Urban heat resilience: Impact of green structure on outdoor thermal comfort

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Abstract

Considering climate change in urban planning strategies is becoming a necessary condition for planners and designers to build climate-resilient cities.

Outdoor thermal comfort is an important factor in promoting outdoor activities, and an essential criterion for evaluating the quality of the urban environment. Heat-resilient public spaces can provide high-performance outdoor environments in a changing climate. To assess the impact of green structures on outdoor thermal comfort and heat stress, this study examines the heat resilience of a city center in Annaba, a coastal city in Algeria with a typical Mediterranean climate. Based on numerical simulations, this study aims to better characterize the impact of urban design on outdoor thermal comfort. The biometeorological index (UTCI) is used to evaluate heat stress at the pedestrian level. The Universal thermal index (UTC) is estimated using three-dimensional microclimatic modeling software (ENVI_met4).

The results show that while modeling methods enable us to simulate different scenarios of design solutions, further field studies are needed to validate and improve their accuracy. This work can be integrated into urban design guidelines for planning and building climate-resilient cities.

***Key words:** Urban heat resilience, urban design, heat stress, Public urban space*

1. Introduction

Cities around the world are facing complex challenges, including climate change, and are striving to become more resilient in the face of the shocks and stresses that come with it. Extreme weather events such as heat waves, floods, droughts and storms have become more frequent in recent times.

Urbanization is one of the main drivers of land-use change and global environmental decline. With the acceleration of urbanization worldwide, it is essential to put in place new policies to preserve urban ecosystems, the diversity of species and the services they provide, in order to ensure more sustainable, resilient and livable cities.

In the twenty-first century, Mediterranean cities are experiencing greater heat stress than ever before. Large cities may experience additional stress discomfort due to the Urban Heat Island (UHI) effect [1], and public life will consequently suffer from increased heat stress. To mitigate urban heat, planners and decision-makers need to promote heat-resilient-building environments to support outdoor activities in heat-stressed conditions [2].

The microclimate generated in an urban unit depends on meteorological conditions, urban geometry, building materials and the presence of water and vegetation.

The urban system can be assimilated into a climate transformer, generating a specific microclimate from meso-climatic conditions. This microclimate corresponds to the urban system's thermal response to meso-climatic environmental solicitations, which result in internal heat transfers of conductive and convective origins, and advective and diffusive exchanges in the urban air [3].

The study of thermal airflow in open spaces is complex. Numerous parameters come into play, such as solar radiation, short and long-wave radiation, prevailing wind, natural convection, building and wall inertia, etc. As a result, a successful design must provide the means to control these parameters and not assign them to hazards.

Nature-based solutions can improve urban living and help to make cities more resilient. Urban green spaces are particularly resistant to heat stress. Less heat in summer means more outdoor living. Heat-resistant public spaces can provide high-performance outdoor environments in the context of climate change [4].

The presence of vegetation is an essential factor in limiting urban heating. The presence of asphalt, concrete, and other impervious surfaces that absorb heat and interrupt the natural cooling effect provided by vegetation led to an increase in city temperatures of 2 to 3°C compared to surrounding rural areas.

Rosenfeld showed that downtown Los Angeles was 2°C cooler between 1882 and 1984 thanks to advances in irrigation and the establishment of orchards. Until 1930 and after the substitution of the green surfaces by asphalt, the city became 3°C warmer [5].

According to Aloy Bernatzky, a small green space in Frankfurt lowers air temperature by 3 to 3.5°C, increases humidity by 5 to 10 % and ventilates pollution. Parks can filter out 80 % of a city's pollution. Inside streets, even in winter and without leaves, plants keep 60 % of their effectiveness in reducing pollution, attenuating noise and increasing oxygen. With a plant belt ranging from 50 to 100, the city recorded a reduction of 3.5°C in air temperature. The extent of cooling is influenced by the size of the green space since we recorded a reduction of 1°C for every 100 m [6]. This depends on the ratio of vegetation to built space. The greater the ratio, the better cooling: for example, a reduction of 0.8°C was recorded for a ratio of 10 % [7].

The cooling effect is mainly determined by species group, vegetation cover, and park size and shape. The temperature can drop by 0.02 °C for every percentage increase in plant cover [8].

The number of summer days with high levels of heat stress is increasing. To contribute to the understanding of the cooling effect of vegetation and the impact of greening strategies on urban heat resilience, the objectives of this paper are to examine the variation in the cooling effect of trees in the city center of Annaba (eastern Algeria) and its relationship with the urban fabric and to examine the thermal influence of trees on the surrounding environments.

Thermal comfort or, when exceeded, thermal stress, is determined by climatic conditions and physiological and psychological adaptation.

Thermal comfort indices are widely used in assessments of the outdoor thermal environment [9]. In this study, the Universal Thermal Climate Index UTCI is used.

UTCI is the equivalent environmental temperature derived from a reference environment. It is defined as the air temperature of the reference environment that produces the same stress index value in comparison with the reference individual's response to the real environment. It is regarded as one of the most comprehensive indices for calculating heat stress in outdoor spaces. This index was developed to have a standard criterion for assessing heat stress in the light of human meteorology and has proved more feasible than any other [10].

2. Case study: Center of Annaba

The city of Annaba was chosen as a case study because it represents a typical example of a Mediterranean city, located in eastern Algeria, with a latitude of 36.9 and a longitude of 7.75. (Figure 1)

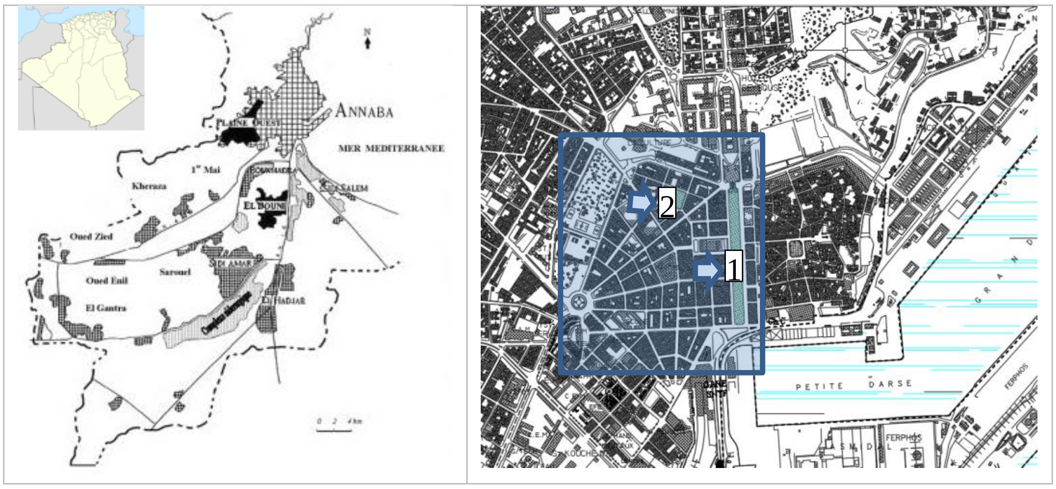


Figure 1. Location of the city center of Annaba. (1)”Cours de la révolution”, (2) ”Place George Ishak”

On the Spatial level, the city represents a patchwork of heterogeneous entities that consist of a traditional core, a colonial core, suburbs, large housing estates, informal settlements, self-built housing and slums.

In this study, the city center is selected. The urban fabric is characterized by a high degree of orderliness, with everything structured around a public space, the “Cours de la revolution”, a distinguished place in Annaba. The particularity of this urban fabric is that it combines two types of plots at once: one in a grid pattern, overlooking the “Cours” and connecting to the second plot at the level of a public market, the other in a concentric radio pattern, radiating out towards “El-Hatteb” [11].

Analysis of the variation in climatic parameters is studied along a seven-point path. It starts at the “Cours de la Révolution”, passes through rue “Tarek Ibn Ziad”, crosses rue “Khemisti Mohamed” and ends at “Place George Ishak” (Figure 2).

Figure 2. Case study presentation

The “Cours” is delimited by majestic buildings ranging in height from 12 to 18m. The most prominent are the town hall and the regional theatre. In the center is a vast esplanade, the picture of a real forum, ideal for strolling and meetings.

It has a linear geometry, a predominantly south-north orientation, an open space with a ratio H/W less than 0.25 and a vegetation fraction of 0.7. It shelters kiosks, most of which are located in the southern part, while the others are in the central part and are linked to ambulant activities.

“Place George Ishak” has a balanced, orthogonal geometry with a vegetation fraction of 0.78. Despite the presence of shady ficus trees and cafeterias reminiscent of the “Cours de la Révolution”, this square place is distinguished by its shape, which is close to a rectangle, and by its size and orientation, which obey the layout of the streets.

3. Methodology

The methodology consists of a comparison between several climatic and bioclimatic parameters such as air temperature (AT), wind speed (Ws), specific humidity (Sq), mean radiant temperature (Mrt) and UTCI, developed according to two scenarios. The first Scenario "A" is applied to the site as it is, while the second Scenario "B", is when no form of vegetation is sheltered.

The study is carried out using the three-dimensional numerical model ENVI met 4.0, which simulates microclimatic changes within urban environments with high spatial and temporal resolution. Model calculations are performed for the hottest period of the year (August 2022).

UTCI integrated with ENVI-met, has been widely used to assess urban microclimate. In the ENVI-met software, the BioMet sub-module (v. 1.0) calculates UTCI to evaluate outdoor thermal comfort.

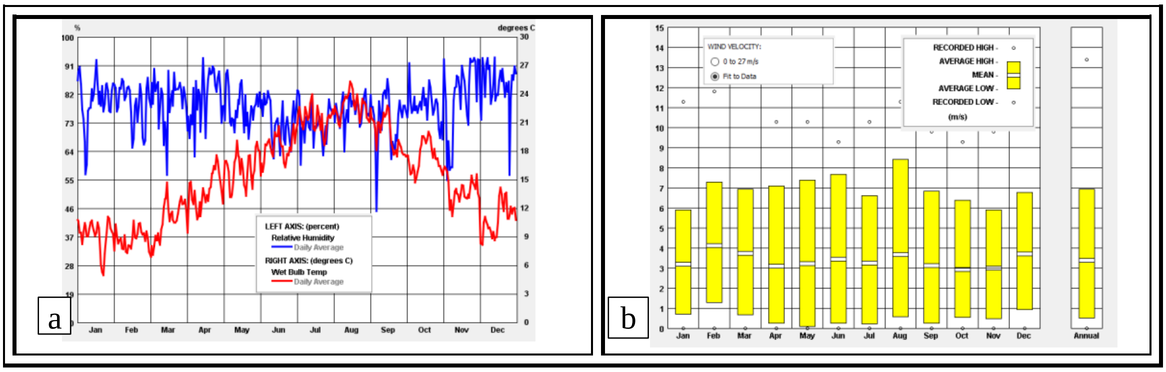
All simulation results referred to a height of 1.5 m above ground level. The assessment scale of UTCI is classified in terms of thermal stress as shown in the table below [10]:

Table 1. Universal Thermal Climate Index (UTCI) assessment

UTCI (°C)	Physiological cold stress
<-40.1	Extreme cold stress
-40.0 - -27.1	Very strong cold stress
-27.0 – -13.1	Strong cold stress
-13.1 – 0.0	Moderate cold stress
0.1 – 9.0	Slight cold stress
9.1 – 26.0	No thermal stress
26.1 – 32.0	Moderate thermal stress
32.1 – 38.0	Strong thermal stress
38.1 – 46.0	Very strong heat stress
>46.1	Extreme heat stress

4. Climate Analysis of Annaba

Annaba has a hot-summer Mediterranean climate (*Csa* in the Köppen climate classification) influenced by the sea and the Mountains (Edough mountains). It features relative seasonal variations characterized by warm to hot, dry summers and mild to cool, wet winters. The main wind direction is North to North-East with a maximum temperature of 31.4°C recorded during August and a minimum temperature of 6.9°C recorded during January. The major climatic challenges in Annaba, revolve around finding the best ways for protection from solar radiation and smart means for increasing air ventilation within the city (Figure 3).



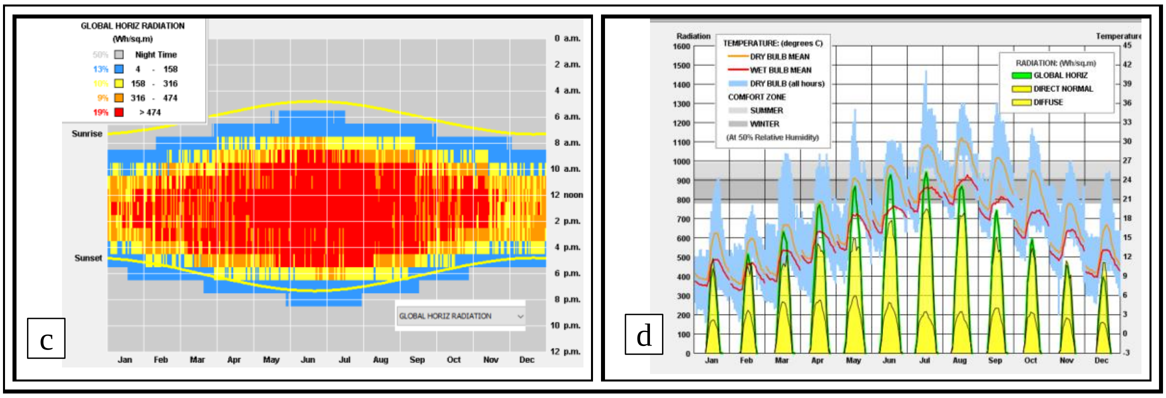


Figure 3. Climate data of the city of Annaba (climate consultant)
(a) Average temperature and relative humidity, (b) wind speed, (c) Global horizontal radiation, (d) Monthly diurnal averages

Relative humidity varies inversely with temperature. Despite some fluctuations, it reaches a maximum value of 76.55% recorded in January and a minimum value of 69.8% recorded in September.

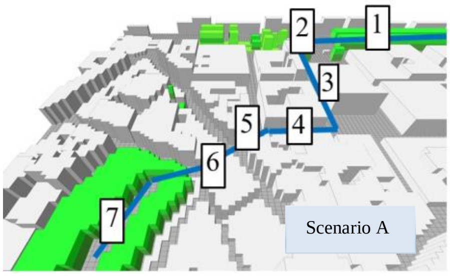
The average maximum horizontal radiation was 7443 wh/m² received during July, with a minimum of 2165 wh/m² received during December. The highest peak in global horizontal illuminance is recorded in summer (61790lx) and the lowest in winter (25933lx). [12]

5. Results and discussions

Generally, UHI intensity is related to the sky view factor and vegetation fraction. The sky view factor (SVF) plays a key role in describing urban climatology. Limited sky view leads to an increase in net heat storage in buildings and an increase in UHI. Trees also limit SVF but do not store much heat, although they do limit outgoing long-wave radiation [13].

According to Figure 4, Pt3 is the most exposed, with a recorded SVF value of 0.77 for both scenarios.

The lowest values are recorded in Pt1, Pt2, Pt7, due to the tree density. They are 0.18, 0.23 and 0.27 respectively. When trees are not considered, as in the second scenario, values increase to 0.8, 0.8 and 0.78.



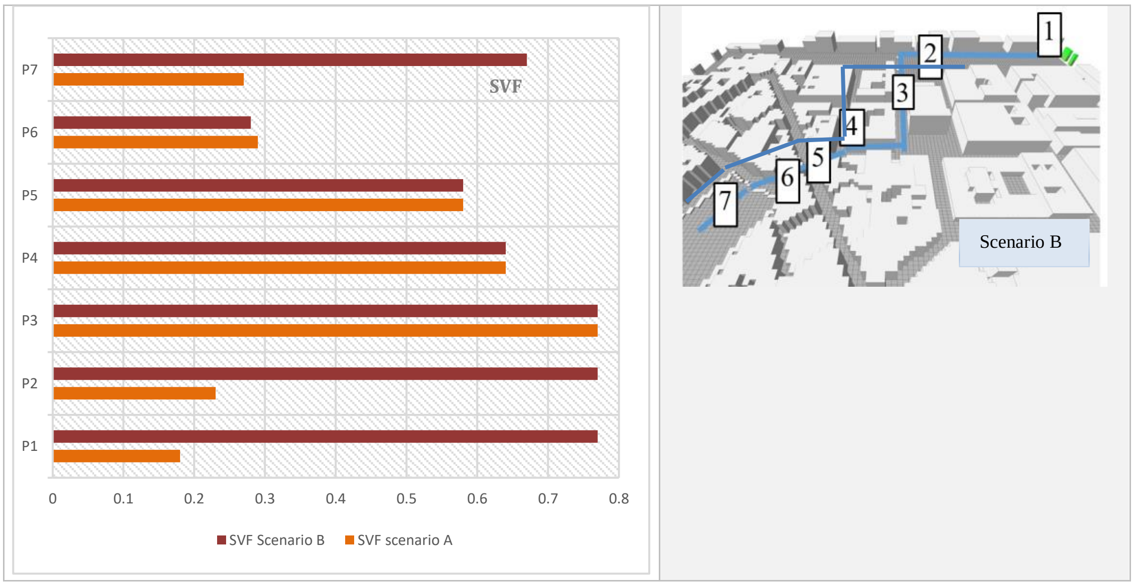


Figure 4. Sky view factor (SVF) comparison

5.1. Impact of vegetation on air temperature

Air temperature is the most important parameter for indoor comfort assessment. Over 50% of heat loss from the human body is due to convection with adjacent air. For outdoor comfort assessment, the effect of air temperature on thermal comfort is significant in the case of high wind speeds, where convection is accelerated.

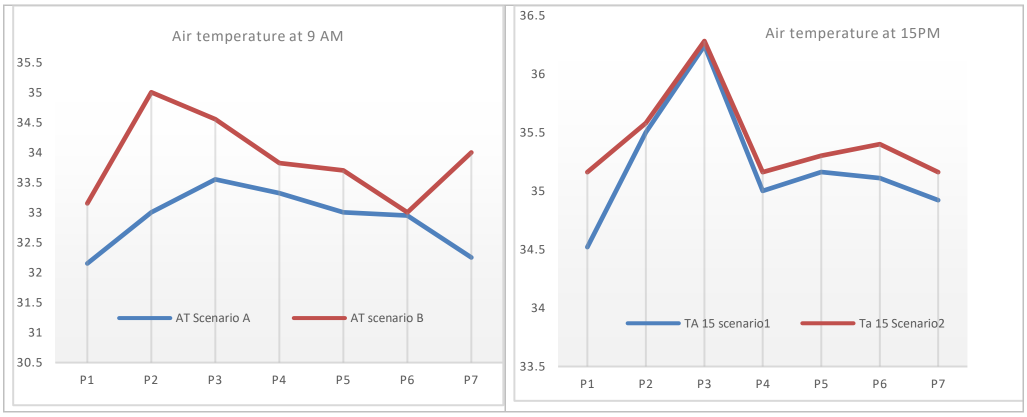


Figure 5. The impact of vegetation on air temperature

Scenario "A" shows lower air temperatures compared to scenario "B" (without vegetation). The difference in temperature varies from point to point (Figure 5). The coolest points are those in the “Cours de la Révolution” and “Place George Ishak”, due to the impact of vegetation in blocking solar radiation. A difference of 1°C was recorded for Pt1 at 9 am and 0.64°c at 3 pm. The difference for Pt7 was of 1.75°C at 9 am and 0.24°C at 3 pm.

The highest temperatures were recorded in Pt3 (SVF=0.77) for both scenarios A and B, obtained values are 33.55°C, 34.55°C at 9 am and 36.24°C, 36.28 at 3 pm respectively (Figure 5). The Maximum average difference, are obtained in the morning.

Steriling and Matzarakis [14], recorded a difference that varies between 0.9°c and 1°c. These results present a reduction of 0.1°c per tree. Almost the same result was found in our case in “Cours de la Révolution” where on 92 trees the average cooling was equal to 0.13°c by tree.

5.2. Impact of vegetation on relative humidity

Relative humidity values recorded early in the morning are high everywhere. Afternoon values are more varied and therefore more representative. Its significant effect depends on the evaporation of water and the consumption of energy when the air is dry. Relative humidity also depends on evapotranspiration, which in turn depends on CO2, soil humidity, leaf structure and density.

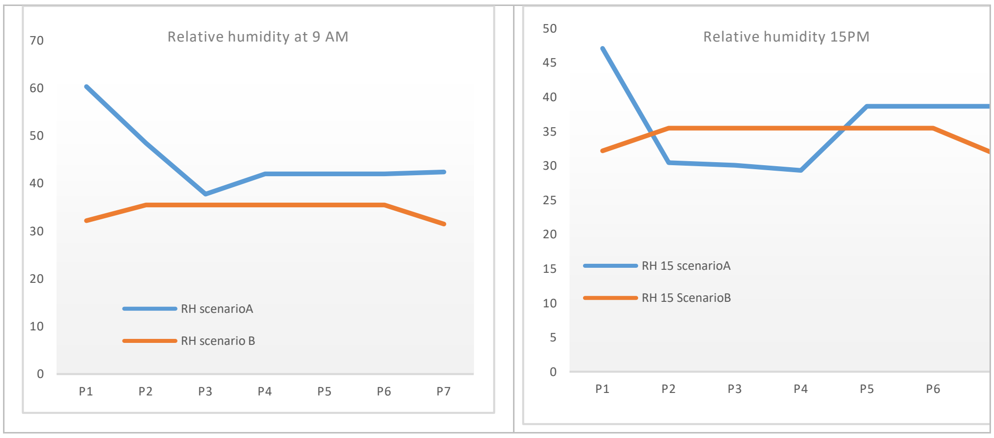


Figure 6. The impact of vegetation on relative humidity

In our study, the results obtained for relative humidity in the morning show that scenario "B" develops lower values compared to "A" (Figure 6). The increase in relative humidity in scenario "A" is caused by tree transpiration.

In the afternoon, relative humidity falls as temperature rises, leading to an increase in stomatal resistance and a consequent reduction in transpiration.

Figure 6 shows that the use of greenery and the planting of trees can lead to an increase in humidity from 3% (Pt7) to 18% (Pt1). The smallest differences in humidity are recorded at point 5 and 6, due to ventilation (sea breeze) and the average difference is of 9%.

It is noticed that the “Cours de la Revolution” has a humidity level of less than 75% in spite of the presence of trees and the humid nature of the area (humidity can reach 90 % and more). This is due to the good orientation (South-North) associated with a good distribution of ventilation corridors generated by buildings and a judicious choice of tree species.

5.3. Impact of vegetation on wind speed

In general, the effect of wind on comfort is divided into two categories: mechanical when wind speed exceeds 5m/s, and thermal when it is lower. The advantage of wind is that it increases heat transfer between the air and the human body, dissipating all the heat acquired by convection and increasing evaporation.

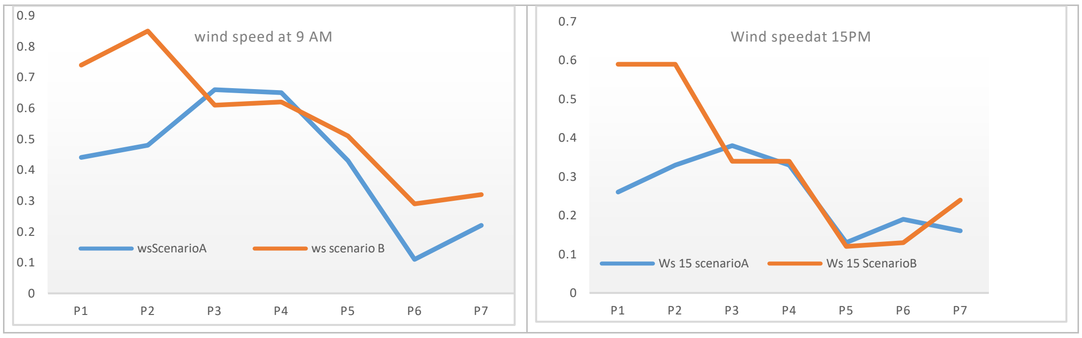


Figure 7. The impact of vegetation on air speed

In general, the wind speed recorded in scenario "A" is of the order of 0.44 to 0.24 m/s. This corresponds to a pleasant sensation. Figure 7 shows that wind speeds in scenario "A" are lower than in scenario "B". This suggests that the trees have had a filtering effect.

With regard to wind speed, an attenuation effect due to vegetation is recorded for Pt1 and pt7. This effect diminishes for points exposed to ventilation corridors generated by the canalisation effect (building layout)

5.4. Impact of vegetation on mean radiant temperature

The mean radiant temperature (Mrt) is the uniform temperature of surrounding surfaces giving off blackbody radiation, with which the human body exchanges the same radiant heat under open space conditions.

It presents the most important parameter in the human energy balance, particularly on hot and sunny days. It has a significant effect on physiological thermal comfort indices such as UTCI.

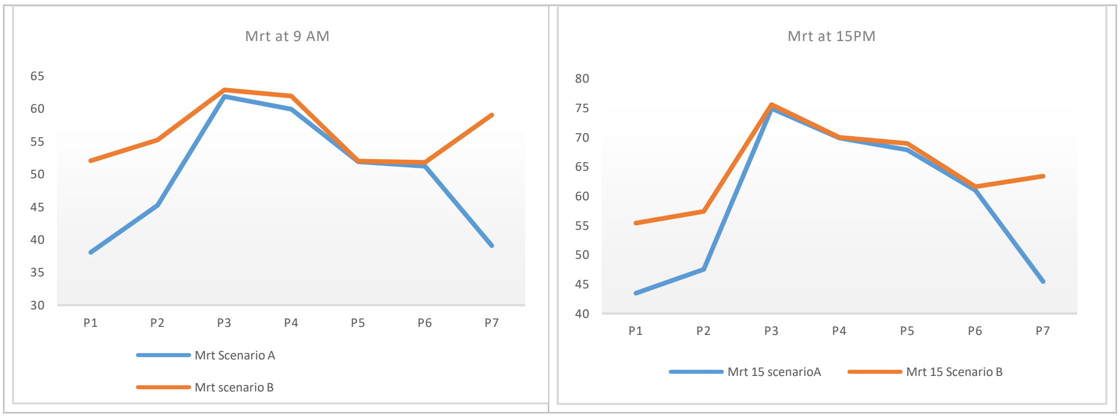


Figure 8. The impact of vegetation on mean radiant temperature (Mrt)

Mrt was calculated using the Envi-met model. The results show very distinct curves over the course of the day (Figure 8). The difference between the mean radiant temperature for the two scenarios is very significant, reaching 29.80°C at 3 pm.

A result close to that found by Matzarakis and al and Streilling and al [15] where they recorded a maximum difference which varies between 30.8°C and 34.1°C.

The presence of trees in scenario "A" had a significant effect on reducing mean radiant temperature and therefore thermal stress. The tree receives part of the direct solar radiation and another significant part of the radiation from surrounding surfaces such as walls and soil. The heat flux is dissipated by evapotranspiration and convective exchanges of sensible heat. The breakdown of heat gain into latent and sensible heat flux depends on water balance and wind conditions.

5.5. Impact of vegetation on UTCI

As with mean radiant temperatures, the two scenarios show two distinct curves, with a maximum difference of 16.63°C recorded at 9 am at Pt1 and Pt7.

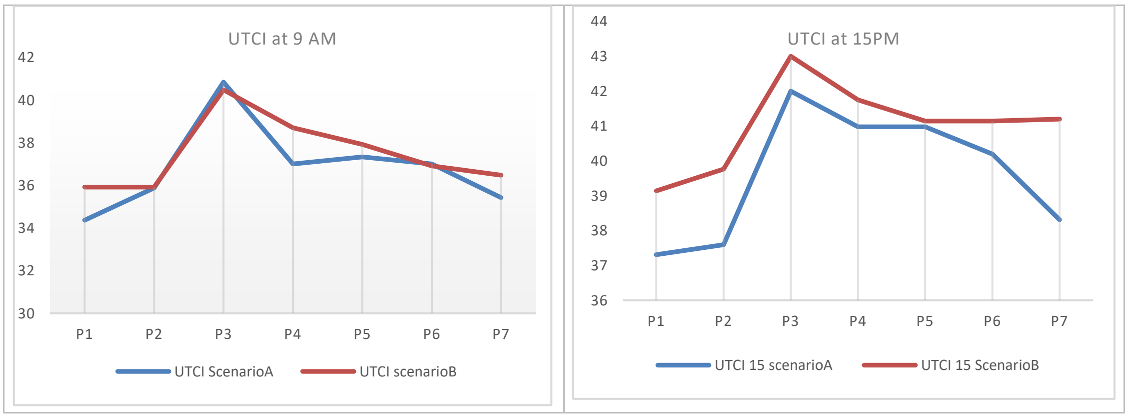


Figure 9. The impact of vegetation on UTCI

According to UTCI values, thermal stress increases after midday (Figure 9). We note that in scenario "A", the UTCI value in pt1 is 34.37°C at 3 pm, mainly due to the increase in mean radiant temperatures. This value corresponds to a strong heat stress according to table 1.

Even though vegetation had a significant effect when comparing the two scenarios. In the afternoon, the result values remain outside the comfort range and show a sensation of heat stress. It should also be pointed out that further studies are needed to revise these thermal stress thresholds in extreme heat cases specific to our climatic context.

In addition to the effect of vegetation, our tour of the city center highlighted the impact of the orientation and the SVF of the urban canyons on thermal stress. the N-S oriented street (Pt5 and Pt6) is exposed for less time to solar radiation than the E-W street (Pt3) and offers less uncomfortable comfort conditions than points located in streets oriented perpendicular to the route in this fabric.

6. Conclusion

Vegetation plays a major role in providing urban areas with resilience capacity for urban sustainability. This study suggests that the design of urban canyons with appropriate orientation can mitigate the UHI effect.

The results show that the modeling methods can simulate different design solution scenarios which can be validated and improved by further field studies.

The cooling rate of outdoor spaces depends on tree species. Consideration must be given to tree silhouette, trunk shape and height, crown, permeability, transmission, leaves shape and size, leaf area index density (LAID), growth regime, maintenance and irrigation.

It is also important to adopt a strategic position that takes into account the path of the sun and prevailing winds.

This study is the first step in an in-depth examination of urban heat resilience. It calls for further analysis and research on a larger number of case studies to show how cities can be designed to be more resilient to different types of urban heat.

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