Microclimate Analysis for Street Tree Planting in Hot and Humid Cities

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Abstract: This study investigates how different vegetation species and intensities affect pedestrian comfort in a hot and humid city. The study was conducted in three stages: Firstly, five different scenarios *(unvegetated, sparse tree crown-low density, sparse tree crown-high density, dense tree crown-high density and dense tree crown-low density)* were investigated to enhance pedestrians' thermal comfort. Secondly, the ENVI-met model was used to evaluate the microclimatic changes for these different vegetation scenarios in pedestrian line. Finally, the results of the study suggest the need for further investigation to study whether the thermal mass effect of the plants increases the simulation accuracy regarding outdoor thermal comfort.

Keywords: Microclimate, tree planting, cities

1 Introduction

The climate in the city differs noticeably from the climate in rural areas. The climate change is predicted to have a noticeable effect on thermal comfort in public spaces in cities. Daytime outdoor thermal comfort is of great importance because of the intensive use of public places during the day. An important of daytime microclimatic conditions affects by solar radiation. This becomes a problem in countries with hot and moderate climatic conditions. Urban environments will encounter the following issues in particular: limited air ventilation structures, the probability of increasing thermal stress because of the setup of radiation through reflection, local heat fluxes and higher heat storage capacity, which will increase through block layout and the volume of buildings. To deal with future urban climate conditions, urban planners, architects, landscape architects and property developers need reliable information about changing microclimate conditions to create a suitable design component relating to building style, block layout, shading facilities, urban greenery and street trees; therefore, the designed environment will be adapted appropriately to future climate change (LOIBL et al. 2010).

In the present day, bioclimatic planning and design are widespread concepts in the field of architecture and urban planning that have been extensively studied in the last half-century. On the landscape architecture site, this new bioclimatic concept was revealed in the 1980s (ROBINETTE 1983); however, it has been theorised, developed and applied to a great extent in the last two decades (BROWN & GILLESPIE 1995, ATTIA & DUCHHARD 2011). The primary objective of bioclimatic landscape design is to provide a more comfortable and safer microclimate for human habitats especially in urban areas. Thus, green spaces should be planned to mitigate bioclimatic challenges, such as urban heat islands, wind and dust storms and air pollution (BOC 2016). Today, many studies demonstrate the benefit of vegetation, urban street trees and urban green space (FAHMY et al. 2011, RUSSO et al. 2016). As a result, greenery is generally a low priority in highly-developed cities. With limited land available for urban greenery, it is essential to understand the thermal behaviour of roadside trees in built environments, use suitable methods for planting street trees and find appropriate planting locations considering the local climate (TAN et al. 2017).

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This determination focussed on the evaluation of the microclimatic effect of planting roadside trees from the viewpoint of enhancing pedestrian comfort in the context of high-density cities in hot and humid climates. In the study, different scenarios for the same area in the same climatic season are analysed using a comparative study based on different factors. Scenarios simulated the domain of varying vegetation species (sparse and dense tree crown) and vegetation density (low and high-density planting). All the analysed projects are concerned with improving the microclimatic condition of the urban street for pedestrian thermal comfort via landscape elements, specifically woody vegetation. Microclimatic variables (solar radiation, air and surface temperature, humidity and wind speed) were measured on site to assess the impact of the urban street tree density in hot and humid summer conditions in August.

2 Study Area and Climatic Conditions

The study area selected was Adana (37°00′N 35°19′E) in Turkey. Adana has a typical Mediterranean climate, with cool, wet winters and hot, dry summers (Figure 1). The mean daily maximum air temperature is approximately 31 °C in July and August. During the summer months, the daily mean relative humidity remains high (above 80%) with values usually exceeding 85% during the night. The weather in August is arid with no rainfall. The average daily precipitation is a feeble 8.8 mm (0.3 in). It is sunny approximately 87.5% of the daylight hours (Turkish State Meteorological Service 2017) (Figure 2).

Because of the heavy climatic summer seasonal conditions, August was selected for the simulations. In addition, we chose a site on Adana's busy pedestrian and densely built-up street as Turgut Özal Avenue for our simulation.

Fig. 1: The study area of Adana, Turkey

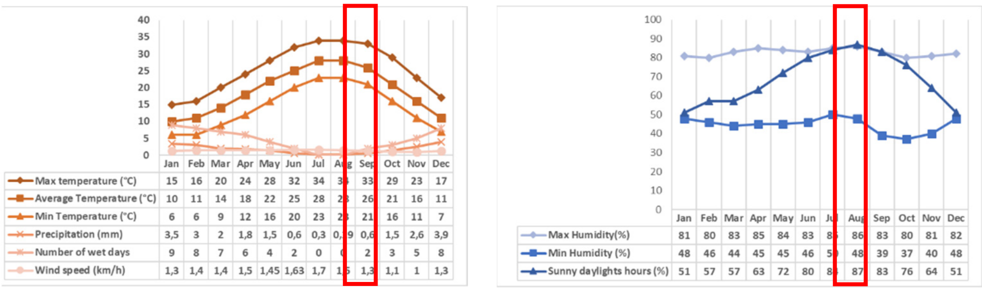


Fig. 2: The monthly climatic data of Adana from 1975 to 2015 (Turkish State Meteorological Service 2017)

3 Methodology

This study's methodology comprises five stages (Figure 3):

- Digitising the study area from survey studies, aerial photography and the Adana city Implementary Development Plan (1/1000 scale).
- Determining planning strategies (the existing situation and different vegetation species and density) for roadside tree planting and outdoor comfort enhancement.
- Mapping the microclimatic conditions of the study area using ENVI-met.
- Comparing the results in the study area.
- Developing suggestions according to the findings.

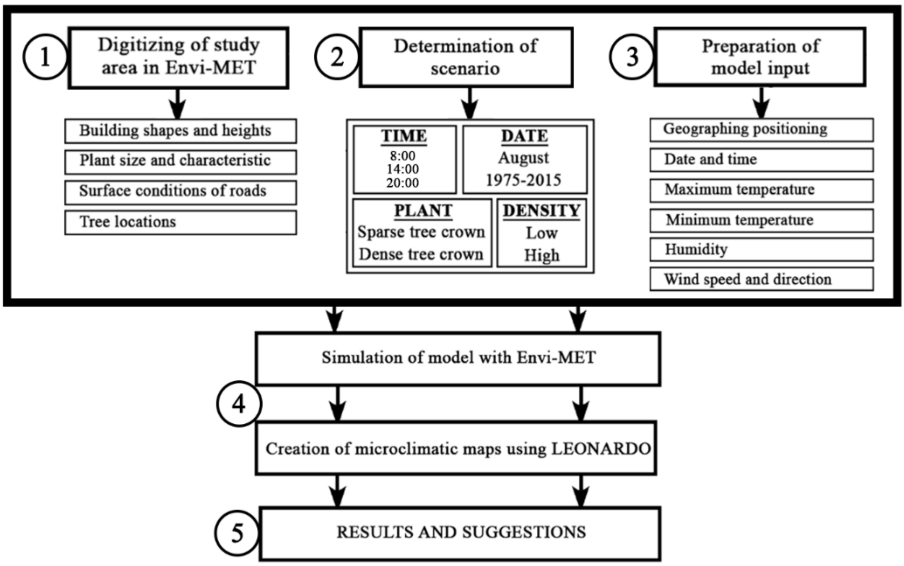


Fig. 3: Flow chart of the methodology

3.1 ENVI-met Microclimate Model

Envi-met, a three-dimensional microclimate model, was developed to simulate the relation of surface vegetation and air in an urban atmosphere with a typical resolution of 0.5 – 10 meters in space and 10 seconds in time. This model calculates the dynamics of the microclimate during a daily cycle (24 to 48 hours) using fundamental laws of fluid dynamics and thermodynamics. It is mainly used to assess several aspects of urban canyons and vegetation effects on outdoor thermal comfort and urban heat island mitigation several configurations. These vary depending on location, climatic conditions, building density and height and vegetation type and quantity. It can, therefore, be a validated method for climate simulations (BRUSE 1999, OZKERESTECI et al. 2003).

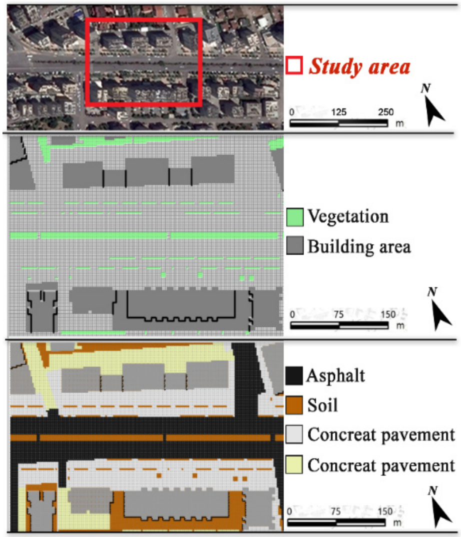
The model also includes a simulation programme with some basic design features. These are i) simulation of the entire coupled climate system including fluid mechanics, thermodynamics, pollutant dispersion; ii) a high-resolution model resolving single buildings; iii) simulation of surface-vegetation-atmosphere processes such as photosynthesis rate; iv) usage of state-of-the-art computational techniques and v) easy-to-use interface and input/output data handling (OZKERESTECI et al. 2003).

The working principle of the model consists of three interfaces. At the first interface, the study area defines input data of digital maps. Therefore, it is essential to produce basic data from other geographic information systems and generate the data itself in ENVI-mets cartography format. This stage can be quite complicated depending on the selected outlying area. The programme allows users to enter data on a high (0.5 by 0.5 m) and a coarse (1 by 1 km) spatial resolution. The second interface is the configuration editor, where databases for land use (building, soil and surface, vegetation) and climate conditions (such as humidity, air temperature, temporal input, etc.) are entered. The third is the modelling interface with additional parameters, and then the modelling process takes place. The LEONARDO interface interprets and visualises the model results. Since all these interfaces are open to the public, they can be developed, and new modules can be added (BRUSE 1999).

3.2 Digitising the Study Area and Model Input

The model continually simulates the atmospheric processes of each grid cell in a spatially and temporally related manner. Our study area (21,600 m^2) consists of 180 × 120 × 20 cells. This selected study area will allow the results of the model to examine different street tree planting studies. Thus, the grid resolution was selected as one by one meter, and the grid was rotated 19° towards the east to minimise diagonal block orientation, thereby avoiding staged shapes. This spatial resolution tolerates the investigation of small-scale interactions between individual buildings, surfaces and vegetation (BRUSE 2004).

The workspace is simulated using the dataset in 2D and 3D circumstances using an input dataset for each grid. These datasets are building shapes and heights, vegetation (plant size, type, height, structure and texture) and characteristics related to shading/wind protection, surface conditions of roads, tree locations, surface roughness and moisture content (Figure 4).



MAIN DATA	
Date of start simulation	*Typical summer day August 15, 2017*
Time of start simulation	*00:00-23:59*
Wind speed at 10 m height (m/s)	*1*
Wind direction (°)	*225° (South-West)*
Roughness lenght	*0.01*
Initial air temperature (°C)	*28.85 °C*
Max temperature (°C)	*34 °C*
Min Temperature (°C)	*24 °C*
Average Temperature (°C)	*29 °C*
Specific humidity at 2500 m (g/kg)	*7*
Relative humidity at 2 m height (%)	*70%*
Max Humidity (%)	*86 %*
Min Humidity (%)	*48 %*
Wind speed (km/h)	*1,5 km/h*
Sunny (Cloudy) daylights hours (%)	*87 %*
SPATIAL DATA	
Longitude (°)	*35°19′*
Latitude (°)	*37°02′*
Time zone	*UTC+03:00*
Spatial resolution	*180x180x35*
Grid size	*1m x 1m x 3m*

Fig. 4: Digitising the study area in ENVI-met and input data for the ENVI-met simulations

The model was run using input data, which includes geographical position, simulation date and time, wind speed and direction at ground level, the initial temperature at ground level and the specific and relative humidity for the study area. The simulations were initiated using climatic data (between 1975 and 2015) obtained from a weather station at Adana (37°00′ N, 35°20′ E, approximately 6 km northwest to that of the measurement location). Global solar radiation is calculated by the programme based on latitude, longitude and time zone. The simulation period for this paper is within the ‘hot period’ in August because of the heavy climatic summer season conditions. The measurements with which the simulations have been compared were taken during the same period. Input data required to initiate ENVI-met simulations are shown on the right side of Figure 4.

3.3 Determination of Scenarios

To examine the effects of vegetation density on urban microclimates, the results of regional climate simulations have been applied to simulate the different scenarios of microclimates of a similar day. Results of the simulations are discussed regarding air temperature, wind speed and direction, humidity and solar radiation in the hot-humid outdoors for roadside tree planting. The following options are compared to the existing situation at the site mentioned above:

- Time of start simulation: 00.00 – 23.59
- Characteristic of the plant: Sparse tree crown and dense tree crown
- Plantation density: Low and high

4 Results

To examine the effects of different plantation of roadside trees, the study was conducted for five different scenarios: i) no vegetation, ii) sparse tree crown-low density, iii) sparse tree crown-high density, iv) dense tree crown-high density and v) dense tree crown-low density. To forecast the microclimatic changes for different scenarios, a simulation tool, ENVI-met, was used. Simulation results of a typical hot and humid summer day (August 15) of the years 1975-2015 have been selected to serve as input for microscale simulations.

The mean radiant temperature (MRT), along with wind speed/direction, air temperature and relative humidity are the variables mainly influencing thermal bioclimatic conditions (LIN 2010, KANTOR & UNGER 2011, HWANG et al. 2011). Therefore, graphs of air temperature, solar radiation, relative humidity and wind speed/direction were generated in 24 hour-charts in the first stage (Figure 5). In the second step, the times (8.00, 14.00 and 20.00) when the highest intensity of the pedestrian was determined, and MRT maps were visualised in LEONARDO (Figure 6).

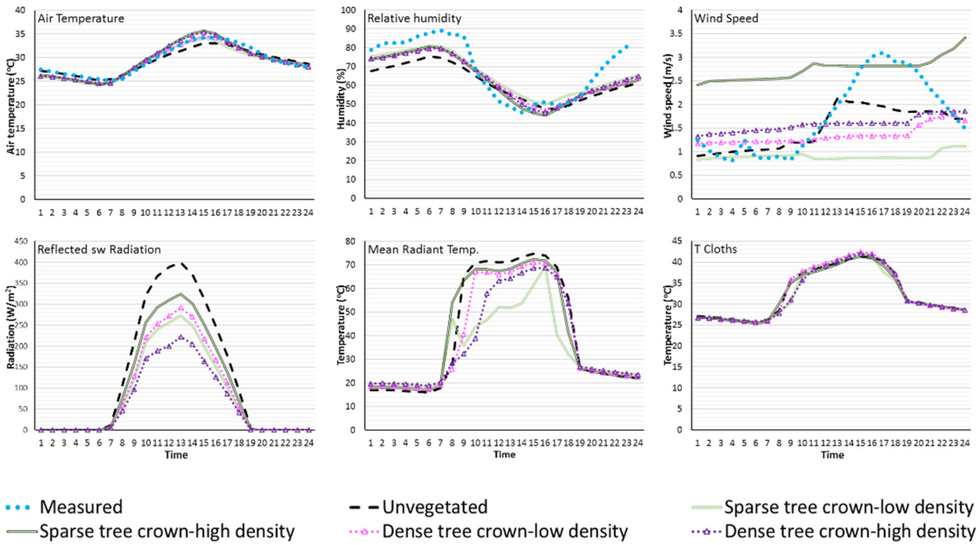


Fig. 5: Average change of some variables on Aug. 15 of five different plantation scenarios

When we compare the results of the variables in simulation, slight differences were found in air temperature for all simulations. In the unvegetated simulation, relative humidity is lower during night according to the vegetation simulations. However, during the daytime, the relative humidity is higher than vegetation simulations. While both reflected that radiation and MRT are higher in the unvegetated simulation during the daytime, these are the lowest in the high-density vegetation scenarios.

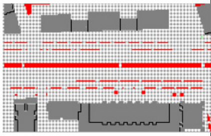
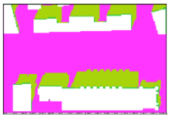
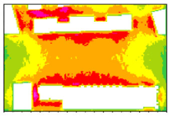
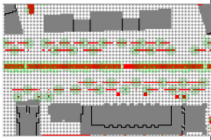
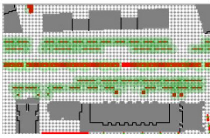
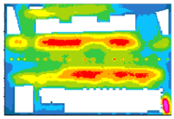
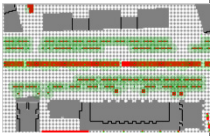
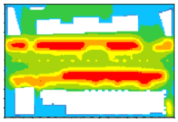
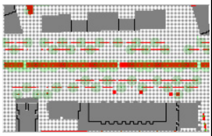
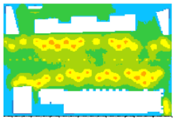
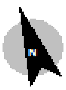
	Simulation Input	8.00	14.00	20.00
Unvegetated				
		Max: 55.38 °C Min: 27.33 °C	Max: 73.76 °C Min: 52.02 °C	Max: 24.93 °C Min: 24.30 °C
Sparse tree crown Low density				
		Max: 55.58 °C Min: 26.76 °C	Max: 72.84 °C Min: 51.27 °C	Max: 25.87 °C Min: 24.03 °C
Sparse tree crown High density				
		Max: 55.04 °C Min: 26.20 °C	Max: 71.49 °C Min: 49.77 °C	Max: 25.86 °C Min: 24.00 °C
Dense tree crown High density				
		Max: 54.32 °C Min: 24.68 °C	Max: 67.53 °C Min: 44.29 °C	Max: 26.87 °C Min: 23.74 °C
Dense tree crown Low density				
		Max: 54.75 °C Min: 25.26 °C	Max: 70.50 °C Min: 47.64 °C	Max: 26.22 °C Min: 23.93 °C
Legend		> 26 °C 26-30 °C 30-34 °C 34-38 °C 38-42 °C 42-46 °C 46-50 °C 50-54 °C 54-58 °C <58 °C	> 49 °C 49-51 °C 51-53 °C 53-55 °C 55-57 °C 57-59 °C 59-61 °C 61-63 °C 63-65 °C <65 °C	> 23 °C 23.50 °C 24.00 °C 24.50 °C 25.00 °C 25.50 °C 26.00 °C 26.50 °C 27.00 °C <27 °C

Fig. 6: The results of Envi-met model simulation for MRT

The results of this study, which evaluated different plantation strategies, demonstrate that the MRT profoundly affects pedestrian thermal comfort. The sudden MRT drop after sunset (20.00) and the equilibrium with the air temperature at the same time (Figure 6) suggest the need for further investigation to study the thermal mass effect of the plants. Therefore, while dense tree crown-high plantation was found to be more suitable at 8.00 and 14.00, low-density planting groups, regardless of plant crown texture, were found to be more appropriate at 20.00. This is thought to be because of two reasons related to the high-density plantation having a higher temperature at night. First, the plants are breathing instead of experiencing photosynthesis in the evening. Second, the low-density plantation does not interfere with the speed and direction of wind flow. As a result, medium-density planting will be suitable for hot climatic zones.

5 Conclusion

This study examined the bioclimatic effects of two different tree characteristics – as tree crown density and plantation density – in urban streets. During the daytime (before 20.00), high crown and plantation density is more suitable, but during the nighttime (after 20.00), low-density plantation is ideal for tree planting irrespective the crown density because it does not affect wind speed and direction. However, species-based assessments are needed to obtain more beneficial results. In addition, the outdoor comfort level will boost the city in several aspects: encouragement of cycling and walking will attract more people to comfort zones in the city, business and tourism has the potential to increase in the area. ENVI-met has incorporated building geometry and vegetation to provide a way to simulate the urban environment in terms of factors such as wind speed, air temperature, MRT. However, there is still room for further investigation on the reliability of some output parameters, especially for the calculation of MRT (as suggested by previous research results). To increase the accuracy of MRT and outdoor comfort simulations, it may be necessary to combine ENVI-met with other simulation software.

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