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The simulation of the impact of the spatial distribution of vegetation on the urban microclimate: A case study in Mostaganem

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A R T I C L E I N F O

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A B S T R A C T

Increasing vegetation is one of the solutions proposed to mitigate the phenomenon of urban heat islands. The present research aims to study the effect of the spatial distribution of vegetation on the urban microclimate during the summer period. The city of Mostaganem with its Mediterranean climate was chosen as a case study. Based on meteorological data collected on a hot day in July, the study is carried out using the ENVI-met 4.4.5. Scenarios of different vegetation layouts were carried out. Air, mean radiant and surface temperatures are the microclimatic parameters that have been analyzed for each of the scenarios, and in order to study the outdoor thermal comfort, the Predicted Mean Vote (PMV) is chosen as the comfort index, it compares the average value of the votes of a large group of people on the thermal sensation scale. The study revealed that tree alignments can have a cooling effect on the city temperature close to 1.2°C. However, its impact on reducing the surface temperature can reach up to 4 °C. The introduction of vegetation on the site had the overall effect of lowering the air temperature and therefore relatively improving the level of comfort compared to the reference scenario. But, in order to reduce discomfort to an acceptable level during the day, vegetation can be simultaneously accommodated by city parameters such as urban form.

1. Introduction

Since the Industrial Age, the world urban population has steadily increased. However, the demographic dynamics accelerated sharply by the middle of the 20th century, which led to a significant increase in urbanization and the emergence of large cities and constantly evolving metropolises. Rapid urban growth makes residents more vulnerable to the impact of climate, which according to the 5threport of the Intergovernmental Panel on Climate Change (IPCC) could warm by 0.3 to 4.8 °C by 2100 (IPCC, 2013).

Algeria, a North African country with a Mediterranean climate is not spared from climate warming. Boucherf (2004) shows

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significant annual temperature and rainfall changes recorded in Algeria's northern regions. These changes are shown to have a strong interannual variation and vary with cities (Ibka, 2013).

Most urban areas consume a large part of fossil energy and electricity and produce more than 75% of anthropogenic carbon emissions (Brown, 2001; Grimmond et al., 2002; Svirejeva-Hopkins et al., 2004) and make a significant contribution to global warming. In addition to this warming component, cities have a singular thermal signature represented by an urban heat island (UHI) - a temperature gradient across the city characterized by a positive temperature difference between urbanized areas and their immediate surroundings (Oke, 1982; Bounoua et al., 2009, 2017, 2018; Imhoff et al., 2010; Zhang et al., 2012; Fathi et al., 2019).

For a long time, cities have tried to provide protection from solar heat. For example, the Mediterranean vernacular architecture and the M'Zab architecture in Algeria are good examples of houses that have been designed to adapt to the harsh climatic summer conditions of the region. While it appears that contemporary urban planning has lost these historic bioclimatic reflexes, there is today an emergence of interest in the urban heat island phenomenon which represents one of the major concerns of cities. The urban heat island is a phenomenon specific to the city. It is generated by its building materials which absorb energy faster than the surrounding vegetated areas (e.g., Bounoua et al., 2015), its shape (e.g., Zhang et al., 2012), and its socioeconomic activities (e.g., Grimmond et al., 2002). However, there is a clear scientific consensus that the UHI is dominantly caused by the reduction in the fraction of vegetation present in cities and the consequent reduction of plants' evaporative cooling (Bounoua et al., 2009, 2015). Vegetation, through its evapotranspiration capacity, shade, colour, and roughness, modifies the radiative, hydrologic, and aerodynamic properties of urban environment and acts as a strong modulator of the city's surface energy balance (Bounoua et al., 2015). These elements alter surface climate and confer to the city a strategic role of mitigation of the UHI and potential adaptation to climate warming (Mills et al., 1991; DeMunck et al., 2014).

Plants, present in the city in various forms and quantities, have different influences on its microclimate. For example, Oliveira et al. (2011) found that an urban park of 0.24 ha affects the air temperature of surrounding streets; this is based on in situ measurement campaign in the Campo de Ourique district in Lisbon. While Shashua-Bar and Hoffman (2002) and Shashua-Bar et al. (2010) have shown that there is an important correlation between canopy cover and the cooling effect of trees on a street in Athens, the authors calculated the cooling effect of trees by taking the difference between the calculated air temperature in the street with trees and that calculated in the same street without trees. On the other hand, an air temperature difference of 2 °C has been recorded between a grassy area in a park and asphalt and concrete surfaces in parking lots, from measurements of air temperatures over a park in Tama New town in Tokyo (Ca et al., 1998). Bounoua et al. (2015) argues that the choice and amount of plant species in cities play a commanding role in modulating cities' overall surface temperature and can be used as a potential 'cooling' mechanism to alleviate the excess warming generated by impervious surfaces and reduce domestic energy consumption.

The various studies on vegetation and its effect on the microclimate are generally carried out using models, tracing the arrangements (construction, trees, water bodies, etc.), then modeling their effects on temperature, wind, sunshine, and air humidity (Ali-Toudert, 2005; Robitu et al., 2006; Bouyer, 2009; Bounoua et al., 2009, 2015).

The increased presence of plants in cities, through their ability to absorb carbon dioxide as well as to clean and refresh the air, is a strategy of great interest to decrease the presence and effects of urban heat islands (Jutras and Roy-lefrançois, 2015; Bounoua et al., 2015). In this context, our work focuses on the impact of the spatial distribution of urban vegetation on the microclimate of an urban area in the city of Mostaganem, a medium-sized city located in north-west Algeria (Fig. 1). It covers an area of about 5000 ha and has a population of 350,245 inhabitants according to the National Statistics Office (General Census of Population and Housing RGPH, 2018). Its semi-arid climate is characterized by dry and hot summers and mild and wet winters. During the last decade, the city has experienced remarkable social and economic development which resulted in significant urban sprawl (Bentekhici and Youcefi, 2013;

Fig. 1. Location of the city of Mostaganem and the study area.

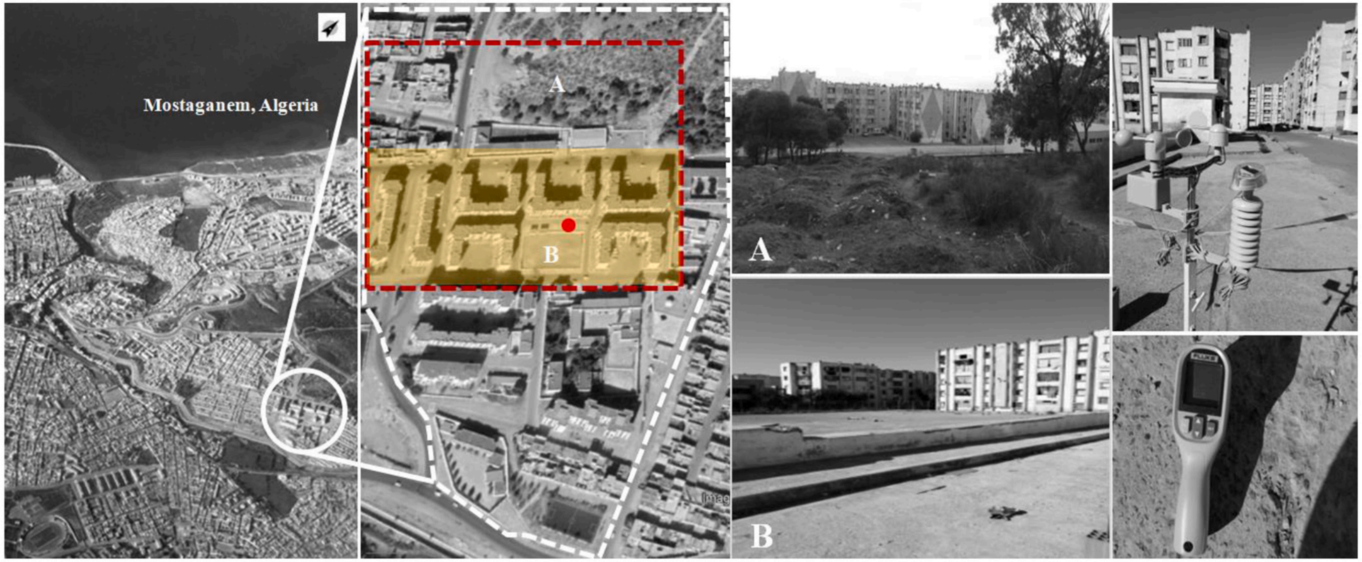

Fig. 2. Location of the study area in the city of Mostaganem (left 2 panels), white dashed line represents the estate of El Houria, red dashed line represents the limit of the study area. The yellow highlighted space represents the area selected for averaging the modeloutputs. The red dot represents the location of the meteorological station and the infrared thermometer (shown on the right panel). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Yamani and Trache, 2020). Its built-up area growth between 1977 and 2000 was estimated at 169% (Bendjelid, 2005).With its maritime frontage, Mostaganem has an appreciable tourism potential, and the study of outdoor thermal comfort in the city is of central importance in defining its touristic identity.

In this study, we use a three-dimensional urban microclimate model that accounts for radiative, aeraulic and vegetation effects, along with onsite measurements to assess the amplitude of the urban heat island in the core of the city of Mostaganem and simulate scenarios of vegetation configurations to best mitigate the surface temperature increase in the city.

2. Materials and method

2.1. The study area

The study's experimental site is in the estate *El Houria* located to the east of Mostaganem (Fig. 2). It is made up of 7 collective housing buildings, a market, an administrative building, and part of the *Dunes Forest* which limits the district to the north (Fig. 2A). This forest is exposed to different types of stress: water erosion, fires, and illegal logging, which cause it to be sparse with large clearings. The dominant tree species in the forest is the Aleppo pine (*P. halepensis*).

In the center of the site, a 50 m x40m space (Fig. 2B), formerly intended as a playground, now represents an empty space without any function. The buildings around this space are 15 stories high, and the average Sky View Factor (SVF) of the surrounding streets estimated with the Rayman software (Matzarakis et al., 2009) from the fisheyes type photos is 0.49 (Fig. 3).

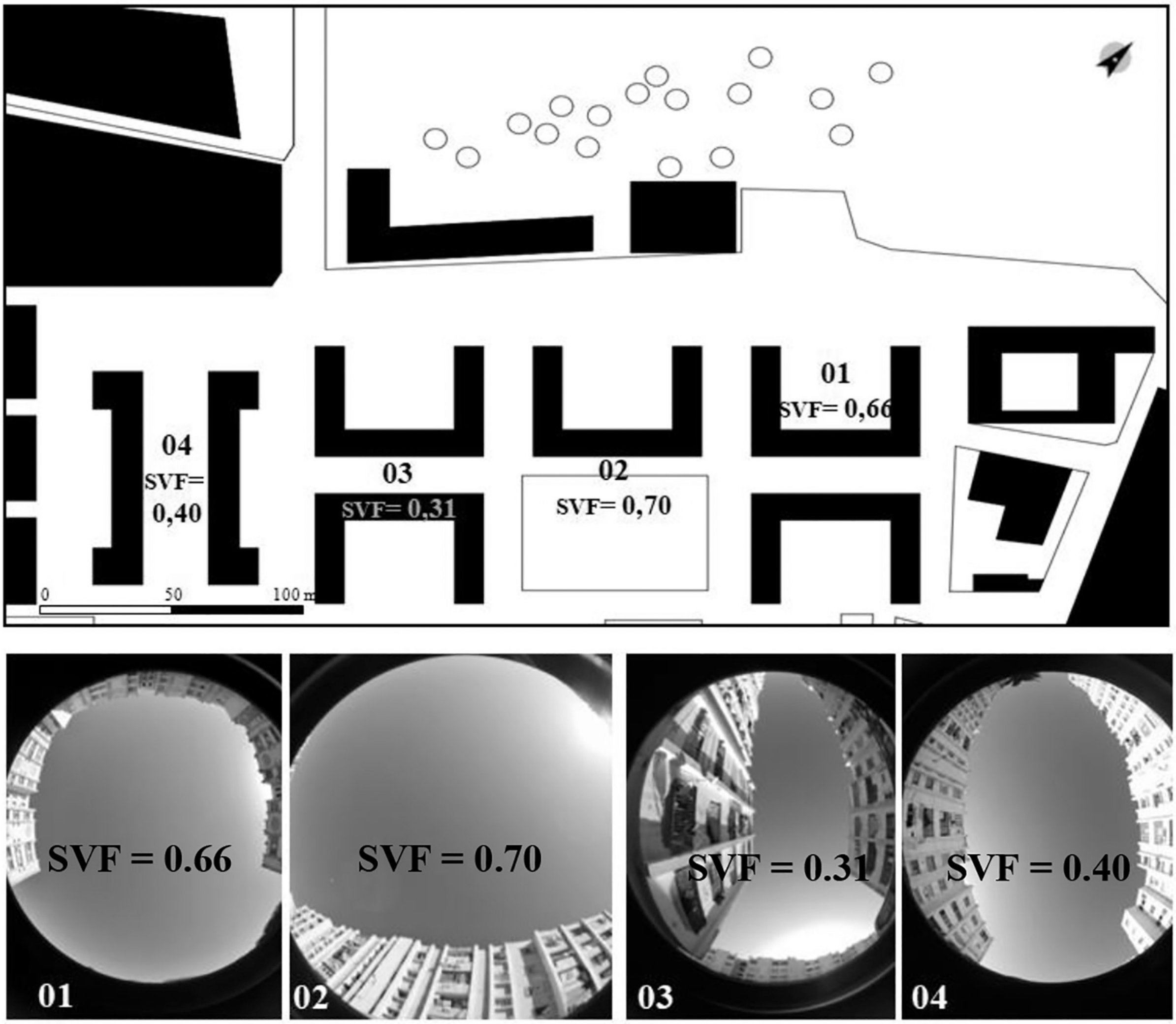

Fig. 3. Location of hemispherical photographs in the site and the sky view factor (SVF) values calculated by Rayman hemispheric pictures taken with camera equipped with a 180°Fisheye lens for 4 points in the site(bottom panel).

2.2. Field measurements

A campaign to measure microclimatic parameters was carried out in the experimentation site on July 25th, 2020. This day is considered a hot and dry summer day. The choice of the date and the purpose of these measurements is to calibrate the ENVI-met model before starting the parametric simulations.

The measured parameters include air temperature, relative humidity, wind speed and direction. These measurements were taken for 24 h continuously using a PCE-FWS-20 weather station installed at a height of 1.20 m above ground in the center of the study area, in a place open to the sky with an SVF of 0.7 (see Fig. 3) and protected from pedestrian traffic as shown in Fig. 2.

Simultaneously, the soil temperature was recorded manually with a FLUKE 59 MAX+ infrared thermometer. Because of the COVID-19 pandemic-imposed sanitation curfew, we were obliged to respect the confinement schedule, and restricted to take measurements only from 8 a.m. to 4 p.m. of the same day.

2.3. Model description

For this study, the simulation is carried out by ENVI-met4.4.5. This three-dimensional urban model was chosen because it can deal with the different aspects of the urban microclimate, both thermodynamic and aeraulic, while considering the effects of vegetation (Bruse and Fleer, 1998; Huttner, 2012). Unlike models dedicated to small-scale building or city analysis, Envi-met simulates the urban field on the scale of an urban fragment, from the canyon street to the neighborhood. In general, results obtained from this model are in good agreement with field measurements (e.g., Jansson, 2006).

ENVI-met is marked by its ability to handle high spatial resolution which varies between 0.5 m and 10 m and a time-step of 10s, as the interactions between the atmosphere, soil, vegetation, and buildings are simulated on a microscopic scale. The model has been widely used in research assessing the impact of vegetation and urban development on the microclimate and outdoor thermal comfort (Gusson and Duarte, 2016; Shinzato et al., 2017; Yang et al., 2018). Envi-met is composed of 3 models: an atmospheric model, a surface model, and a vegetation model. Vegetation is treated as a porous obstacle to wind and solar radiation. In addition, the physiological processes of evapotranspiration and photosynthesis are considered, and different types of vegetation with specific properties can be used. Soil is also considered to be a volume made up of several layers and can be of different types.

Since the release of version ENVI-met 4, the simple forcing function has allowed a better calibration between simulated and measured data (Huttner and Bruse, 2009). This function ingests the input data for initialization and calibration of the model. This study uses the initial meteorological conditions taken onsite (Table 1) as input to generate the simple forcing to the model. According to the Mostaganem's official meteorological station, the 25th of July 2020 is a day with stable weather conditions, low wind speed and without rainfall. The duration of the model simulation was 24 h, starting at 00:00 and ending at 23:00 for each simulation.

2.4. Model simulations

Once the model is calibrated, the study is realized by developing a control simulation and four distinct scenarios based on different vegetation arrangements.

The control simulation consists of reproducing the situation with the actual vegetation existing on the site (sparse trees) (Fig. 4A). The site with the dimension of 250 m x250m (62,500 m^2) is introduced into the model with grid geometry of 50x50x40 grids along the X, Y, Z axes respectively, and a grid spacing of 5 m along the 3 axes. With such fine resolution of 5 m, we ensure to adequately

Table 1
Initial setting for the scenario's simulations.

Start and duration of mode run	
Start date of simulation	25/07/2020
Start time	00:00:00
Total simulation times	24
Initial meteorological conditions	
Wind speed at 10 m heigh (m/s)	3
Wind direction (deg)	225
Roughness length at measurement site	0,01
Min. and max. Temperature of atmosphere (°C)	14 min – 37.1 max
Min. and max. Relative humidity in 2 m (%)	21 min – 88 max
Building temperature	25 °C (constant)
Output intervals	
Receptors and buildings (min)	30
All other files (min)	60
Initial soil conditions	Soil humidity (%) Initial temperature (°C)
Upper layer (0–20 cm)	70 19.85 (default values)
Middle layer (20–50 cm)	75 19.85 (default values)
Deep layer (50–200 cm)	75 19.85 (default values)
Bedrock layer (below 200 cm)	75 19.85 (default values)
Solar radiation	
Adjustment factor for solar radiation	1

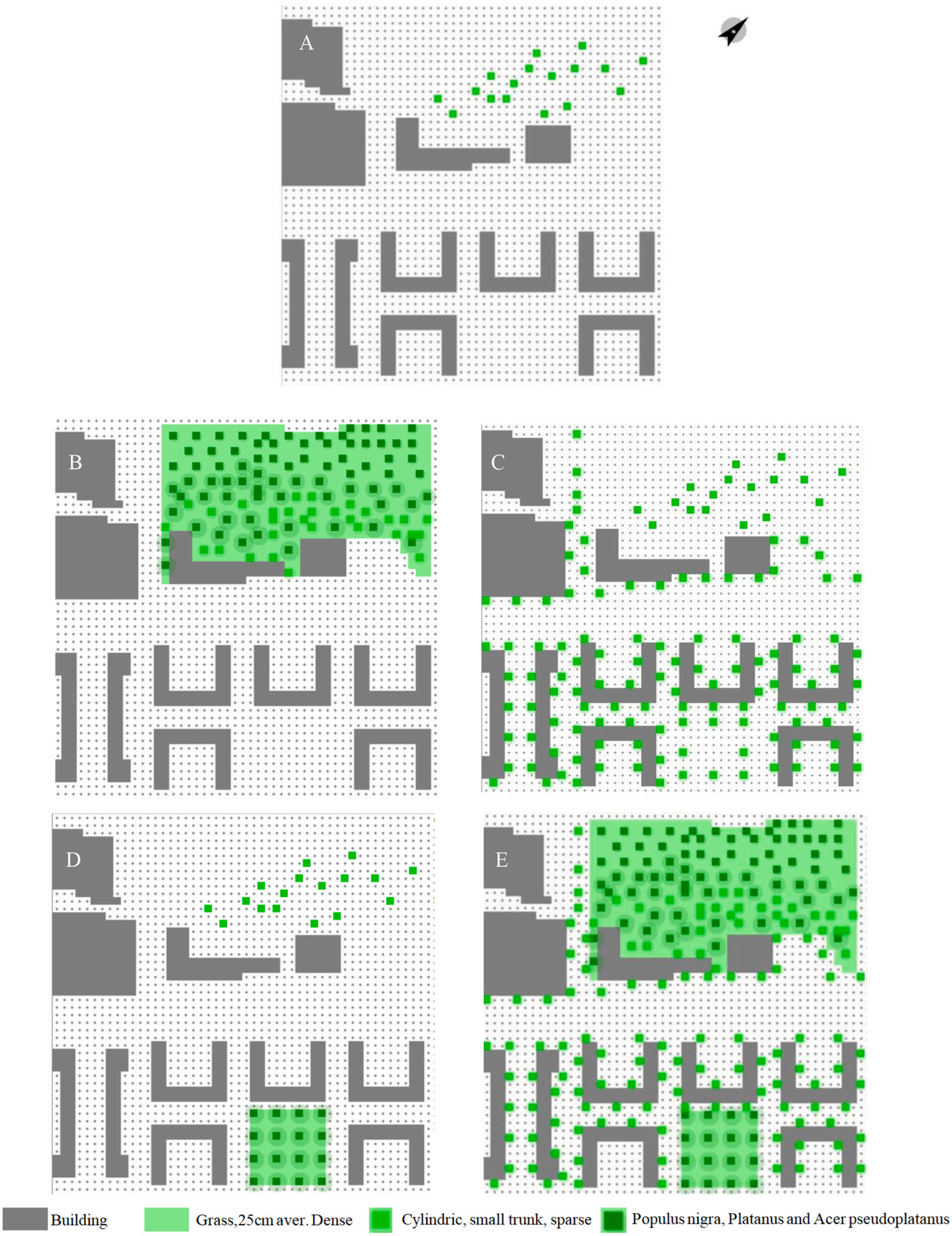

Fig. 4. Scenarios realized: (A) – Base case, (B) – Forest scenario, (C) - street scenario, (D) - park scenario, (E) - combined scenario.

characterize the vegetation and buildings and capture their complex interactions in the urban area (Huttner, 2012).

The first three scenarios were designed with different spatial arrangements of the vegetation, keeping the same urban form and materials, while the fourth scenario represents a combination of the three scenarios (Fig. 4B–E). For the first scenario**,** the goal was to densify the forest by grouping the vegetation in a single sector of the site, in the form of an urban forest to assess its effect on the microclimate (Fig. 4B). In the second scenario, the vegetation is arranged as rows of trees along the streets to assess the impact of randomly dispersed vegetation canopies on the area microclimate (Fig. 4C). Finally, in the third scenario, the central space between the buildings has been arranged as an urban park (Fig. 4D), which will allow us to assess the effect of an average-size urban park on the surface temperature of the experimental site. Finally, the fourth scenario provides the combined impact of the different vegetation arrangements on the surface climate (Fig. 4E).

Unlike the previous version of ENVI-met 3 which had a 1D plant database, the ENVI-met 4 version contains a three-dimensional one, with the possibility to create new types of vegetation and plants through existing tools (Duarte et al., 2015). In this study, the trees were personalized to adapt to the species present in the site's forest (needleleaf and broadleaf), with stress tolerance to the local Mediterranean climate. For the baseline case (A); cylindric, small trunk, sparse, with a height of 5 m tree type was used. This type corresponds to the same size and height of the trees existing in the *Dune'sForest* (Aleppo pine, with height of about 5 m). The forest has been densified in scenario (B) using Mediterranean forest tree types: conifers with a height of about 10 m for *P. nigra* and 20 m for *Platanus*, the soil has been replaced by an herbaceous carpet: *Grass 25 cm aver dense*, which according to Jean-Paul HETIER (Jean-paul and Charles, 1989) behaves in a different way in wooded areas of Mediterranean regions. For the second scenario, tree alignment (C) and the urban park (D) were designed with plane tree types and heights: *Platanus*(15 m) and *A. pseudoplatanus*(15 m). Indeed, the plane tree is an alignment tree used to structure major roads in colonial towns and villages in Algeria. Scenario (E) combines the same trees in the same arrangements as in individual scenarios.

Indeed, the change in the type, number and location of trees can influence the comparison of the impact of the spatial distribution of trees in different scenarios. But in our case the nature of the scenarios required a certain number, type, and location of trees. For example, the number of trees in the forest is greater than that of an average-size park. Furthermore, grouping the vegetation overlarge or medium surfaces or distributing it in the site to study the effect of the impact of spatial distribution, required different locations of the trees. In the scenarios, different tree types were used to assess the impact of the choice of plants on the urban microclimate.

For the irrigation hypothesis, new techniques are privileged, which have the advantage of minimizing the use of water through fair and localized irrigation, and therefore more efficient in reducing interception losses by evaporation. These techniques include irrigation bags, which have proven their efficiency in several cities around the world.

3. Results and discussion

The results of the simulations for different microclimate parameters such as air temperature, mean radiant temperature, surface temperature, humidity, wind speed, as well as comfort indices, were obtained and processed. The results are presented in the form of two-dimensional distribution and diurnal variations. Mean values and other statistics are also presented. For this study, the mean values are obtained over the highlighted area shown in Fig. 2. This area is considered important in the site because of the concentration of buildings. In general, the analysis of the mean value of an area in an experimentation site is more representative than that of a single receiver which represents one point in the site (Duarte et al., 2015). The vegetation in scenarios B and E is outside of this control area, but our goal was to analyze the effect of these scenarios on the control area. This can be achieved by the transport of part the vegetation effect (e.g., air temperature, relative humidity) in the selected zone by wind flow.

In the present study, the microclimate parameters analyzed are air, mean radiant and surface temperatures. They are simulated at the height of 1.5 m. To assess the outdoor thermal comfort, the Predicted Mean Vote (PMV) is chosen as the comfort index.

3.1. Air temperature

To check the difference between measured and simulated values; the root-mean-square error (RMSE), the mean absolute error (MAE) and the index of agreement (d) were calculated. The Index (d) is a standardized measure of the degree of model prediction error and varies between 0 and 1, with a value of 1 indicating a perfect match and 0 indicating no agreement at all (Willmott, 1981). Table 2 shows these indicators for the baseline simulation and indicates a good agreement between simulated and observed parameters. The air temperature simulation resulted in a RMSE of 1.20 °C with a mean absolute error of 0.85 °C. Except between 9 and 10 a.m. when the model underestimated the observed air temperature by 3.5 °C to 4 °C respectively, for the rest of the day the discrepancies between observed and simulated temperatures were within 1 °C (Fig. 5A), a value within the accuracy of the measurement instrument aboard the PCE-FWS-20 weather station (Manual Meteorological Station PCE-FWS-20, 2016).On the other hand, the simulation of the surface temperature, which in the model entails the resolution of the surface energy balance, showed a better agreement with day time measurements (Fig. 5B). The precision of the 59 MAX + infrared thermometer is reported to be 2 °C (Infrared Thermometer 59MAX/59

Table 2
Quantitative measures of performance for the baseline simulation.

Variable	Root mean square error (RMSE)	Maximum absolute error (MAE)	Index of agreement (d)
Air température °C	1.20	0.85	0.98
Surface température °C	1.99	1 .46	0.98

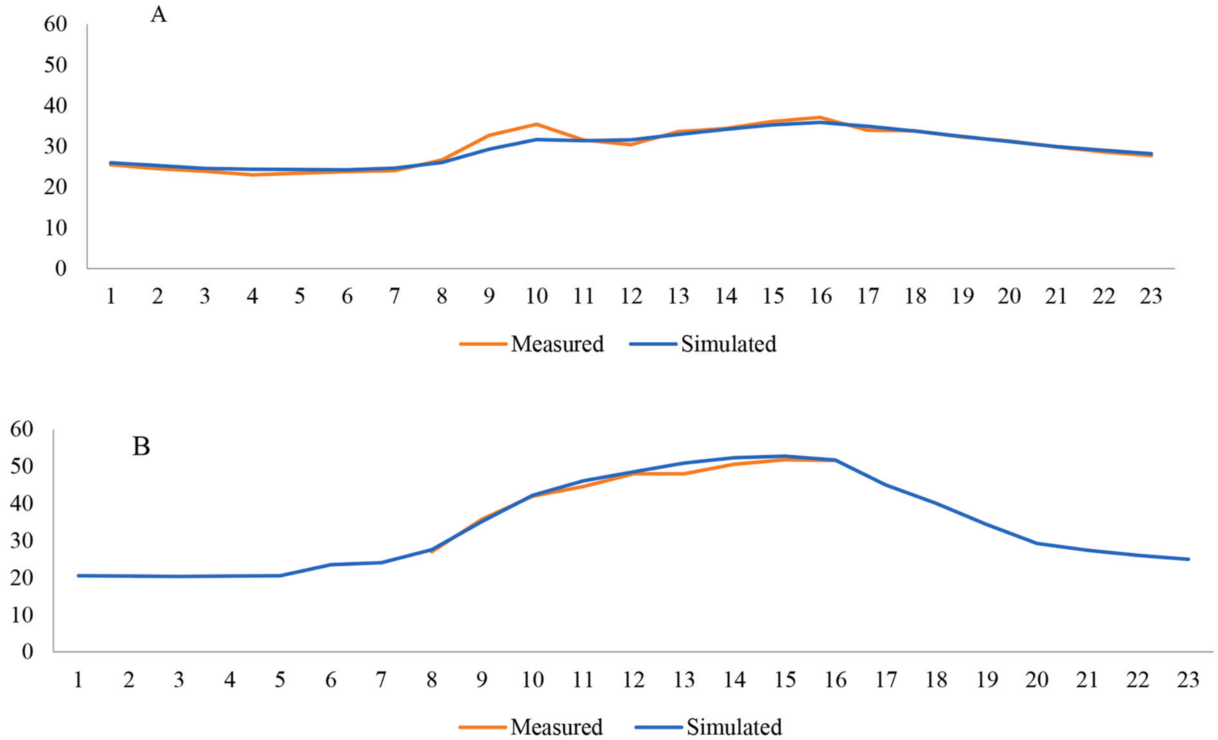

Fig. 5. Measured on site and simulated temperatures for the baseline simulation A): air temperature and B) surface temperature. For the surface temperature, measurements were restricted by Covid19 - imposed curfew from 8 am to 4 pm.

MAX+, 2013). For reasons beyond our control (COVID19 imposed curfew), our experiments were shortened. However, our simulation's objective was to assess the effect of spatial distribution of vegetation on the urban microclimate during the summer period, with the hypothesis that abundance of non-stressed vegetation may mitigate the urban heat island phenomenon. Therefore, and in this context, the comparison of results between scenarios is much more valuable in terms of interpretation than the difference between measured and simulated air temperature.

The spatial distribution of the air temperature for the baseline scenario (A), as well as differences between the various scenarios and the baseline at 2 p.m., a time of maximum insolation, is shown in Fig. 6. For the baseline (A), the simulated air temperature around the building area (see Fig. 2B) varies between 33°Cand 34 °C, slightly less than that between the buildings on the left side of the site that exhibited temperatures greater than 36 °C. However, in the current forest (see Fig. 2A), the simulated temperature varies between 34 °C and 35 °C, higher by about1°C than that of the bare ground around the buildings. This is believed to be due to plants being physiologically stressed. The physiological stress is most likely a combination of both high ambient temperature and lack of rainfall during this time of the year over the region of study. Indeed, the main species populating the existing forest is Aleppo Pine – a needleleaf evergreen tree composition, characterized by a half inhibition temperature for photosynthes is around 30 °C (Sellers et al., 1996). This means that at this temperature, the trees close their stomates by half and therefore most of the absorbed solar energy is shunted to sensible heat instead of latent heat of transpiration, thus increasing the temperature. Our simulation over this area, resulted in temperatures between 34 °C and 35 °C, which is above and beyond the tree's half inhibition temperature threshold. On the main road made up mainly of asphalt, separating the buildings from the forest, the simulated temperatures are highest and vary between 35 °C and 36 °C (Fig. 6A). On the left edge of our study area, a different urban fabric exists; it is made up of a group of two stories residential housing built with concrete and still. These constructions warm up quickly during the day and reach a maximum around mid-day. In the event of north-westerly breeze, the heat is advected between the buildings and along the street lines.

In the first scenario (Fig. 6B) where the forest has been densified by trees having more tolerance to heat and drought stresses, the model simulated a remarkable cooling up to 1.20 °C over the densely forested area while the surrounding areas exhibited a significant cooling, ranging between 0.40 °C and 0.80 °C. This cooling up, may also be due to change in ground cover. Elsewhere, no significant change in temperature was simulated. This result shows that the densification of the forest by appropriate tree species has allowed the creation of an island of freshness and is in line with previous studies (e.g.,Imhoff et al., 2010) that show, in cities built in arid areas, irrigated trees do contribute to cooling the urban core and creating an urban heat sink, compared to their desert-like surroundings.

In the scenario of tree alignments (Fig. 6C), the air temperature dropped between 0.40 °C and 0.80 °C in most of the areas covered by trees. This slightly weaker cooling was expected and is due to the sparse distribution of trees. However, because of the weak wind from the southwest direction (along the street) there was no cross wind mixing and the street temperature exhibited no significant change. Similarly, in the park scenario (Fig. 6D) the impact on temperature was a cooling between 0.40 °C and 0.80 °C with a small

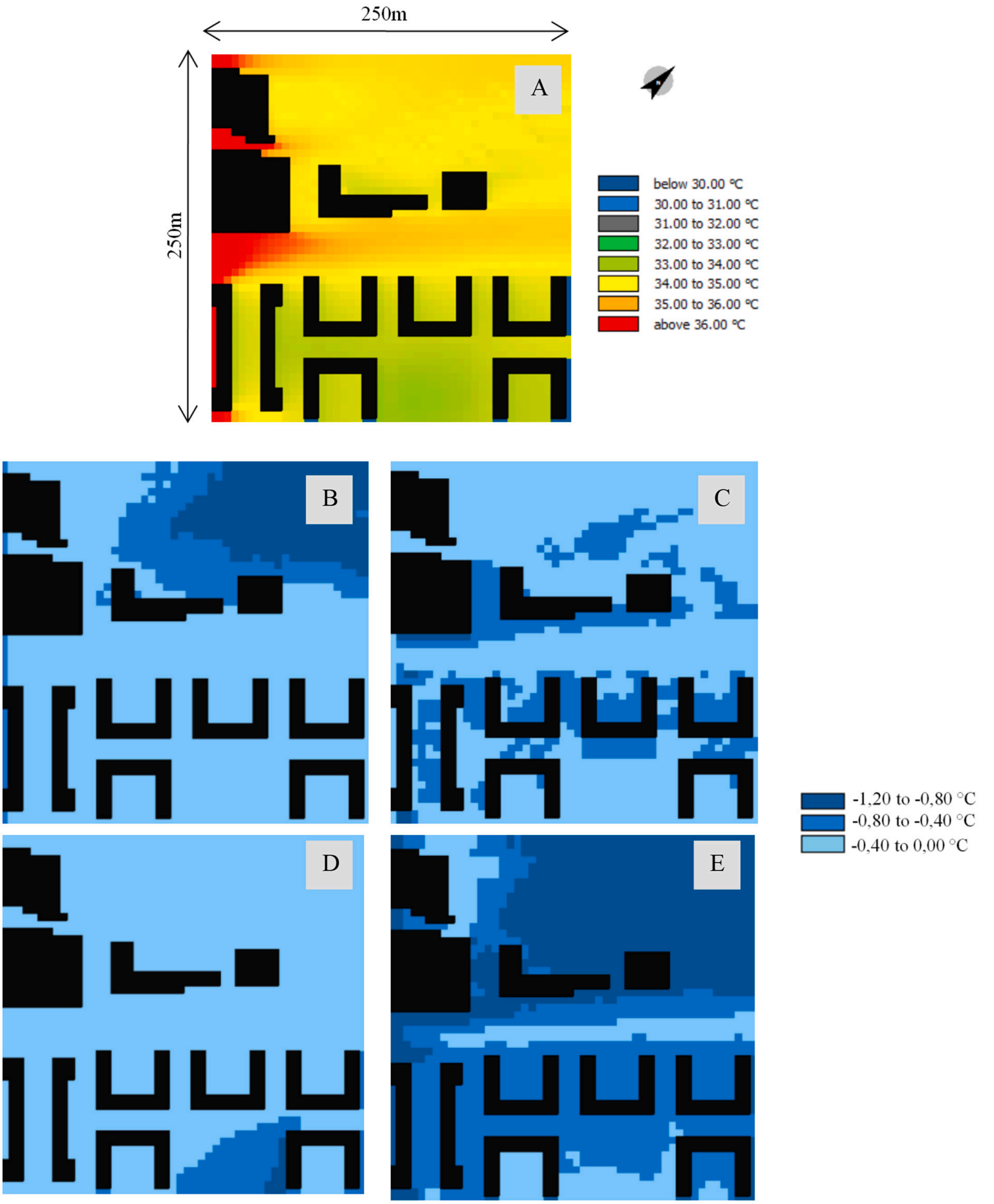

Fig. 6. Air temperature result at 2 pm for: (A) the base scenario, (B) the difference between the air temperature of the scenario and the baseline: (C) same as (B) but for tree alignment scenario, (D) same as (B) but for the park scenario, (E) same as (B) but for the combined scenario. Warm air on the left edge of the domain in the base scenario is due to advection by northerly breeze from hot, concrete-built residential housing.

area in the building's shadow showing decrease in temperature reaching 1.2 °C. In areas where no trees were added, the temperature difference between the scenario and the baseline was confined between −0.40 and + 0.00 which is considered not significant.

In all three scenarios, the air temperature decreased. However, the forest densification appears to have the strongest impact on the temperature whereas the street alignment cooled a larger surface.Therefore, considering the area average temperature as a metric, the street alignment scenario appears to be the most suitable configuration for modulating down the city's temperature as it covers more surface. This result was expected as the scenario has the largest tree fraction and is in line with results from several previous studies (Spronken-Smith and Oke, 1998; Hamada and Ohta, 2010; Duarte et al., 2015; Yang et al., 2018).The fourth scenario (Fig. 6E) basically resulted in the spatial superimposition of the first three scenarios' effects. While having the same cooling intensity, the spatial coverage increased to affect the entire area.

We constructed the analog of scenario E by adding the separate effects of scenarios B, C and D averaged spatially over the entire area at 2 p.m. (Table 3). The similarity between the impact obtained using the analog and the combined scenario indicates that the interactions between land cover and air temperature are linearly additive and can then be treated independently. That is, during days without wind, as is the case in these simulations, the temperature of each parcel of land is determined by its vegetative cover effect which appears to be local. This linearity is unlikely to sustain moderate winds which will advect temperature horizontally and homogenize it over the entire area, suggesting that high density trees will have a stronger effect.

Fig. 7 shows the diurnal variation of the area-average temperature difference between the first three scenarios and the baseline and clearly reveals the role played by the vegetation in the modulation of the air temperature within the urban setting. It is noticeable that during night time when vegetation is dormant and there is no transpiration, the three scenarios have about the same area average temperature and are warmer than the baseline. This is more evident for the forest and park scenarios than the street scenario. During night time, trees act as a barrier to outgoing longwave radiation and trap it within the surface boundary layer. In the baseline scenario, characterized by few sparse trees in the forested area, more of the outgoing longwave radiation is lost to the atmosphere. To the contrary, during daytime when trees are physiologically active, all three scenarios are cooler than the baseline, especially between 2 and 4 p.m. local time when the evaporative cooling and the shading in the tree alignment scenario have resulted in an area average cooling close to 1.2 °C. This suggests that the choice of tree species and their density play an important role in the cooling of surface temperature and should be considered when planning for urban design, heat mitigation and energy consumption (Bounoua et al., 2015).

3.2. Mean radiant temperature

The main element that influences the mean radiant temperature (MRT) is the trees' and buildings' shade. Shade can limit the amount of solar radiation received by buildings and streets, therefore reducing the amount of heat absorbed by hard surfaces. The simulated mean radiant temperature at 2 p.m. under the shade of buildings and trees varied between 50 °C and 53 °C during the baseline simulation. During the three scenarios, the addition of trees resulted in an average mean radiant temperature cooling ranging from −3.72 °C for the park scenario to −10.58 °C for the tree alignment scenario (Table 4). Like the air temperature, the diurnal variation of the MRT for the three scenarios (not shown) revealed a slight warming during the nighttime and a strong cooling during daytime for all three scenarios compared to the baseline. At 2 p.m. local time, the greatest difference is observed for the tree alignment scenario (C) with a maximum MRT cooling of −10.58C°. This is due to the shade being equally distributed on the site, resulting in a cooler mean radiant temperature. Indeed, in their study, Yang et al. (2018) have shown that vegetation has a more significant impact on the MRT than other parameters such as the albedo of materials.

3.3. Ground surface temperature

The contribution of vegetation in reducing the surface temperature is more evident. The replacement of the three zones by trees resulted in a ground surface temperature reduction from −3 °C to −4 °C, with the tree alignment scenario causing the maximum cooling of −4.2 °C at 2 p.m. However, it is worth noting that our simulations resulted in a reduction in ground surface temperature much less than that simulated by Spangenberg et al. (2008) who found a ground surface temperature reduction of 12 °C after the planting of dense trees. We believe that the difference in the intensity of the cooling resides in the fact that, in Spangenberg et al. (2008) study, the height to width ratio in the canyon of 2.2 was almost double that ofour study.

In the baseline scenario, the simulation recorded a maximum ground surface temperature varying between 53 °C and 56 °C, over the asphalt's surfaces. This material covers most of the ground surface of the site (streets and spaces between the buildings) with almost no vegetation except for the trees of the forest. The simulated ground surface temperature difference between an asphalt alley within the buildings in the baseline and the tree alignment scenario is −3 °C. In the case of the forest where the soil is bare, the ground surface temperature recorded at 2 p.m. was between 42 °C and 44 °C. After the arrangement of trees and the herbaceous carpet, a decrease of

Table 3
Average temperature at 2 pm and difference between scenarios and baseline. The value of the analog has been obtained adding differences of the three scenarios (see text for details).

	Baseline	Forest	Street trees	Park	Combined	Analog
Temperature	33.93	33.5	33.55	33.74	32.89	
Temperature difference	–	−0.43	−0.38	−0.19	−1.04	−1

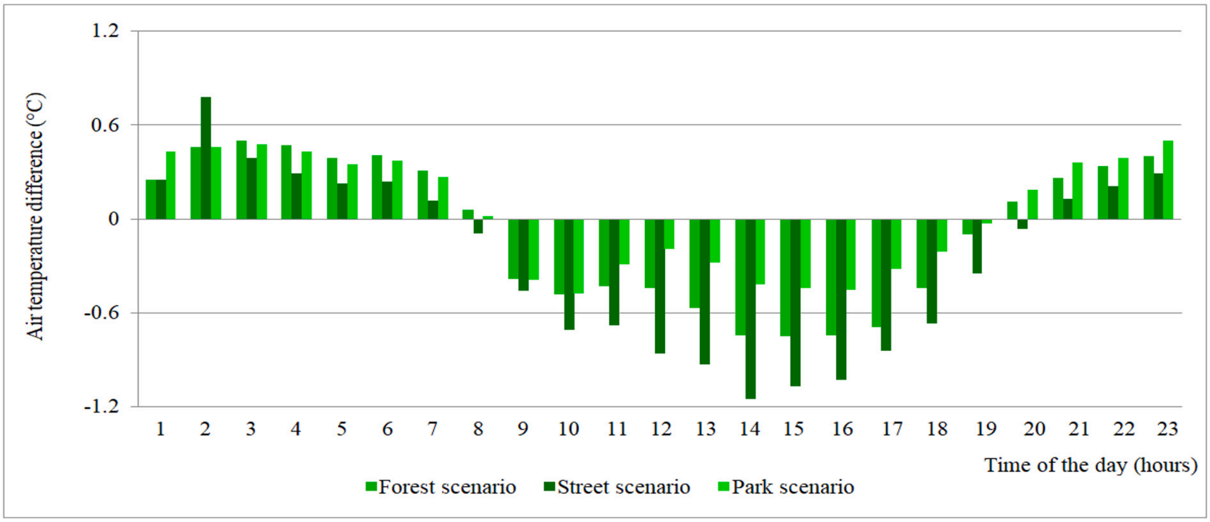

Fig. 7. The difference between the average air temperature of the base scenario and the three vegetation scenarios in the selected area.

Table 4
Average mean radiant temperature difference between scenarios and the baseline at 2 pm.

Forest scenario	Tree alignment scenario	Park scenario
−4.88 °C	−10.58 °C	−3.72 °C

4 °C was simulated.

El Houria subdivision emerged in the 1990's following an ill-conceived urbanization policy fueled by a sudden increase in population and housing demand. The situation led to a rapid creation of dense neighborhoods neglecting the basic environmental rules of choice of material, green space and inclusion of water bodies in urban settings. These all added up to create an urban space with high surface temperatures in summer. The difference in temperature between the impervious urban core and the surrounding vegetated land suggests an urban heat island of about 1.2 °C. Note that surface urban heat islands are relatively related to the size of the urban

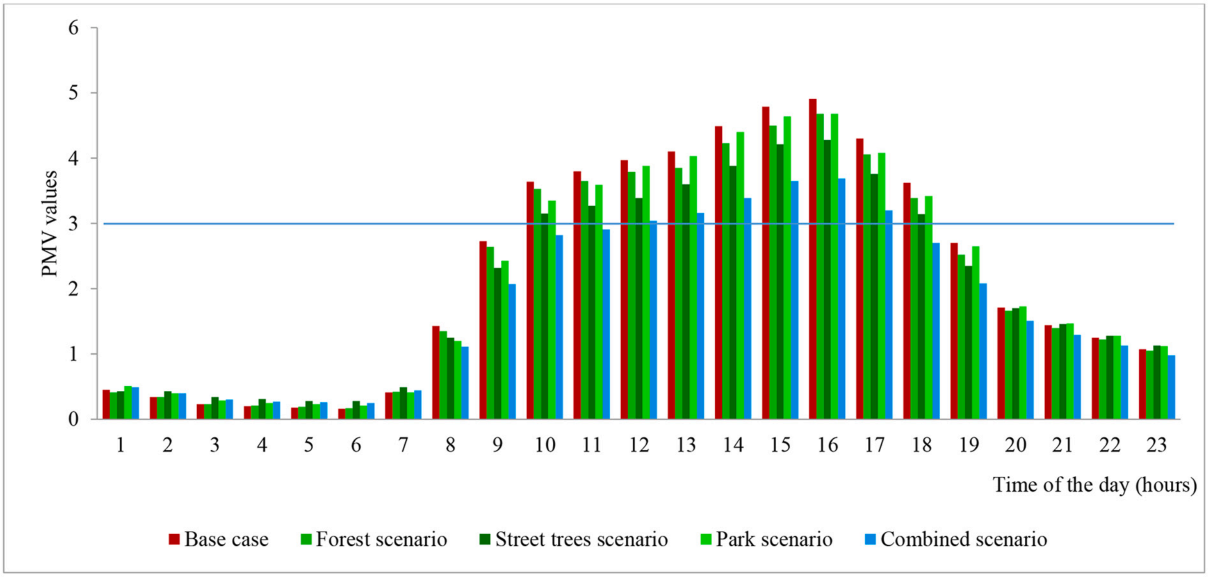

Fig. 8. Diurnal variation of the PMV for the four scenarios as compared to the baseline. The horizontal light-blue line represents the highest discomfort value of 3 (see text for details). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

area (Li et al., 2017).

3.4. Thermal comfort parameter

The Predicted Mean Vote (PMV) is chosen as an evaluation index of thermal comfort. It compares the average value of the votes of a large group of people on the thermal sensation scale using the following 7 points: +3 very hot, +2 hot, +1 slightly warm, 0 neither hot nor cold, −1 slightly cold, −2 cold, −3 very cold (Fanger, 1970). Fanger's model is not perfect and has been questioned by other researchers (e.g., Fergus Nicol, 2004), and this is true for most models. However, within the scope of its application, Fanger's PMV is widely used to evaluate the thermal comfort of indoor human body. The PMV model is developed based on experiments where human body is close to thermal neutral state, when there is a linear relationship between skin temperature, perspiration rate and human activity intensity.

Fig. 8 shows the diurnal variation of the PMV values for the four scenarios as compared to the baseline. To be considered neutral, the PMV needs to be around zero so that the sensation is neither hot nor cold. It is clear from the results that none of the four simulations correspond to the neutral level of comfort. Indeed, the only time when PMV values are between 0 and 1 is during nighttime between 1 and 7 a.m. local time (Fig. 8). This level of nocturnal comfort is basically determined by the ambient climate and not by the composition of the urban area. During this period, the PMV values are similar for all scenarios including the baseline. It is remarkable, however, that as the sun rises, the PMV quickly increases to reach a level beyond the tolerable value of 3 at 10 a.m. and remains higher until about 6 p.m. for all cases. This suggests that during summer, in the city of Mostaganem, the level of heat discomfort is high during the entire day and part of the evening, having both health and energy consumption implications. The introduction of the vegetation on the site had an overall effect of lowering the air temperature and therefore relatively improved the comfort level compared to the baseline scenario. Individually, the street alignment scenario appears to yield the most comfort compared to the other two scenarios. However, it is not enough to reduce the discomfort to an acceptable level during the daytime (Fig. 8). The fourth scenario, which combines all three scenarios, resulted in comfort levels much less than the maximum of 3 for most of the daytime except from 1 to 5 p.m., suggesting that the city needs to not only have a higher tree density but also tree species that are heat and drought resistant. The diurnal variation of the PMV values for all cases, including the baseline, informs about the capacity of heat retention in the city. The solar energy absorbed by the building material peaks at around 4 p.m., and while the local sunset in the city happens between 8 and 9 p.m., the temperature remains high all the way to after midnight leading to PMVs greater than 1 for all cases. Given the impact of the vegetation scenarios and the baseline temperature, it should be theoretically possible to arrange land cover elements (trees, buildings, water bodies, grassy areas) in such proportions to obtain a desired surface climate with a PMV less than 3 during the peak of solar insolation. It is speculated that irrigation of trees may have brought temperature further down in all cases, thus leading to a PMV value for the combined scenario that is within the acceptable range of 1 to 2. To reduce discomfort to an acceptable level during the day, vegetation can be simultaneously accommodated by city parameters such as urban form, since the urban configuration can modify the energy balances and influence the local thermal environment (Yue et al., 2019).

4. Concluding remarks

The city of Mostaganem is relatively small compared to other cities in Algeria, but it is in full economic expansion and growing rapidly. Most of its urbanization is happening on the fertile agricultural land of the coastal zone. Our analysis shows that air temperature in the city can reach more than 36 °C during daytime and is highly correlated to land cover with the vegetation playing an important role. The surface temperature is even warmer. Within the city limits, in scenarios which introduced distributed vegetation, temperature decreased up to 1.20 °C. Considering the area-average temperature change as a standard for comparison, we find the street alignment scenario to be the most suitable configuration for cooling the city's temperature as it covers more surface with heat- and drought-tolerant trees. The densification of an existing urban forest and a creation of a park also reduced temperature but not as much as the street alignment scenario. In fact, our study stands at odds with a previous study by Oliveira et al. (2011) which found that an urban park of 0.24 ha was enough to affect the surface temperature. Our park scenario resulted in the smallest impact and none of the scenarios reduced the temperature to an acceptable daytime comfort level.

The role of vegetation in modulating the urban temperature has been discussed in several studies (e.g; Duarte et al., 2015; Bounoua et al., 2015; Lachir et al., 2016). Through evaporation, trees create a cooling mechanism and, if chosen appropriately and planted in abundance within the urban tissue, they could mitigate urban heating, decrease the risk of health issues, and reduce energy consumption.

Furthermore, the vegetation helps to accompany the architecture by underlining its heights and volumes while creating shade for pedestrians and providing a comfortable outdoor temperature. In many places green roofs have been considered. This design choice takes advantage of the surface of the buildings by introducing plants and embracing their benefits. Known as the third dimension of urban gardening, these benefits associated with Mediterranean climate have already been evaluated (e.g.,Cascone, 2019). The green roofs must meet standards in terms of execution and choice of appropriate vegetation. Several studies have shown the ecological impacts of these vegetated roofs, in that they improve thermal comfort (Di Giuseppe and D'Orazio, 2015), control stormwater runoff (Carter and Rasmussen, 2006), reduce energy consumption (Castleton et al., 2010) and lower the concentrations of phosphorus, nitrogen, and heavy metals in the runoff (Cascone, 2019). It is therefore time for the city's representatives to act in this regard and for architects and urbanists to take vegetation into account in the early stages of design. Not only must vegetation be an integral part of architectural and urban projects, but it must also be addressed in legal texts pertaining to urban regulations as well to mitigate the urban warming.

Author statement

B.N. and B.L. designed the study and the scenarios. B.N. staged and performed the simulations. B.N. and B.L. performed the main analysis with contributions from A.M. and M.M, E.L and N.J.

B.N. led the writing of the paper with help from B.L. N.J. and E.L, A.M. and M.M.

N.J and E.L helped edit and format the paper, the figures, and the tables. All authors have read and agreed to the published version of the manuscript.

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