrt are decreased by respectively 0.29 °C and 20.04 °C; while in winter, they reach respectively 6.92 °C and 13.22 °C, compared the reference scenario characterized by 6.28 °C (Ta) and 23.47 °C (Tmrt). These results in a summer PET improvement from 34.92 °C to 26.16 ˚C, thus moving from an original hot thermal sensation to a slightly warm one. Based on the outcomes of the study, it is possible to provide useful design recommendation for urban adaptation plans.

Key words: Pedestrian comfort, Urban greening, Trees design, Urban microclimate, UHI mitigation, ENVI-met

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1. Introduction

Extreme thermal stress events have considerably increased in recent years, both in frequency and in magnitude, and this trend is expected to continue with future global warming, especially in some world regions as southwest Asia [1, 2]. This will most probably exacerbate other challenges, such as the buildings energy use for cooling with consequent greenhouse gas (GHG) emissions; the ability to work resulting in lower productivity; the durability of building materials and infrastructures, the possibility to use public spaces thus constraining social life and, above all, public health directly as well as by increasing the burden of air pollution. Excess heat is an increasing threat to human life. According to Mora et al. around 30% of the world's population is currently exposed to climatic conditions exceeding a deadly threshold for at least 20 days a year and this percentage is projected to increase to ~48% even in a scenario with drastic reduction of GHG emissions [3]. The world population will reach 9.9 billion by 2050, up 2.3 billion or 29 percent from an estimated 7.6 billion people now, while 66% of the population will live in cities (85% in more developed regions) according to projections by Population Reference Bureau (PRB) [4]. Urban Heat Island (UHI), the phenomenon resulting in the increase of temperature in dense areas of cities in comparison with rural areas, is then exacerbating too. Thus, the compound effect of climate change and urbanization on urban comfort and health problems is more and more concerning especially for weak and disadvantaged groups (elderly and sick people) [5]. Many cities, especially in Europe, are already working on mitigation strategies for climate change, i.e. decreasing energy use and GHG emissions [6]. However, even if global GHG emissions were to stop today, climate change would continue for many decades as a result of the inertia of the climate system. Therefore, it is also vital and urgent to develop strategies to adapt cities to the unavoidable impacts of heat stress. Urban adaptation is a systemic approach, with a long-term perspective, that aims to change urban design and structures, an integral part of city development and regeneration [6]. It is still a novel challenge and item on the agendas of most cities, thus the level of awareness of adaptation still needs to be improved, while the UHI assessment methods and countermeasures to be more and more investigated and applied. Recommendations for urban design mitigation strategies need to be based on scientific findings from the urban human-biometeorological perspective [7]. The human thermo-physiological processes and the local thermal environment, in terms of air temperature (Ta) mean radiant temperature (Tmrt), wind speed (v) and relative humidity (RH), affects the human perception of heat. In the last four decades several thermal comfort assessment indices have been developed and applied to urban contexts, to represent the thermal environment from a human thermo-physiological perspective. Among them, the physiologically equivalent temperature (PET) [8] is preferable to other thermal indexes because of its unit (°C), which makes results more comprehensible to urban planners not so familiar with modern human-biometeorological terminology [9]. In literature, a growing number of studies have been conducted on strategies for improving the urban thermal environment and pedestrian thermal comfort such as changing the urban geometry, planting vegetation, using cool surfaces, and incorporating bodies of water [10]. Some existing research [11, 12] focuses on urban form in various countries with different climatic characteristics. Their results illustrated that changing the urban dimensions and proportions considerably impacts the air temperature and shading of the cities envelope. Li et al. [13] studied and analysed the landscape morphology of the street canyon in Harbin. They believed that changing the landscape morphology of the street canyon is the better way to improve the thermal environment of the urban areas as it does not require changing the forms of existing buildings.

The use of “green” in the cities, including green roofs, green walls, parks and tree planting, is a well-established adaptation strategy, which affects urban microclimate and comfort through several processes, especially evapotranspiration, shading, interaction with air movement. Compared to other solutions, it presents several advantages, in terms of environmental and aesthetic benefits, effectiveness, reduced costs and relative ease of implementation [14, 15]. Several authors compared the performance of different overheating mitigation solutions. Taleghani compared the effect of vegetation and high albedo materials on thermal comfort in urban open spaces, demonstrating that although highly reflective materials reduce urban air temperature, they increase the re-radiation of sun to the pedestrians. The author then suggests vegetation as a better design choice for improving pedestrian thermal comfort [16]. Also a recent work reported a comparison of mitigation effect (maximum reductions in Ta and PET) among different strategies - urban geometry, vegetation, reflective surface, water bodies- based on field measurements and numerical studies [10]. The results revealed similar median reductions in Ta (2.1 K, 2.0 K, 1.9 K, and 1.8 K for changing geometry, adding vegetation, using reflective surface, and incorporating a water body, respectively), while major variations were obtained for PET. Changing urban geometry presented the greatest cooling effect (a median reduction of 18.0 K), followed by adding vegetation (a median reduction of 13.0 K). However, Aboelata [17] believed that trees are ineffective in reducing air temperature in the streets of aspect ratio (H/W) 1:1 in all orientations in hot arid climates. He evaluated different three suggested vegetation scenarios (20% trees, 50% trees and 70% grass) and his results showed that scenario (50% trees) enhances physiologically equivalent temperature (PET) in streets of aspect ratio (H/W) 1:1 in all orientations. In addition, a number of studies have shown that reflective surface causes a median increase in PET of 2.7 K, worsening the outdoor thermal comfort in summer [10]. Therefore, correlation between the mean radiant temperature (Tmrt) with physiologically equivalent temperature (PET)is high and is the most important factor influencing PET in the urban area [18].

In recent decades, a number of studies especially focused on the cooling effect of urban greening, as demonstrated by several review works in the field [12, 19, 20].

The majority of field experimental works demonstrate that urban greening contributes to the UHI mitigation in open spaces during daytime, focusing on air and surface temperature reduction, while cooling magnitude depends on several factors as urban shape, vegetation typologies and extensions, climate and period of the year [17, 21-24]. Yan et al. [25] analysed one-year field experiment data with various land-use types in a subtropical climate in China. Their findings illustrated that adding vegetation significantly impact on air temperature reduction and areas with vegetation coverage greater than 55% create a relatively stable thermal environment for the dwellers. Based on observational data of existing green spaces retrieved from about fifty papers, Bowler et al. in 2010 demonstrated that urban greening, such as parks and trees, may act to cool the environment on average by 1°C compared to a non-green site, while cooling differences are due to the vegetation extension and typologies [26]. However, conducting field studies in real urban settings can be challenging due to the combined effect of multiple variables and the lack of experimental control. Thus, numerical modelling and simulations have been increasingly used to validate, analyse and predict urban thermal environments. Among computational fluid dynamic models, ENVI-met is a three-dimensional small-scale CFD model that simulates surface-plant-air-interactions in urban environments resulting micro-meteorological phenomena within the urban canopy and boundary layer [27]. It is extensively and successfully applied in literature to evaluate the micro-meteorological and human-biometeorological impacts of different urban climate design strategies [28, 29] and can be considered as a very helpful tool for urban climate analysis provided a deep knowledge and understanding of the tools' limits [30].

ENVI-met applications related to the assessment of urban greening can be found in several studies, limited to microclimate (e.g. [31-33] or extended to pedestrian comfort evaluation (e.g. [7, 14, 24, 34]. A comprehensive review of ENVI-met use in this context is reported in [30]. Especially focusing on trees, Wang et al. simulated different scenarios of tree planting patterns and trees sizes. They emphasize the beneficial effect on Ta of increasing tree crown diameter and on planting trees without space between the tree crowns [32]. Wu et al. tested four scenarios with different spatial arrangements of trees in an ENVI-met model of a residential neighbourhood with high-rise apartment buildings in Beijing. They found how different spatial arrangements had differentiated effects depending on the location of buildings shadows [35]. Aminipouri et al. [36] in their research on six local climate zones for a hot summer day concluded that adding street trees has the potential to offset Tmrt increases under the best scenario. Recently, Zölch et al. assessed the microclimate influence of typical greening design options for rectangular public squares during a hot summer day during day and night time conditions, by applying a validated version of the ENVI-met V4 against field Ta and RH data. They highlighted the impact of number and placement of trees as well as share and placement of meadow areas for better wind flow and less heat storage at least for night time cooling [24]. As recently observed by several authors, the findings of studies on the impact of urban greening show large variations of air temperature and PET reductions, due to the different configurations of the compared cases and the different climate conditions in various studies [10]. The cooling potential of trees varies according to their characteristics, which are leaf area index, tree height, trunk height, crown height and crown width [12]. Deng et al. [37] worked on tree crown spectroscopy on the radiative performance of ten planted tree species in the UK. Their results showed that tree species selection in urban heat stress mitigation depends on the combination of tree crown morphology, solar altitude and leaf size. They presented that infrared transflection towards pedestrians and buildings is considerable. Hence tree crown transflection should be primarily towards sky on the sunlit side of trees. Bartesaghi Koc et al. analysed 165 studies from 2010 to 2017 investigating the cooling effects of green infrastructure to identify knowledge gaps and potential directions for future research. Results revealed that little is known about the thermal benefits of urban greening in tropical and desert climates, developing countries, and southern-hemisphere regions which are experiencing significant urbanization and population growth and are severely affected by heatwaves [38]. Lai et al. highlight that a larger cooling effect is achieved when mitigation strategies are applied in hotter climates, due to the greater potential for heat reduction [10]. Furthermore, they stress that most of the existing studies focused on only a few typical summer days in one city. However, a design that improves thermal comfort in summer may cause discomfort in winter. To our best knowledge, only few studies so far investigated the effects of greenery and trees on outdoor climate and thermal comfort in winter [12, 39, 40]. Thus, it is necessary to consider the influence of climate at different times of the year [10].

The necessity of this research is expanding the existing knowledge on urban trees design, focusing on tree cover and tree species (local and non-local species) impact on human thermal comfort next to the microclimate, on summer and winter seasons, to verify how to reach a proper control of summer heat stress while not worsening the winter microclimate. The case study(Aseman-e-Tabriz residential complex) have been chosen in Tabriz, Iran, characterised by a steppe climate. Microclimate and human-biometeorological simulations using ENVI-met software were conducted for typical summer and winter days.

With respect to human thermal comfort and urban design recommendations, the following issues are stressed by the study: (i) the current tree configuration and four alternative trees design scenarios in the study site, (ii) the ENVI-met model validation against field measurements (iii) the local microclimate in terms of Ta and RH (iv) pedestrian comfort in terms of Tmrt and PET, (v) summer and winter days, (vi) steppe climate.

2. Material and methods

2.1 Study area microclimate monitoring

The study site is a residential area in the city of Tabriz (38˚8´North, 48˚15´East, 1350 m asl), the largest city in northwestern Iran, with a population of nearly 1,400,000. Tabriz has a steppe climate [41] (Figure 1), with low precipitation (318 mm on average). The average temperature for the year in Tabriz is 12.8°C. The warmest month, on average, is July with an average temperature of 26.7°C. The coolest month on average is January, with an average temperature of 2.8°C.

Fig.1. Location of the selected site in Tabriz, Iran.

Aseman-e-Tabriz residential complex is designed in 9.4 hectares and in the form of 928 residential units. The complex has 16 towers with 18 floors, surrounded by street canyons with asphalt surfaces, grasslands and trees (Table 1).

The index of “FAR”(Floor Area Rate) of the apartment blocks is 20% and the ratio of open space(green space and road area) to the total area is about 65% (Table 1) and the index of open space per unit in the complex is 66 m^2, while the standard rate of open space per (residential)unit is 20 m^2 as the building code in City Plan. In detail, greening (grass and vegetation) actually covers about 46% of the district surface, however, the total number of trees on the site is quite limited, totaling 153. In other words, there is a tree every 286 m^2 (green space) and 17 trees per hectare.

Almost all the trees in the site are coniferous (pine-cypress, a needle tree) which are non-local species, approximately 7 meters high with a crown diameter of about 3 meters (Figure 2).

Table. 1. Profile of land cover types (area and percentage) in the Aseman-e-Tabriz study area

Open space elements	Area (m^2)	Percent (%)
Apartment blocks	19000	20.25
Green spaces (grass and vegetation)	43875	46.65
Roads (Asphalt)	16963	18.04
Water	420	0.44

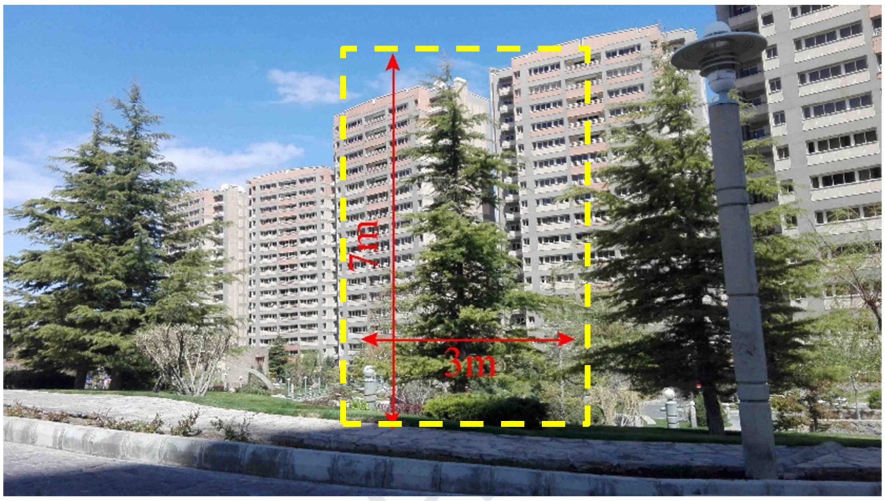

Fig. 2. A view of the residential complex of Aseman-e-Tabriz (a tree's exemplary dimensions in red)

Air temperature (Ta) and relative humidity (RH) were measured in 10 points of the site of Aseman-e-Tabriz. The measurement device was placed 1.5m above ground (Figure 3). The measured data were collected from 09:00-17:00 in the local time on 31 January, 2 and 3 February. The specifications and technical data of the measurement equipment are illustrated in Table 2.

Fig. 3. Land cover type and measurement points on the site of Aseman-e-Tabriz.

Table. 2. Specifications and technical data of the measuring instruments

Parameter	**Sensor type**	**Measuring range**	**Accuracy**	**Output resolution**	**Measuring rate**
Temperature	Testo 610	-10 to +50 °C	±0.5 °C	0.1 °C	1 s
Relative Humidity	Testo 610	0 to 100 %RH	±2.5 %RH (5 to 95 %RH)	0.1 %RH	1 s

2.2 ENVI-met modelling and validation

In this study, numerical simulations are conducted using ENVI-met v4 and output data were used in the RayMan model 2.1 (Matzarakis, Rutz, & Mayer, 2007) to calculate PET [8].10 thermal sensation levels are defined over a scale ranging from extreme heat stress to extreme cold stress, related to 9 PET classes. The thermal comfort zone is considered between 18 and 23˚C PET [9] (Table 3).

Table. 3. Categorization of PET level for different thermal sensation and physiological stress

PET	**Thermal sensation**	**Grade of Physiological stress**
Below -4		
	Very cold	**Extreme cold stress**
4		
	Cold	**Strong cold stress**
8		
	Cool	**Moderate cold stress**
13		
	Slightly cold	**Slight cold stress**
18		
	Comfortable	**Neutral**
23		
	Slightly warm	**Slight heat stress**
29		
	Warm	**Moderate heat stress**
35		
	Hot	**Strong heat stress**
41		
	Very hot	**Extreme heat stress**
Above +41		

The simulated domain representing the study area was divided into a three-dimensional grid of 90*60*60 cells with dimensions 6*6*6, covering a total surface of 194400 m^2 and 5 nesting grids to each side. The vertical grid near the ground surface was divided into five equidistant sub-grids of 0.2 m to improve calculation efficiency.

For each grid cell the specific soil profiles or patches of surfaces was modeled considering the available natural or artificial materials of the software database.

The meteorological variables, including dry air temperature, air pressure, specific humidity, wind speed and direction, and cloud sky cover, were set based on the meteorological data collected by Tabriz stations and reported in the Iranian Meteorological Organization website [42]. Data were extracted for the software validation days (31 January, 2 and 3 February 2017) and for the summer and winter days (respectively 22 June 2017 and 22 December 2017) considered as simulation days.

A daily simulation period 9:00-17:00 was defined. Table 4 summarizes the main domain features, simulation timing and meteorological data of the ENVI-met model on both simulation days.

Table. 4. Domain features, simulation timing and meteorological data of the ENVI-met model on both simulation days.

Domain features		
Location	38˚8´N 48˚15´E	
Elevation (m asl)	1350	
Climate	BSk	
Domain size	90*60*60	
Grids spatial resolution	Horizontally:6m; Vertically: 6m	
Simulation timing		
Simulation day	2017.06.22	2017.12.22
Simulation period	9:00 am - 17:00 pm	
Initial meteorological data		
Dry Bulb Temperature (˚C)	24.2	2.9
Relative Humidity (%)	32	73
Wind Speed 10 m a.g.l.(m/s)	4.9	2.1
Wind Direction (degree)	120	250
Cloud cover	0	0

Height, crown length and diameter, and leaf area index (LAI) were estimated for the trees within the simulation domain (coniferous-deciduous) using on-site measurements and set in the “Albero” subcategory database included in ENVI-met. The root features were left as the software default values.

RayMan was used for the PET evaluation, considering individual variables such as physiological characteristics, height, weight, age and gender. In this study, a population composed by males of about 35 years old, 175 cm and 75 kg has been selected, with a static clothing insulation index of 0.2 in summer and 0.9 in winter, and metabolic rate at 90 W/m^2 based on ISO 9920:2007 and ISO 8996:2004.

10 virtual receptors to get climatic data in ENVI-met simulation (A to J) have been defined according to the field measurement points. Figure 4 represents the simulation domain with the main surfaces’ properties and the receptors.

Fig. 4. Representation of the base ENVI-met model (current greening situation)

2.3 Numerical simulations

Once the ENVI-met model, representing the current Aseman-e-Tabriz study area configuration, has been validated against field measurement data, it has been used to evaluate the impact of different greening patterns on microclimate characteristics, including air temperature, relative humidity and mean radiant temperature. Finally, has been calculated the PET values with the RayMan model. Four different scenarios with regard to trees number and species were simulated on the selected summer solstice (22.06.2014) and winter solstice (22.12.2014), to assess the impact of the mitigation strategy on summer and evaluate the eventual disadvantages on winter season (Figure 5, Table 5):

- case 1: as the base model (same number of trees, 153) but with a different tree species (acacia-beech, a deciduous tree);
- case 2: compared to the base model, a greater number of trees (270) and a different tree species (acacia-beech, a deciduous tree);
- case 3: as case 2, but with a greater number of trees (405);
- case 4: as case 3, but with a greater number of trees (540).

With these configurations, the comparison among the base case and case 1 could reveal the impact of trees species, while the differences among cases 2, 3 and 4 will be more related to the trees number.

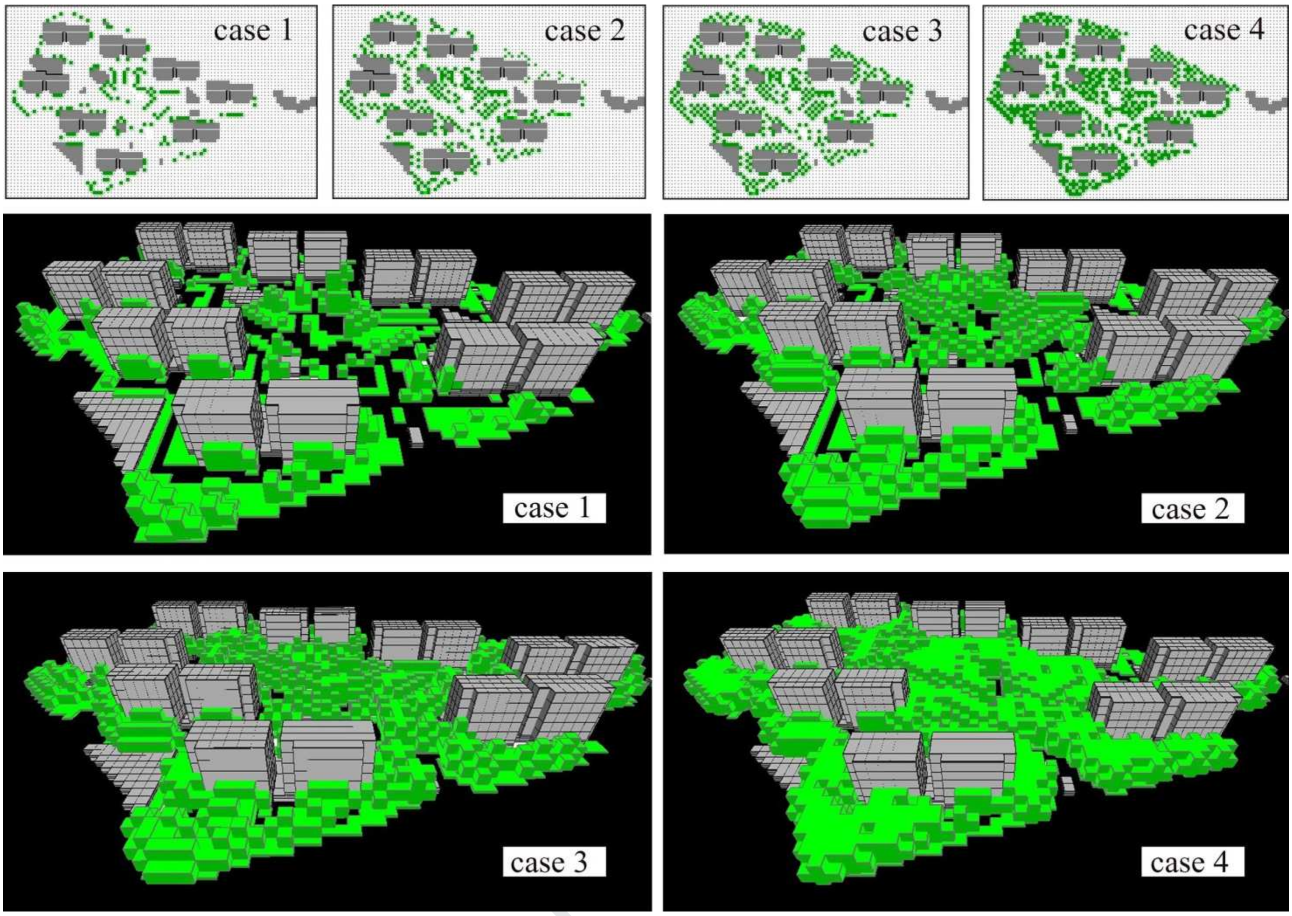

Fig.5. Visualization of the four different simulation scenarios on ENVI-met

Table. 5. Simulated cases in terms of number and species of trees for the different scenarios in the ENVI-met model.

	Simulation scenarios				
	Base case	c1	c2	c3	c4
Trees species	Needle tree (pine-cypress)	Deciduous tree (acacia- beech)	Deciduous tree (acacia- beech)	Deciduous tree (acacia- beech)	Deciduous tree (acacia- beech)
Number of trees per hectare	17	17	30	45	60
Total number of trees	153	153	270	405	540
Trees distance from each other (~)	-	-	12m	10m	9m

3. Results

3.1 Field measurements and model validation

The ENVI-met model was validated considering the hourly observed and predicted air temperature and relative humidity during 31 January, 2 and 3 February 2017 in the period 09:00-17:00. Figure 6 and Figure 7 represent the measured and simulated data, respectively for Ta and RH, in the measurement average value among all receptors. From a qualitative point of view, trends highlight a good agreement among observed and predicted data.

A quantitative measure of the model performance was conducted considering the data in all measurement points/receptors and calculating the correlation coefficients (R^2), the root mean square error (RMSE), the probability value (P-values). Obtained results are reported in Figure 8 and demonstrate a satisfactory performance of the model, with R^2 over 0.89, and a P-value under 0.05.

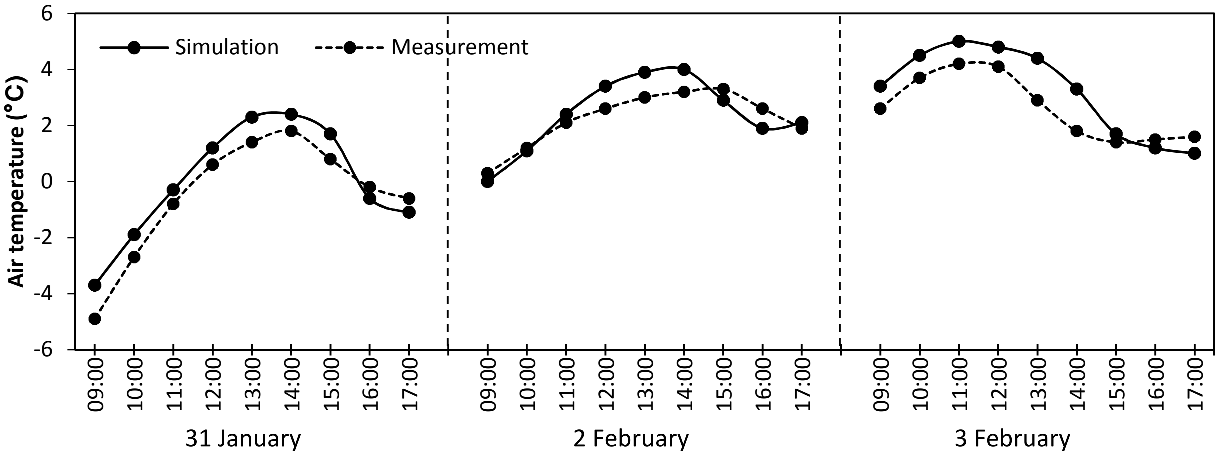

Fig.6. ENVI-met simulated and measured data of air temperature, on 31 January, 2 and 3 February (09:00-17:00)

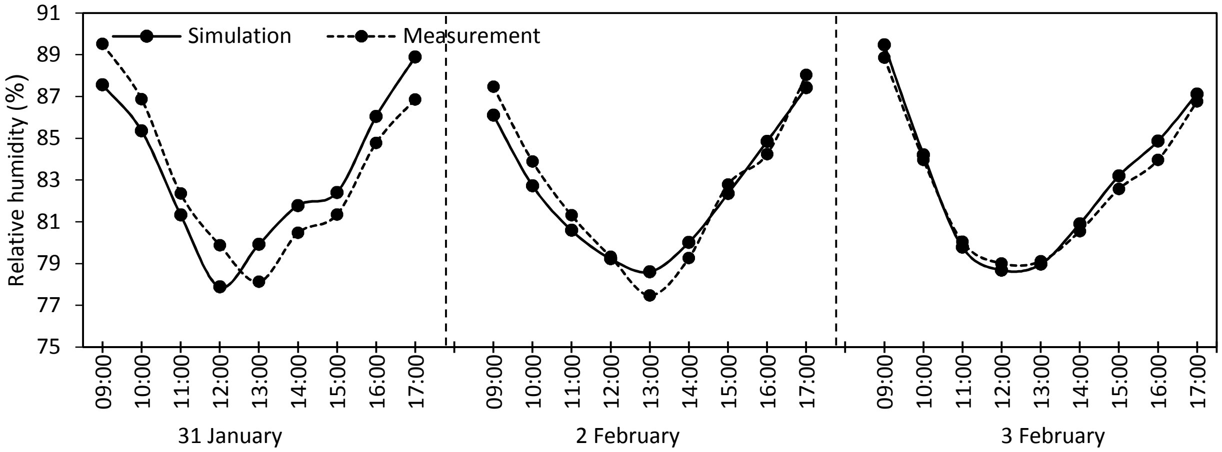

Fig.7. ENVI-met simulated and measured data of relative humidity, on 31 January, 2 and 3 February (09:00-17:00 local time)

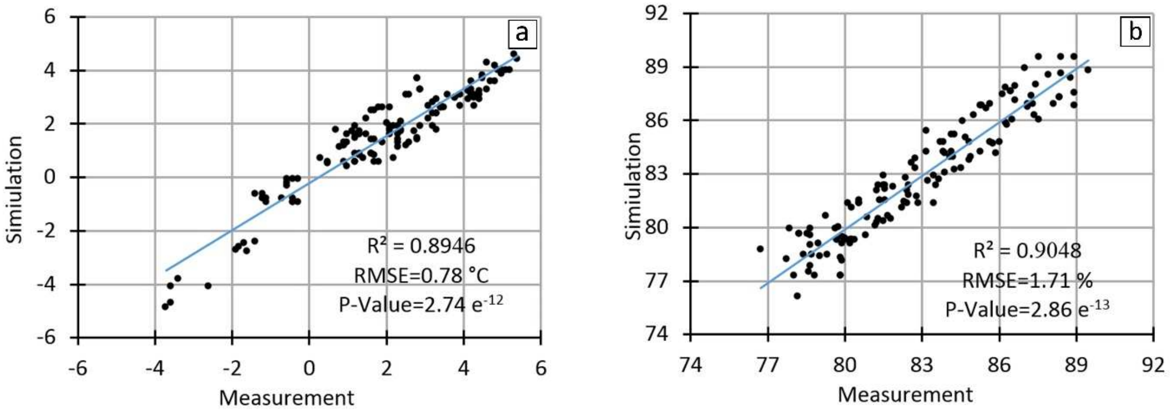

Fig.8. Relationship between simulated and measured data of air temperature (a) and relative humidity (b), on 31 January, 2 and 3 February (09:00-17:00).

3.2 Impact of greenery scenarios on microclimate

The simulation results in terms of Ta, RH, Tmrt are reported for a height of 1.5 m agl to approximate the human-biometeorological reference height [43] and presented in two ways: (i) 2-D maps with colored-coded ranges extracted from LEONARDO tool included in ENVI-met (Figure 9, 10, 11, 12), (ii) box-plots of the values collected in all receptors (Figures 13, 14, 15, 16).

Figure 9 show the distribution in the simulation domain of the air temperature and relative humidity at 13:00 (22.06.2017), for the base case model. The Ta range is 25.48-29.36 ˚C, and that for RH is 43.30-54.49 % in summer. On the other hand, in the winter day, the Ta range is 2.48-9.02 ˚C and RH is 72.65-89.76 %.

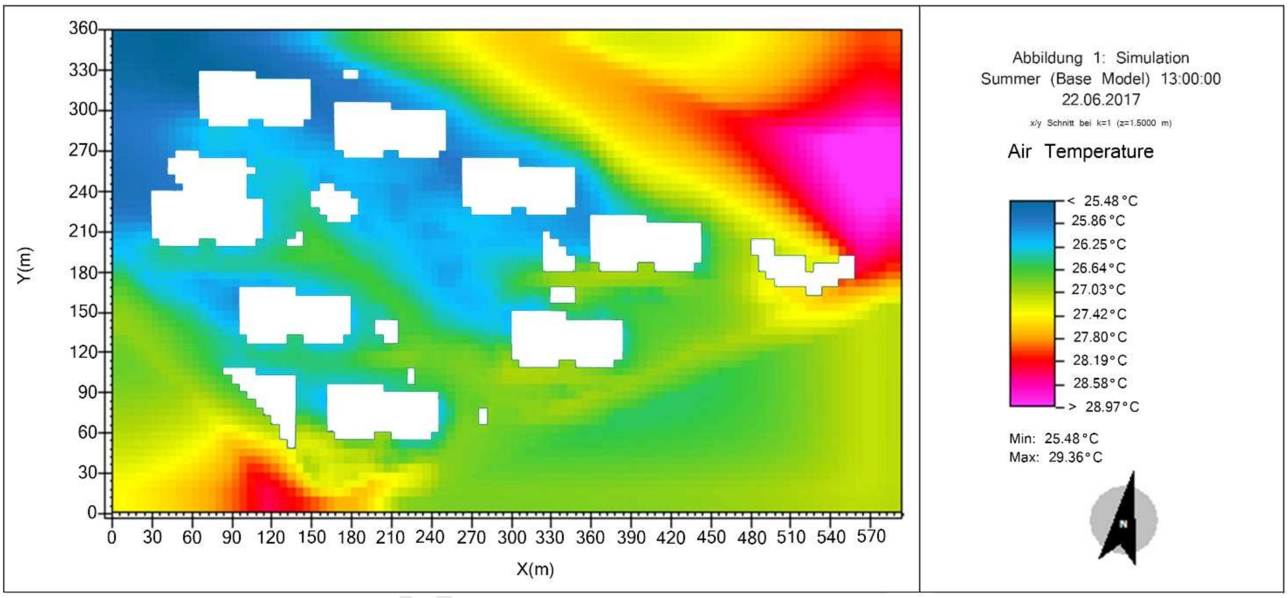

Fig. 9. Distribution of simulated air temperature at a height of 1.5 m agl in the simulation domain at 1 pm in the hot summer day (22 June 2017), base case model

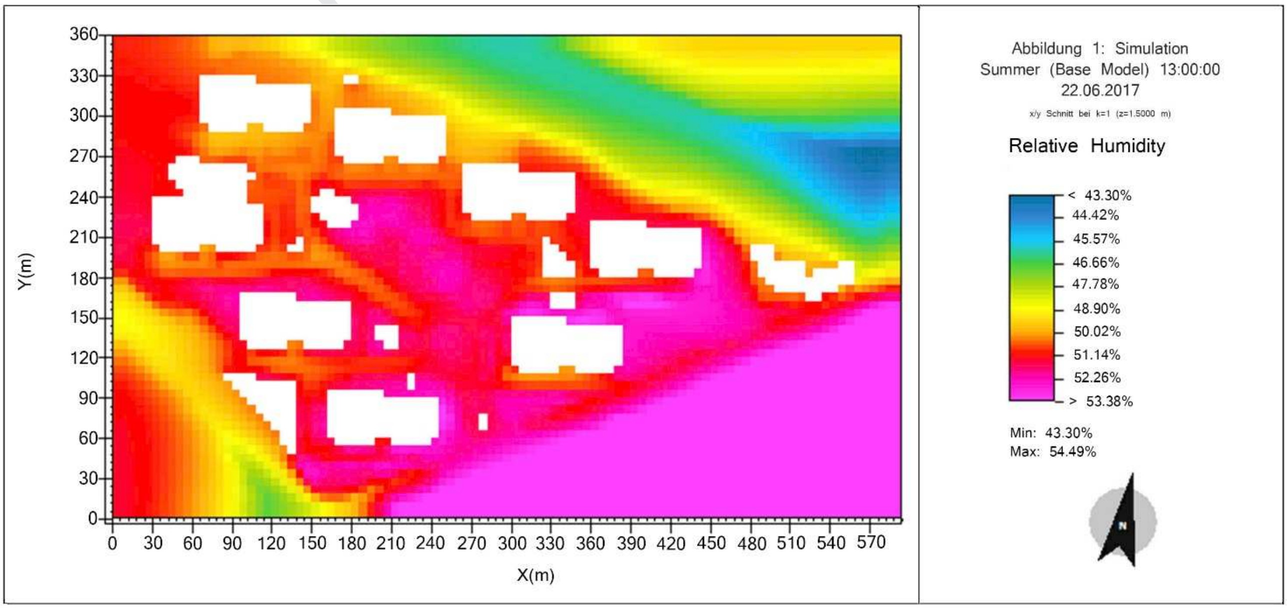

Fig. 10. Distribution of simulated and relative humidity at a height of 1.5 m agl in the simulation domain at 1 pm in the hot summer day (22 June 2017), base case model

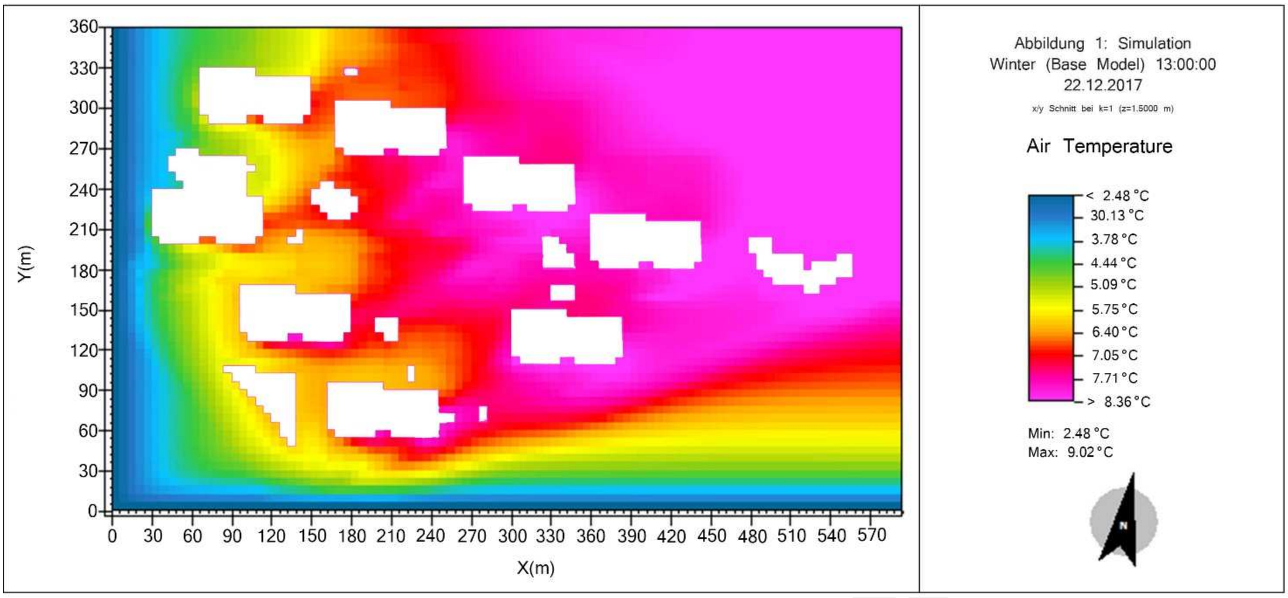

Fig. 11. Distribution of simulated air temperature at a height of 1.5 m agl in the simulation domain at 1 pm in the cold winter day (22 December 2017), base case model

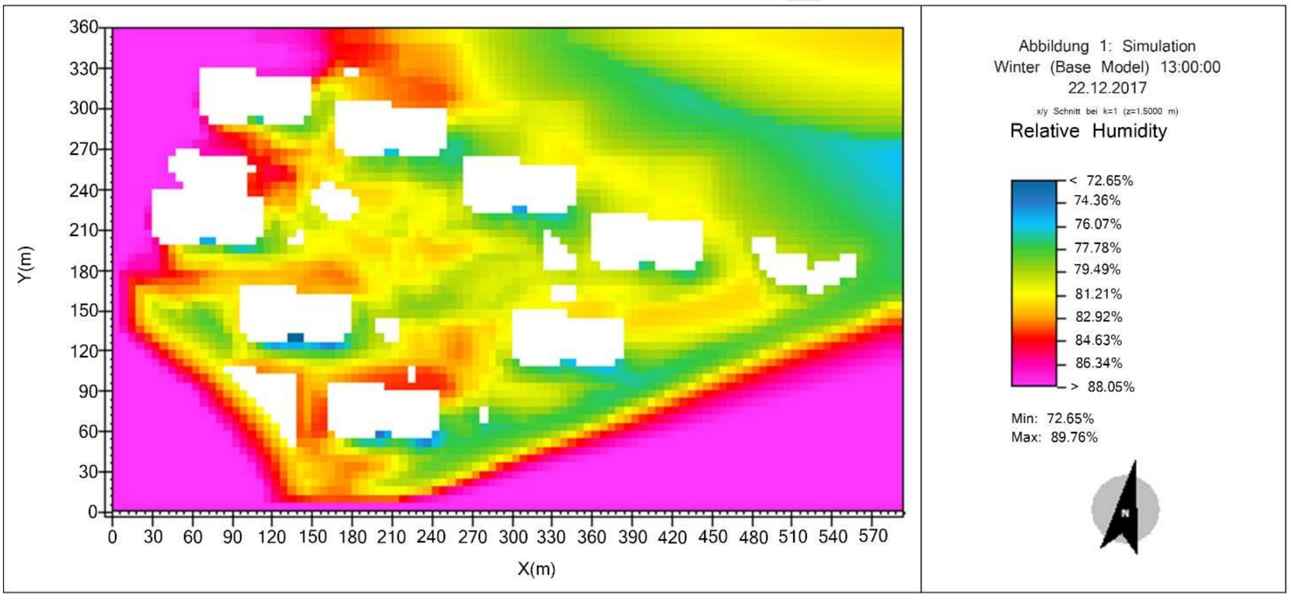

Fig. 12. Distribution of simulated relative humidity at a height of 1.5 m agl in the simulation domain at 1 pm in the cold winter day (22 December 2017), base case model

To assess the influence of trees on microclimate, we represented the box-plots of Ta, Tmrt, Rh at the pedestrian level (1.5 m agl) during the simulation days, distributed for all receptors and averaged during the simulation time (09:00-17:00) for all scenarios.

The average TA and Tmrt during the whole day in the base model are respectively 26.20 and 59.93°C.Concerning the summer heat mitigation effect of the different greening scenarios, results show benefits provided by the four scenarios (c1 – c4) compared to the base case, with average Ta reduction of respectively 0.1 ˚C, 0.2 ˚C, 0.29 ˚C and 0.33 ˚C (Figure 13) and average Tmrt reduction of respectively 6.23 ˚C, 12.17 ˚C, 20.04 ˚C and 21.18 ˚C (figure 14).

"With regard to results, the base model and c1 show a significant difference with the cases 2-4. This is because the number of trees in the base model and case1 are less than in other cases and these differences have created a wide zone of Tmrt in different parts of the site.

According to these results, scenario c1 (where the number of trees is the same of the base case, but a different tree species is selected) presents a similar performance to the reference scenario, while c4, which presents a more than tripled number of trees, supplyies the greater cooling benefit compared to the base model.

Concerning the winter evaluation, it is useful to assess if the most performing scenarios in summer could provide disadvantages in winter time, increasing the pedestian cold stress. Compared to the base model, the four scenarios (c1 – c4) provides reduction of Ta by respectively 0.34 ˚C, 0.49 ˚C, 0.64 ˚C and 0.77 ˚C and of Tmrt by respectively 5.6 ˚C, 8.67 ˚C, 10.25 ˚C and 10.78 ˚C.

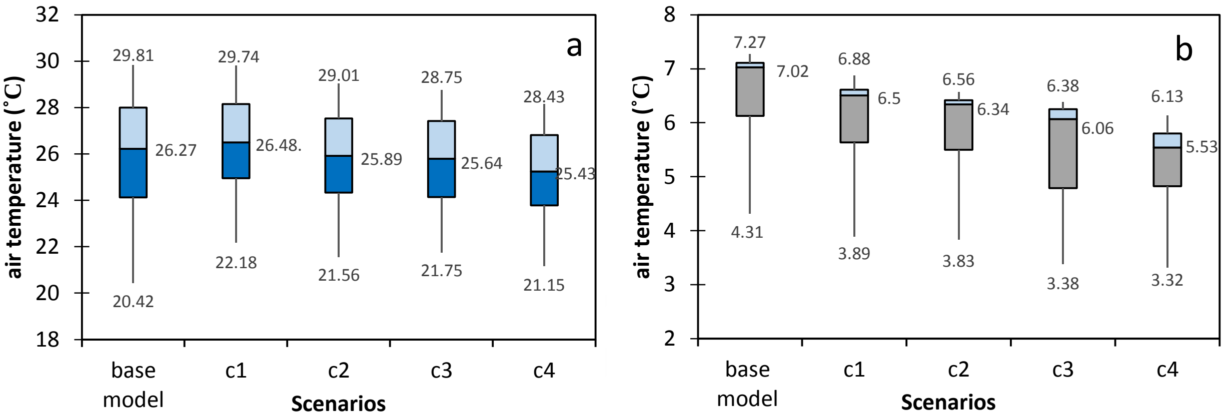

Fig. 13. Average air temperature values at the pedestrian level (1.5 m agl) in the base model and the four scenarios, during the summer (a) and winter (b) simulation days. "The rectangle (the "box") is delimited by the first and third quartiles, and divided inside by the median. The segments (the "whiskers") are delimited by the minimum and maximum values."

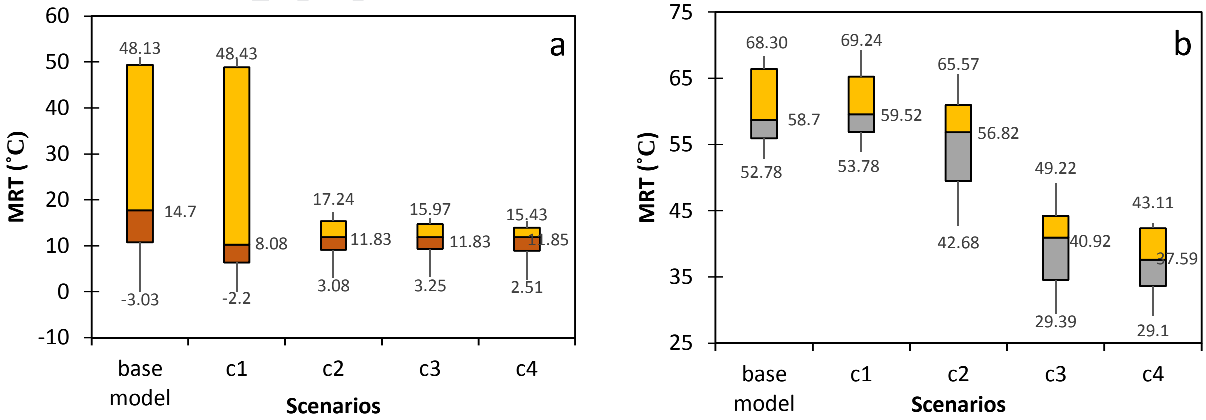

Fig. 14. Average mean radiant temperature values at the pedestrian level (1.5 m agl) in the base model and the four scenarios, during the summer (a) and winter (b) simulation days.

Figure 15 shows the air relative humidity trend in the four scenarios. As expected, increasing the tree number in the residental district also induces a slight increase of the relative humidity, even if it can be considered rather negligeble.

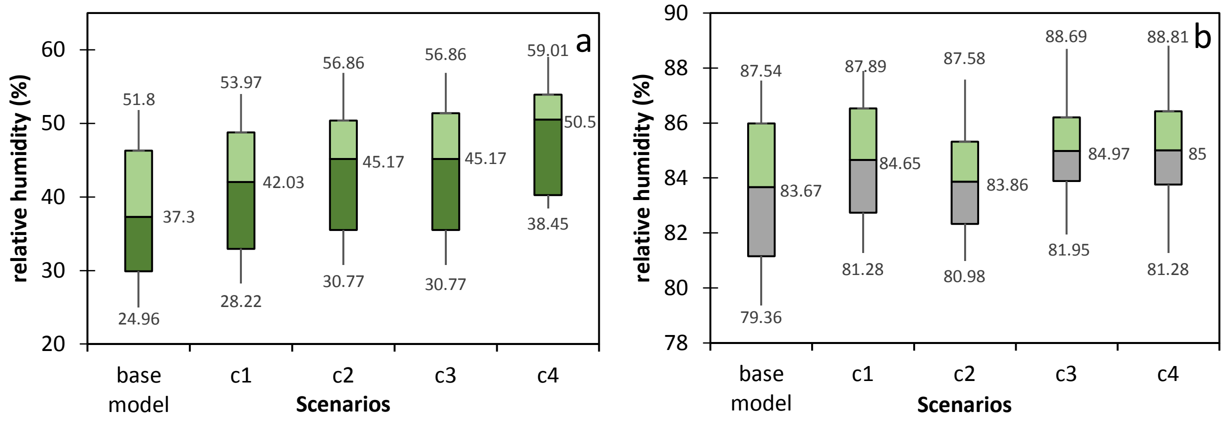

Fig.15. Average relative humidity values at the pedestrian level (1.5 m agl) in the base model and the four scenarios, during the summer (a) and winter (b) simulation days.

According to figure 16, the results show that increasing the number of trees, as well as changing the species of trees can reduce the wind speed compared to the base model in summer and winter.

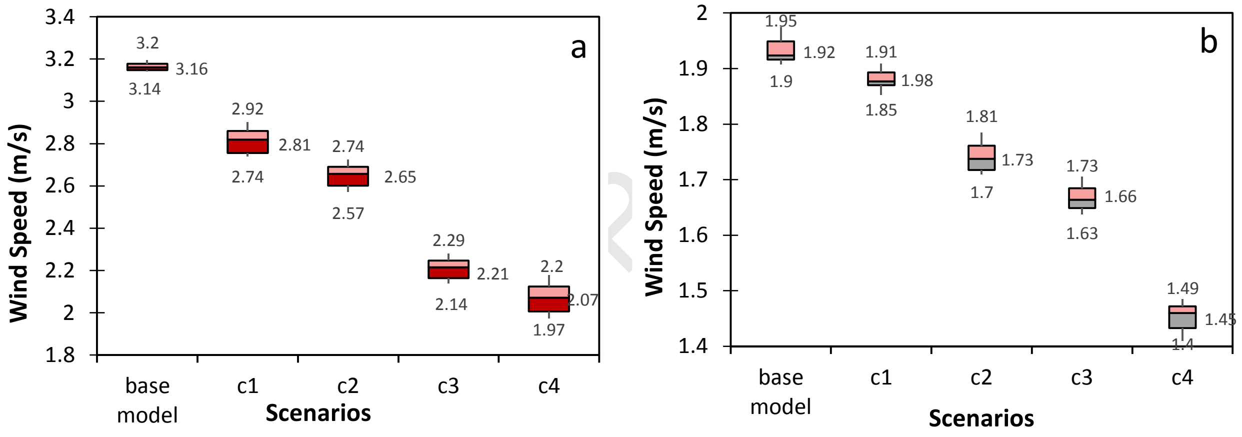

Fig.16. Average wind speed values at the pedestrian level (1.5w m agl) in the base model and the four scenarios, during the summer (a) and winter (b) simulation days.

3.3 Impact of greenery scenarios on human comfort

When the physiological equivalent temperature (PET) is between 18 - 23 °C, thermal condition can be considered in comfortable zone (Table 1). Simulation results show that the average PET in the base model is 34.92 °C (hot sensation) and 5.97 °C in winter (cold sensation). Therefore, based on PET index, the site suffers from both hot stress in summer and cold stress in winter.

Figure 17 represents the box-plots of calculated PET at the pedestrian level (1.5 m agl) during the simulation days, distributed for all receptors and averaged during the simulation time (09:00-17:00) for all scenarios. According to the results, the best performing scenarios in terms of summer thermal comfort are c3 and c4 with 26.16 °C and 25.14 °C respectively (slightly warm sensation), while they provide only a slight worsening of the thermal sensation in winter (c3: 5.34 °C and c4: 5.08 °C).

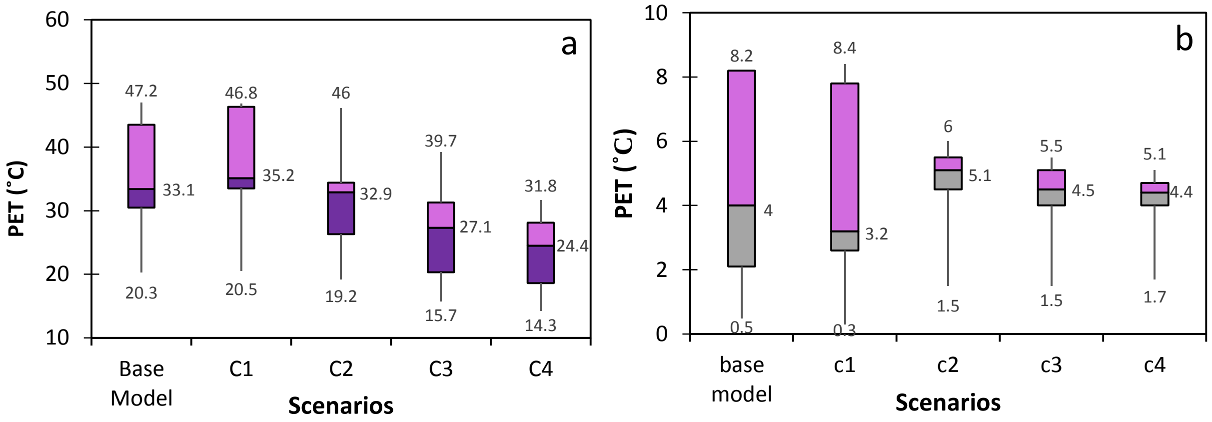

Figure 17. Average of PET values at the pedestrian level (1.5 m agl) in the base model and the four scenarios, during the summer (a) and winter (b) simulation days

For better understanding, table 6 summarizes the average differences of Ta, RH, Tmrt and PET compared to the base model in summer and winter season.

Table.6. Average Ta, RH, MRT and PET changes compared to base model in summer and winter season

Simulation cases		Average air temperature change (°C)	Average Relative humidity change (%)	Average MRT change (°C)	Average PET change (°C)
Summer	Case 1	-0.10	+0.92	-6.23	-1.95
	Case 2	-0.20	+2.32	-12.17	-4.92
	Case 3	-0.29	+3.51	-20.04	-8.76
	Case 4	-0.33	+4.72	-21.18	-9.78
Winter	Case 1	-0.34	+0.30	-5.6	-1
	Case 2	-0.49	-0.12	-8.67	-0.90
	Case 3	-0.64	-0.20	-10.25	-0.63
	Case 4	-0.77	+0.15	-10.78	-0.89

4. Discussion

Urban design should increasingly take into account the impact of climate -and even more of actual “changing” climate- on pedestrian comfort outdoors, as this strongly affect human health and well-being in cities.

As demonstrated in literature, the use of urban green, and especially of trees, is beneficial for the mitigation of UHI, and testified by an air temperature reduction, whose magnitude depend on the specific climates. However, also the human-biometeorological perspective should be considered, and variables such as mean radiant temperature and thermo-physiological indices (e.g. physiologically equivalent temperature, PET) are useful to express human thermal comfort. In this sense, the use of trees is particularly beneficial during summer season for its shading action against solar radiation [26, 44, 45].

Nevertheless, urban greening configuration could also affect human thermal sensation in cold season, in those climates characterised by a considerable temperature range between summer and winter. This aspect is less investigated in the literature [10, 12, 39]. Moreover, few studies address the beneficial effect of greening in desert climates and developing countries [38]. This work contributes to fill these gaps by providing an exemplary application of numerical assessments of microclimate and comfort outdoor in a residential district in Tabriz, Iran, characterised by a Steppe climate.

Urban design with climate implications should follow recommendations based on systematical and accurate analysis of the local microclimate and pedestrian comfort in relation to alternative configurations. This can be obtained through numerical simulation tools such as ENVI-met, validated against measurement data, whose efficacy is largely testified in the literature [30]. In this research, a model of the residential district was realised with ENVI-met v4 and satisfactorily validated against data of Ta and RH collected for three days. It was then used to test different realistic trees scenarios implementable in the studied area. Based on the simulation results, the optimized green scheme for summer and winter comfort could be determined. In the specific study, it is scenario c3, characterised by 405 deciduous tree (acacia- beech). In this case, the following main microclimate and comfort outcomes can be summarized:

- The average daily air temperature in summer is decreased by 0.29 °C (reaching 25.91 °C) while the maximum peak by 28.86 °C (against original 30.26 °C). In winter, the counterproductive average daily air temperature decrease is only by 0.64 °C, compared to an initial average Ta of 6.28 °C;
- The corresponding change of RH both in summer and winter is modest and can be considered irrelevant for the environmental comfort;
- The average daily Tmrt in summer in scenario c3 is 39.89 °C, which corresponds to a reduction of 20.04 °C compared to the base case. In winter, Tmrt decreases by 10.25 °C, against 23.47 °C of the base case. Thus, the environmental microclimate in winter has only slightly deteriorated;
- Based on PET indexes, the main problem on the site in its actual configuration is summer thermal overheating, numerically expressed by a PET of 34.92 °C (hot sensation). In scenario c3 in summer, PET reaches 26.16 °C which is closer to the comfort zone (slightly warm sensation). By contrast, in winter, PET slight worse, reaching 5.34 °C.

Even if provided in a specific climate and urban context, the present work aims to contribute to push more and more urban designers and policymakers to take into account the benefits of using greening in the cities for the improvement of pedestrian comfort, by using accurate and validated assessment tools.

5. Conclusions

In a series of investigations that have been conducted on the improvement of outdoor thermal comfort, trees have played an important role in the urban ecosystem; Including optimal use of sunlight, creating a microclimate in urban spaces, reducing the impact of heat islands, improving the urban landscape are indicated. Therefore, to optimal usage of the trees in urban areas, it is imperative to use the principles that make tree species more selective and systematical. In this study, the effect of number and tree species on climate characteristics and thermal comfort in a residential district in Tabriz, which is located in BSk climate, is investigated. Numerical simulations were conducted using the micro-meteorological model ENVI-met V4, validated against Ta and RH data, on four different greening scenarios. Results allowed to suggest the optimal design option compared to the actual district configuration for both heat and cold stress, respectively typical of summer and winter seasons in the studied area. In summary, the average daily air temperature and Tmrt in summer are decreased by 0.29 °C and 20.04 °C respectively; Hence PET reaches 26.16 °C which is closer to the comfort zone (slightly warm sensation). The best scenario consists of adding to the site a number of trees more than tripled and on using a deciduous tree typology to avoid excessive solar shading in winter.

In future work, further design features could be addressed, especially taking into account the relation among trees and the extent and placement of existing grass areas, and results translated into a set of practical rules and design guidelines for urban designers and policymakers.

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Highlight

- Four scenarios with different trees species and patterns were simulated during typical summer and winter days.
- From a qualitative point of view, trends highlight a good agreement among observed and predicted data.
- Urban greening design can reduce mean radiant temperatures by 20.04 °C.
- The corresponding change of RH both in summer and winter is modest and can be considered irrelevant for the environmental comfort.

Declaration of Interest Statement

Manuscript title: **Effect of tree cover and tree species on microclimate and pedestrian comfort in a residential district in Iran**

We have the pleasure of sending you the manuscript entitled "**Effect of tree cover and tree species on microclimate and pedestrian comfort in a residential district in Iran**" authored by **Saeid Teshnehdel, Hassan Akbari, Elisa Di Giuseppe and Robert D. Brown** to be considered for publication as a research article in your prestigious journal of Journal of Building and Environment. Paper is containing original research and has not been submitted / published earlier in any journal and is not being considered for publication elsewhere. All authors have seen and approved the manuscript and have contributed significantly for the paper.

The authors of this paper certify that we have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

Best regards,
Hassan Akbari, Ph.D