OPTIMISING THE URBAN ENVIRONMENT THROUGH HOLISTIC MICROCLIMATE MODELLING: THE CASE OF BEIRUT'S PERI-CENTER

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ABSTRACT

Various studies have suggested that urbanisation may significantly alter microclimate conditions. To address this, expanding urban vegetation cover can be used to aid the dissipation of excess heat through enhancing evapotranspiration. This study aims to numerically assess and optimize the use of green corridors to reconnect leftover and in-between building plots within Beirut city centre through the use of ENVI-met V4, a holistic microclimate modelling system used to optimize green infrastructure strategy to improve pedestrian comfort levels.

Analysis results illustrate the significant effect of urban intervention strategies in decreasing pedestrian heat stress, where the air temperature is reduced by 4-5 (PET) °C. Furthermore, a correlation between the leaf area density and PET values was identified.

In the wider context, this work supports the case for the application of ecological urbanism supported by integrated micro-urban environment modelling as a catalyst for the improvement of the quality of urban space.

Keywords: urban heat island, green infrastructure, human thermal comfort, PET, ENVI-met V4, Beirut.

INTRODUCTION

Expanding urbanization has a significant impact on the thermal and aerodynamic properties of the earth's surface (Oke, 2002). This results in a phenomenon known as the Urban Heat Island (UHI), which is accelerated by the solar absorption and re-radiation within the dense urban fabric, widening the gap in temperature between the city and its outskirts (Oke et al., 1991).

In a densely populated city with limited green areas like Beirut, urbanization is taking its toll on open spaces, causing an increase in the intensity of the UHI. The city suffers from heat waves during the summer that contribute to thermal discomfort, an increase in energy consumption, a high concentration of air pollutants, along with health problems (Kaloustian and Diab, 2015). The relationship between temperature and related daily mortality was found to be significant in greater Beirut (El-Zein et al., 2004).

Increasing areas of vegetation, as well as using high albedo surfaces and urban water bodies are among the measures that can be implemented to help mitigate the impacts of the UHI phenomenon (Ng et al., 2012). Although a large number of recent studies have investigated the impact of vegetation on urban microclimate, there is a lack of understanding on how the characteristics of different tree species, including size and arrangement, can alleviate the thermal comfort (Bowler et al., 2010).

This paper aims to address this through the examination of strategies for mitigating the UHI effects in the peri-central districts of Beirut. The analysis employs the 3D microclimate model ENVI-met V4 (Bruse, 2015). The performance and efficiency of the integrated green infrastructure approach defined was verified and evaluated through several objectives and simulation scenarios, in an aim to optimize the generated urban design interventions.

BACKGROUND: ENVIRONMENTAL POTENTIAL OF GREEN INFRASTRUCTURE

"Green infrastructure" constitutes a planned network of natural and semi-natural features such as trees, gardens, green roofs and other planted spaces that provide various ecological, economic and social benefits and enable movement between habitats nodes connected by appropriately vegetated corridors (Fernández-Juricic, 2004). Green Infrastructure can modify the city's energy balance through a number of processes, including direct shading, evapo-transpiration, and the urban breeze cycle processes (Dimoudi and Nikolopoulou, 2003).

In particular, the evaporative cooling process that occurs as a result of the conversion of sensible heat to latent heat combines the evaporation of water from wet surfaces and transpiration of water vapour from plant leaves into the atmosphere and facilitates the dissipation of trapped heat (Bowler et al., 2010).

Evapo-transpiration under optimal conditions can cool air temperature by 2-8°C around green spaces and surrounding areas (Akbari et al., 2001; Taha, 1996). Shading from trees also decreases the amount of radiation by reducing the amount of absorbed and stored heat. Fahmy et al. (2010) studied the effect of trees in Cairo's semi-arid climate on the radiant heat fluxes with its urban development.

Although there is evidence that indicates the effectiveness of green infrastructure as an effective environmental control strategy (Gill et al., 2007) various biophysical and socio-political factors may impact its implementation (Byrne and Jinjun, 2009). This is primarily due to the lack of space within dense urban fabric and shortage of accurate quantifiable information that can be used to demonstrate and quantify its potential benefits to relevant decision makers.

BEIRUT PERI-CENTRAL DISTRICTS

Beirut, the capital city of Lebanon, is situated on eastern coast of the Mediterranean. Its climate is characterized by a hot humid summer and a mild winter. During the period when heat stress is most likely to occur, which is mainly during the months of July and August, the maximum average temperature is 33°C occurring between 12:00 and 14:00, and the maximum average relative humidity exceeds 75% (night time).

Growing denser by the day, the city is struggling to conserve the remaining green spaces that have been mostly lost and engulfed by urban growth. Beirut only has 0.8m^2 of green space per capita, well below the World Health Organization recommended minimum of 12m^2 per capita.

According to Chmaitelly et al. (2009 p.177),"rising land values, increasing building densities and the introduction of exotic species are endangering the urban floral diversity in Beirut coastline". A review of historical urban development patterns in Beirut, highlights three distinct zones within it: the city centre, the peri-central belt and the peripheral area. Current zoning laws (established in 1954), created several concentric zones of diminishing floor-to-area ratio extending from the city centre to the periphery (Figure 1). According to Saliba (2013), this zoning law works against conservation principles by allowing the highest allowable densities in the historic core, which increases the area's vulnerability to real estate projects. As such, the Beirut peri-central districts are threatened by market developments that may lead to the degradation of the already diminished built heritage and green areas, replacing them with high-rise buildings.

In this situation of open space deficiency, integrating green infrastructure within this dense fabric has emerged as a considerable challenge. Despite this, Lebanese building law prohibits the building-up of a number of vacant land parcels defining them as "non-constructible" due to their small size and irregular geometry to avoid odd building volumes (Aouad, 2014; El-Achkar, 1998).

Hence, the redevelopment of non-constructible parcels, left over areas, streets and yet the highways infrastructure can potentially provide a useful method by which to ecologically enhance the city's urban fabric by conserving existing habitat patches and integrating them with newly implemented planted areas. However, till this date Beirut Municipality has widely neglected the value of such spaces and has yet to develop a strategic approach for their improvement (Aouad, 2014).

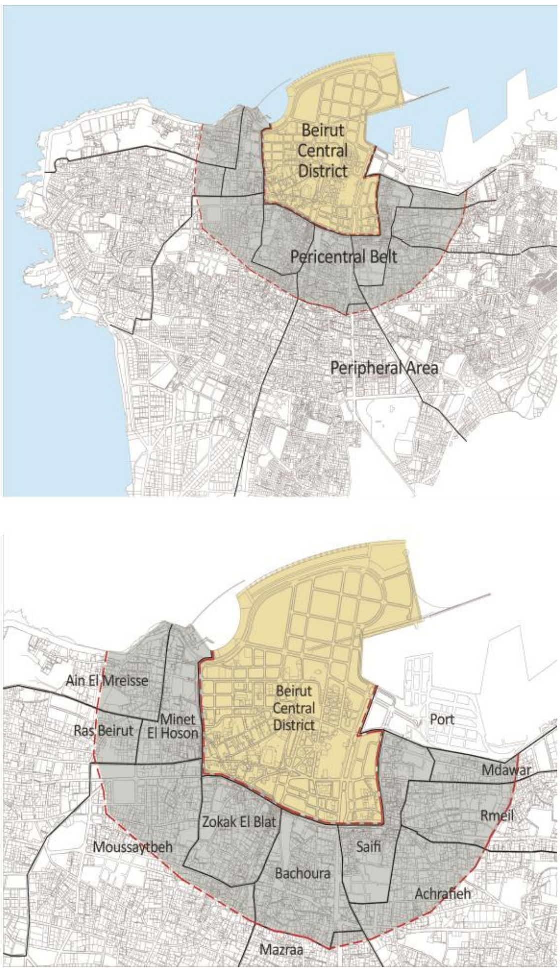

Figure 1Mapping the urban zones of Beirut: 1-a (top) illustrates the main city zones, 1-b (bottom) illustrates the distribution of the peri-central districts Source: Adapted from Lebanese Geographical Information services Maps (2012)

Pilot Study Case

For this study, an urban area located within Beirut peri-central districts was selected for analysis. It is a predominantly residential neighbourhood situated between Saifi and Rmeil districts with new high-rise developments that replaced many old houses and green areas.

This pilot area is characterized by having significant architectural heritage value and some remaining vegetation within dense urban fabric (Figure 2). It is bordered by Georges Haddad Avenue from the east, clearly separated from Beirut Central District. The area has irregular street patterns and urban blocks with a variety of building heights.

Figure 2 The selected domain for modelling and simulation: Saifi /Rmeil Area

STUDY METHODOLOGY

Urban Microclimate Modelling

ENVI-met V4 was used to assess defined "tree-type" scenarios against the existing base case. This holistic microclimate model couples thermal and fluid dynamics in a complex urban geometry and simulates the surface-plant-air interactions which is used to deploy complex urban structure and open spaces based on the principles of fluid dynamics, thermodynamics and laws of atmospheric physics through a holistic analysis methodology (Bruse, 2015). ENVI-met is widely considered to be one of the most accurate micro-scale simulation models that can provide support in understanding the impact of the built environment on the microclimate (Huttner, 2012; Lee et al., 2016). Since it incorporates a huge and complex number of parameters that render its absolute "validation" almost impossible, various validation studies have assessed the accuracy of the most recent version ENVI-met V4, which has been used in this paper. For example, in Yang et al. (2013), the difference mean radiant temperature $\Delta T_{Modelled\text{-}Observed}$ for three impervious surfaces was found to be around 1 °C during the period 10:00-14:00, while Middel et al. (2014) compared three study areas in Phoenix and found that in the hottest site the difference between the modelled and observed temperatures was minimal (44.8°C and 44.4°C, respectively). Finally, it should be noted that ENVI-met is a physics-based model, where the quality of the model results will depend on the accuracy of the input data provided, "if programming errors and conceptual flaws are neglected" (Bruse, M., 2015). This updated version also includes the capability to adjust tree and bush characteristics, including species type, size and leaf area density within ALBERO toolbox, which interprets the selected vegetation as an integrated 3D organism and generates newly modified ones to be directly integrated into ENVI-met V4 database system. DEM (Digital elevation model) is also a newly developed and still experimental feature, which allows modelling the terrain by specifying each grid size altitude above sea level. Since the response to heat exchanges within the environment is related to the physical characteristics of the tree canopy, the understanding of how foliage distribution is capable of cooling air temperature when selecting plant species to utilize is therefore essential. The three-dimensional composition of a tree structure can be represented by two biological parameters. The first, leaf area density (LAD) is defined as the total one-sided leaf area (m^2) within a volume of air (m^3), and second the leaf area index (LAI) defined as the leaf area per unit of ground area covered by the projected area of the crown (Bréda, 2003). LAI is a key parameter in calculating evapo-transpiration equations used as an eco-physiological measure of photosynthetic and transpirational surface (Chen et al., 2005). Therefore, for this study, trees of various characteristics were tested to evaluate pedestrian thermal performance for each species and quantify their thermal benefits on the microclimate using defined thermal indices based on human heat balance considerations. Either a conceptual or a detailed modelling procedure can be implemented for this type of analysis; the latter of which was applied in this study where the walls and roof materials were specified.

Simulation set-up

Modelling the existing urban context of the case study area was based on a digital terrain, taken from Lebanese Geographical Information services and updated from a field survey undertaken in the summer of 2015. The geometric parameters of the 330m x 330m domain was transformed in a model grid with the dimension of 110x110x30 and a grid resolution of 3. An input database (Table 1) was defined for the type of soil, buildings, albedo of streets, and pavements, in addition to the facades materials that were approximated for the solid and glazing ratio.

Table 1 General conditions for simulation

Model Parameter	Model Input Value
Location	Beirut, Lebanon (33.53, 35.31)
Simulation day	15 August 2015
Simulation duration	From 06:00 till 07:00 (25 h)
Simple forcing	Hourly Temp and rel. Humidity
Spatial resolution	Grid size: 100x100x30 dx=3, dy=3, dz= telescoping 5%
Wind direction	220° from North
Nesting Grids	25
U values external walls	Hollow block for solid wall, Glazed for openings For roof: tiles or red clay tiles
Street/ Pavement	Asphalt/ Concrete (used/dirty)
Natural surfaces	Loamy soil/Grass
Pedestrian Clo	0.9 Clo
DEM	From 20 till 40m above sea level

Furthermore, the model considered the topography characteristics of the neighbourhood, which ranges between 20-40 m above sea level. The new forcing function in ENVI-met V4 was used to enhance the consistency of the boundary conditions by determining diurnal variations. The hourly temperature and humidity data for the 24-hour simulation cycle were obtained from the Beirut weather database by calculating the average measurements for a typical Beirut summer day (15th August) over a three-year period (2013-2015) (wunderground, 2015). Within the 24-hour simulation period, the first hour (initialization) was not taken into account in the analysis as well as the time-period ranging from 23:00 till 06:00, which was not deemed accurate for human thermal indices calculations in outdoor spaces (Chow and Brazel, 2012). Based on daily observations taken between August 2005 and 2015, 81.5% of the wind in Beirut is between South and west direction (Windfinder, 2016). Hence, a constant value for the average prevailing wind direction was defined although other values would have been used in forcing boundary conditions in ENVI-met 4.0. It should be noted that varying the wind directions within the levels of the model with large wind shear may cause numerical instability (Huttner, 2012).

Optimized Scenarios Approach

The most common tree species adapted to Beirut climate conditions were identified based on a consultation with a local landscape architect (Sabbagh, 2016). This was undertaken to establish suitability, to classify the trees according to their characteristics (conifers or deciduous) and to determine appropriate location for use (streets or gardens) (Table 2).

Table 2 Trees Species adapted to Beirut climate conditions

Type	ID	H (m)	W (m)	LAD	FA	Loc.
Cypress (Co)	ZY	7	3	0.4	0.3	Ga
Pinus Pinea (Co)	PP	15	11	1.5	0.6	Ga
Tamarix Gallica (Co)	TA	2	3	0.5	0.6	Ga
Albizia Julibrissin (D)	AJ	12	11	0.7	0.6	Sw-Ga
Cercis Siliquastrum (D)	JU	10	11	0.6	0.6	Sw-Ga
Citrus xAurantium (D)	ZI	4	3	0.7	0.4	Sw-Ga
Olea Europaea (D)	OT	4	5	0.5	0.5	Ga
Palm Washingtonia (D)	PW	20	9	0.5	0.6	Sw-Ga
Olea family (Privet) (D)	LI	7	5	0.7	0.7	Sw-Ga
Jacaranda Mimosifo.(D)	NN	9	15	0.4	0.6	Sw-Ga
Platanus Orientalis(D)	B8	20	15	1.1	0.18	Sw-Ga

Key: *Co: Conifers, D: Deciduous, LAD: leaf area density, FA: Foliage Albedo, Loc: Appropriate Location, Ga: Garden, Sw: Sidewalks*

The structural information describing the canopy of each selected species was determined from ALBERO toolbox for a mature tree including height, width and foliage density. Based on this, a number of urban planning scenarios were devised and analysed to investigate the relationship between tree strategies and pedestrian thermal comfort.

The simulation was first carried out for the base case scenarios to understand the effect of the current built environment on the microclimate, taking into account all the existing parameters, including trees. Following this, the proposed mitigation measures were then evaluated and compared to the base case. The assessed scenarios (Table 3) included four selected tree types which were evaluated independently for each case. The scenario which lead to the most effective cooling benefits was then selected for optimization through a combined urban strategy which included integrating green roofs and walls (Figure 3). In ENVI-met V4, the interactions between the vegetation, atmospheric model and soil model occurs through radiative and aerodynamic processes. The structural characteristics of the trees is visualized in a 3D format in the ENVI-met ALBERO toolbox which enables modellers to assign the LAD value for each cell in the 3D tree. A database of each species describes the height and width of the plant, LAD values in each grid, as well as the maximum depth of the roots and the root area density (RAD).

Table 3 Scenarios Description

Scenarios	Description
BC-sc	Base Case Scenario
BC-sc (a)	BC-sc with Palm Washingtonian
BC-sc (b)	BC-sc with Privet (Olea family)
BC-sc (c)	BC-sc with Jacaranda mimosifolia
BC-sc (d)	BC-sc with Platanus Orientalis
BC-sc (e)	BC-sc (d) + roof and green walls
BC-sc (f)	BC-sc (e) + mixed tree species

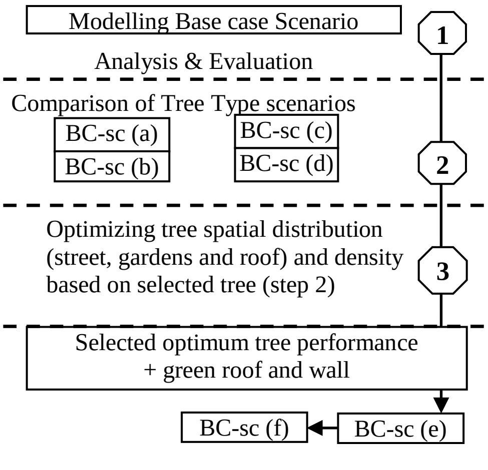

Figure 3 Methodology Flow Chart

Calculating thermal indices through Biomet

The professional version of BioMet 1.0, a post-processor tool for calculating Human Thermal Comfort Indices from ENVI-met model output files can estimate three indices PMV (Predicted Mean Vote, (Fanger, 1973), PET (Physiological Equivalent Temperature, (Matzarakis et al., 1999), and the Universal Thermal Comfort Index (UTCI) (Blazejczyk et al., 2012; Jendritzky et al., 2012). PET, which was selected for this study, is the most advanced of the three indicators and involves a significantly longer calculation time. PET is a thermal index derived from the Munich Energy-balance Model for Individuals (MEMI) to calculate the thermal conditions of the human body (Höppe, 1999). In each grid, BioMet calculates the human thermal bioclimatic from four atmospheric indicators: air temperature, wind speed, relative humidity and mean radiant temperature, and the person’s thermal exchange and metabolic heat production and does not require rerunning the simulation in order to adjust the human parameters.

RESULT ANALYSIS

Base case scenarios

To evaluate the human thermal comfort of the outdoor conditions in the case study, the values of the comfort index PET were extracted from the atmospheric output data, and also derived from the defined human energy balance. The hourly values were calculated from the average of all the (110x110) grids that were traced in each domain. PET values were evaluated according to the human thermal stresses classified by (Matzarakis et al., 1999), which varies between no thermal stress, slight heat stress, moderate heat stress and extreme heat stress in the comfortable and hot conditions.

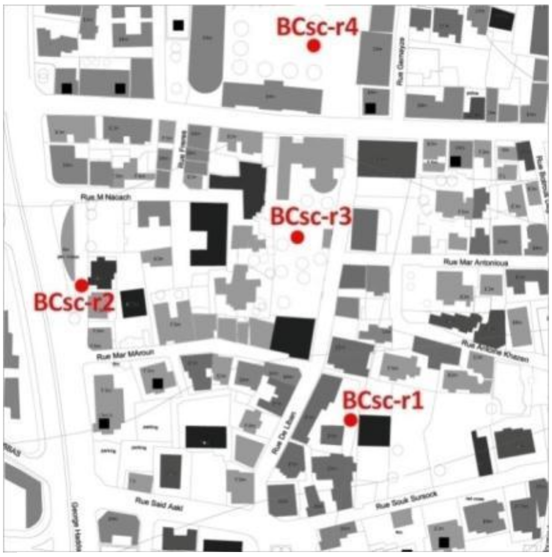

Figure 4 Existing base case map indicating the four selected locations for PET evaluation

As indicated in Figure 5, the mean PET values for the whole domain can be observed from 08:00 till 24:00 (BCsc-Domain Mean PET) where the warmest time of the day is at 14:00. Nevertheless, evaluating a number of defined points highlights the unstable pattern of PET variation, which depends on the grid's proximity to the surfaces, their physical characteristics and the surrounding pattern of building heights and areas of urban voids (Figure 4). For example, high-rise buildings increase the value of PET, especially near dense urban texture blocked by prevailing winds. The four daily trends for the selected points shows that grid (BCsc-r1) located between a high-rise building (77m) and a mid-rise one (18m), exceeds the threshold limit of thermal stress to “very hot” to reach 45°C PET at 12:00 and 48°C PET at 14:00. This condition occurs when the areas are directly exposed to sun, PET increases beyond the threshold of extremel heat stress.

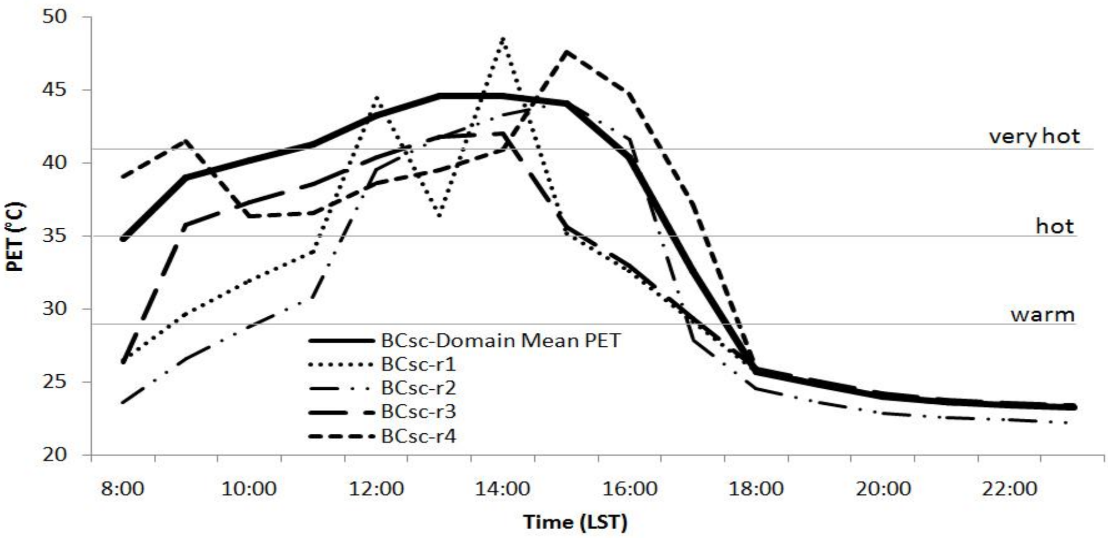

Figure 5 Diurnal variations of PET values at 1.5m above ground on a typical summer day - the domain mean PET (BCsc-domain mean PET) compared with four selected grids: BCsc-r1, BCsc-r2, BCsc-r3 and BCsc-r4.

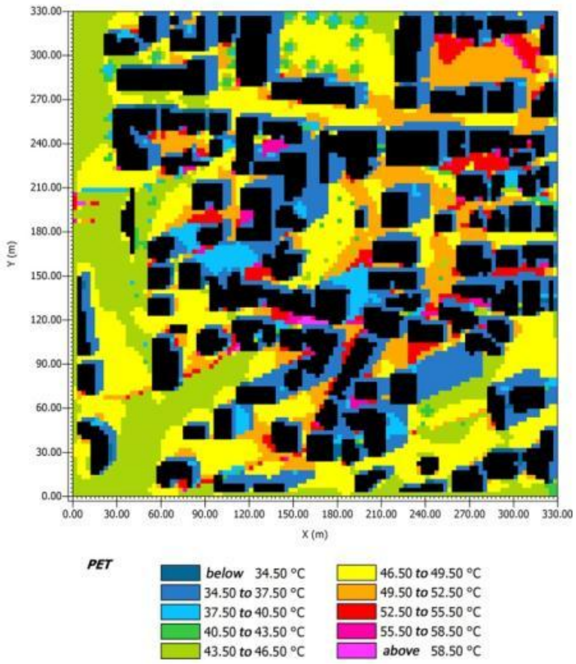

Figure 6 Map of PET (°C) index for the base case at 14:00, horizontal cuts following the topography at 1.5m above ground

However, at a specific time of the day (13:00), the PET value falls 7°C PET below the average of the domain. This altered pattern can be attributed to shading from high-rise buildings, which varies according to the daily sun path.

On the other hand, point (BCsc-r2) is located under the shades of some existing trees at the east side of Georges Haddad Avenue which is highly ventilated due to the width of the avenue alleviating thermal variations of 5°C PET are from 8:00 till 16:00. Furthermore, situated in a an open space and surrounded by the most significant existing number of trees in this domain, point (BCsc-r3) PET values drop more than 3°C PET during the hottest hours of the day through the evapo-transpiration effect of the vegetation. This area also takes advantage from the prevailing wind orientation that blows from "Rue du Liban" street. Additionally, (BCsc-r4) is located in the courtyard of an existing school; the diurnal variations of PET are 3-4 °C PET lower than the average domain due to its location under a tree and within an open space. However, PET exceeds the “very hot” during the day period between 12:00 and 14:00. Figure 6 illustrates the extracted values of the simulated base case domain at the hottest period of the day (14:00). These were visualized through LEONARDO 2014; the visual interface which is now part of ENVI-met V4. The horizontal cuts follow the terrain slope at a height of 1.5m. A relationship between the peak PET values that exceed 49.5°C and the location of narrow street canyons can be observed precisely those that are perpendicular to the prevailing wind. On the contrary, lower PET values are assessed in the wider urban spaces especially when wind blows in their direction. The lowest values are remained considerably below 37.5°C PET in proximity to the shading provided from high-rise buildings and existing vegetation.

Heat Mitigation scenarios

As explained in the methodology, and in order to select the best tree characteristics to enhance the thermal performance of urban spaces, the results of the four case scenarios BC-sc (a), BC-sc (b), BC-sc (c) and BC-sc (d) illustrated in Figure 8 were compared. This demonstrates a directly proportional relationship between the reduction amount of PET values and the optimal tree configurations noting that they all have the same spatial distribution. Thus, compared with the base case, the four tree-type strategies reduce PET values at 14:00 from the threshold of “very hot” to “hot” thermal perception, which is below 41.0°C PET.

A 3°C PET reduction is noticeable from the base case to Palm tree (Washingtonian) scenario, however the lowest PET value among the four cases is BC-sc (d) Platanus Orientalis tree type (Figure 7). This association clarifies the relationship between the vertical distribution of leaf area density and mitigation of heat stress. BC-sc (a) is the least efficient since Palm tree (LAD =0.5) has a long trunk (20m height) producing leaves at the top far away enough from the pedestrian level. BC-sc (b) has better thermal performance than BC-sc (a) due to the foliage ground proximity of the privet tree (Olea family) (LAD=0.7) assigned within the first three meters above ground level.

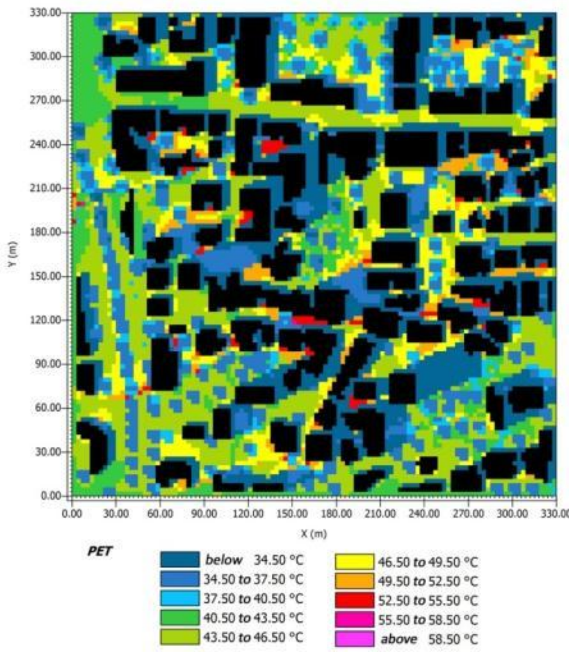

Figure 7 Map of PET (°C) index for BC-sc (d) enhanced with Platanus Orientalis at 14:00, horizontal cuts following the topography at 1.5m above ground

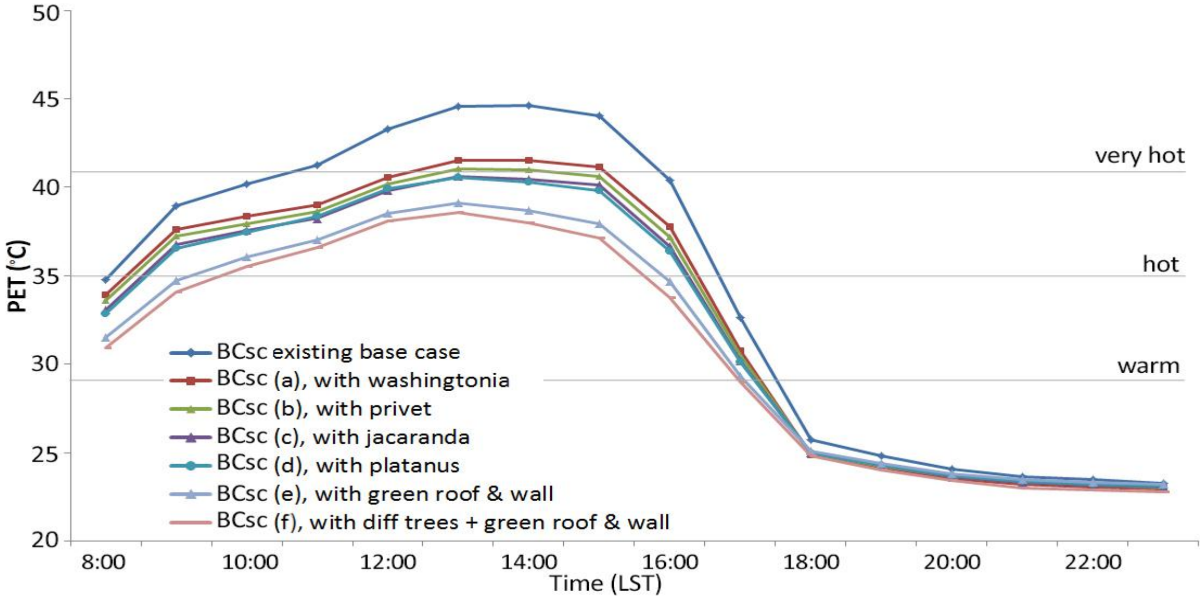

Figure 8 Mean Daily course of PET (°C) values of the base case with enhanced scenarios for Saifi-Rmeil Area

PET values in BC-sc (c) are also significantly reduced where the LAD value for Jacaranda tree (H=9m, W=15m, LAD=0.4) is assigned between 3 and 9m above ground level. The fourth tree type scenario BC-sc (d) is the most effective in mitigating the heat discomfort for pedestrians by reducing more than 5°C PET compared with the base case. The LAD value for Platanus Orientalis used in BCsc (d) scenario (H=20m, W=15m, LAD=1.1) is assigned between 5 and 19m above ground level augmenting evapotranspiration effect. Moreover, adding green roof and green walls at the south facades for BC-sc (d) achieved a further reduction of thermal stress as observed in case BC-sc (e). Additionally, a mixed scenario was conducted by adding diversified tree species to scenario BC-sc (e). It was applied by inserting deciduous trees such as Citrus x Aurantium on sidewalks for narrow streets, Olea Europaea in small empty spaces and large canopy trees such as Platanus Orientalis and Palm Washingtonia on wider streets. Conifer trees including Cypress, Pinus Pinea and Tamarix Gallica were added to larger empty spaces. As a result, the mixed trees scenarios BC-sc (f) achieved the maximum reduction of thermal stress.

Higher density trees in the prevailing wind direction near streets reduce PET values, especially adjacent to open spaces, facilitating additional mixing processes of cooled air through evaporation. Furthermore when increasing wind speed 1m/s, there was a further decrease of PET values by about 2°C PET.

CONCLUSION

Different test scenarios were designed to assess what strategy would be the most effective in decreasing urban heat stress and improving the pedestrian thermal comfort level by modelling and simulating a neighbourhood in Beirut's peri-central districts during the hot summer days.

Based on this study, the following findings can be highlighted:

- Numerical urban modelling allows local microclimate characterisation and evaluates mitigations scenarios.
- Across all strategies, a correlation between the vertical distribution of leaf area density and PET values was identified.
- The influence exerted on PET values is more significant during the hottest period of the day at 14:00.
- Green roofing is more effective for lower building heights that range between 3 and 15m.
- Topography characteristics enhance the cooling effect of the prevailing south-west wind paths, which blows from the sea breeze by ventilating the internal urban fabric and reaches the elevated areas of Beirut's neighbourhoods.

The findings reveal that incorporating green infrastructural strategy in the urban context plays a role in enhancing the outdoor air temperature and can mitigate the urban heat island. Therefore, these performance measures support the development of healthier and walkable communities.

In a general sense, this study can be potentially useful for producing a framework to promote an ecological urbanism approach in the Mediterranean region. Further investigation is needed to integrate pollution dispersion in assessing mitigation measures.

FUTURE WORK

In the context of this research, future work will include validation of the study by applying this approach to other case studies in Beirut. Moreover, field measurements will be conducted to further evaluate the simulated output data.

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