A model-based study on the impact of different tree configurations on the thermal conditions of an urban square

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Abstract The number of studies on mitigation and adaptation strategies aiming at the improvement of the urban microclimate increased remarkably during the last decades. Most studies are focusing on the impact of various design layouts, on thermal environment and pedestrians' thermal sensation. The present study examines the effect of shading trees with different leaf area densities (LAD) on the microclimate and thermal sensation in an urban open area, namely the Syntagma square, Athens, Greece. The microclimatic model ENVI-met was applied to simulate thermal conditions during a summer day when a field monitoring survey has taken place in that square. The Physiologically Equivalent Temperature index (PET) was employed to estimate thermal conditions in the square and the nearby areas. Model results showed that dense vegetation (LAD above 2) has a greater cooling effect compared to sparse vegetation (LAD between 1 and 1.5 and LAD between 0.5 and 1.0) resulting thus to a decrease in daily air temperature and PET at around 0.7 °C and 4 °C, respectively, in areas under tree canopies. Further analysis quantified the effects of various vegetation leaf densities on thermal conditions and thus the importance of the existence of dense vegetation in urban squares under Mediterranean climate conditions.

Keywords: ENVI-met; thermal sensation; microclimatic conditions; leaf area density; summer

1. Introduction

Vegetation is an important design element in improving the urban microclimate and outdoor thermal comfort in urban spaces. Urban greenery contributes to the cooling of the environment both through evapotranspiration and shading (Chatzinikolaou et al. 2018) and through the reduction of long-wave emission from ground surfaces by lowering the amount of solar radiation reflecting from them. The effect on thermal comfort can be significant given a reduction in mean radiant temperature (Shashua Bar et al. 2011). A more targeted research on the shading effects of trees suggests that an overlap of tree crowns should be avoided in order to reduce their wind resistance (Lee et al. 2020), while other studies have shown that structural characteristics of trees i.e. the size, the tree crowns, the leaf area index (LAI) and the leaf area density (LAD) can determine the magnitude of cooling in a microclimate (de Abreu-Harbich et al. 2015, Spangenberg et al. 2008). LAI is defined as 'the ratio of total leaf surface area to total ground area' while LAD is 'the total one-sided leaf area per unit layer volume in each horizontal layer of the tree crown'.

Based on the LAD differentiations, the goal of this research is to investigate the cooling effect of three different tree configurations, with respect to leaf densities, on the microclimate and thermal comfort in Syntagma Square. Such knowledge is valuable for the development of urban design guidelines based on the cooling effect of different tree types in the Mediterranean climate. For the purpose of this study the environmental model ENVI-met (http://www.envimet.com/) was chosen due to its advanced approach to plant atmosphere interactions and its wide range of applications in urban environment studies.

2. Methodology

The objective of this study is to compare the effects of three types of trees with different leaf densities on thermal comfort. Particular attention was given in order for the examined tree types to differentiate only in LAD, but to have similar height, crown diameter and ground surface material (grass). Table 1 shows the characteristics of the three examined tree types. In all, a total of 8 trees per tree type was found to meet these criteria (Figure 1). Hereafter, to describe the results of this study, the tree type codes of the examined trees will be used, namely $Tree_{LowLAD}$, $Tree_{MediumLAD}$ and $Tree_{HighLAD}$. The cooling effect of each examined tree type is determined based on the thermal conditions of the 'reference point', a treeless point of the square located over grass (Figure 1). The numerical simulations of the effect of the different types of vegetation on microclimate were performed with ENVI-met 4.4.5 (http://www.envimet.com/). Human thermal sensation was assessed using the physiologically equivalent temperature (PET, ºC) (Höppe 1999).

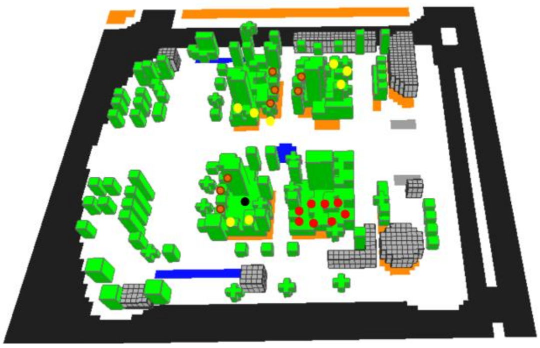

Figure 1. (a) Three-dimentional area input file for ENVI-met (green objects: total number of trees in the study area; grey objects: buildings; blue shapes: water fountains). The examined trees are presented in the figure [red dots: examined trees with LAD 2m²/m³ (tree code: $Tree_{HighLAD}$); brown dots: examined trees with LAD 1.1-1.5m²/m³ (tree code: $Tree_{MediumLAD}$); yellow dots: examined trees with LAD 0.5-1.0 m²/m³ (tree code: $Tree_{LowLAD}$); black dot: reference point]. The tree positions are indicative of the area in which they are located within the square.

Table 1. Physical configurations of examined tree types.

	Tree types		
Code Name	$Tree_{LowLAD}$	$Tree_{MediumLAD}$	$Tree_{HighLAD}$
Height (m)	4	4	5
Crown diameter (m)	3	3	3
LAD (m^2/m^3)	0.5-1.0	1.0-1.5	2
LAI (m^2/m^2)	1.4	2.2	4
Ground surface coverage	Grass	Grass	Grass
Number of trees examined	8	8	8
Leaf type	Deciduous	Deciduous	Deciduous

2.1. Study area

Syntagma Square (37°58΄N 23°43΄ E) has a size of 100 m x 100 m and it is the central square of Athens. According to Koppen's classification (Beck et al. 2018), the climate of Athens is Mediterranean, mildly humid with dry, warm and hot summers. More details regarding the city's climate are presented in the work of Tseliou et al. (2016).

2.2. Model simulation and thermal sensation evaluation

The three-dimensional environmental model ENVI-met (Bruse and Fleer 1998) was employed for the human-biometeorological simulations. The model simulates the aerodynamics, thermodynamics, and radiation balance in complex urban structures with a resolution that may vary from 0.5 m to 10 m. Numerical simulations were performed for 15 July 2010, when meteorological measurements had also been conducted (Pantavou et al 2013). Table 2 presents the meteorological parameters that were recorded from the nearest meteorological station and that were used as input data for the model simulation. Koletsis et al. (2019) already evaluated the model simulation accuracy for the examined date at the study area. Syntagma Square was digitised resulting in 150 x 150 x 30 cells with a resolution of 1.5 m x 1.5 m x 2.0 m (Figure 1).

Table 2. Meteorological conditions on 15 July, 2010.

Meteorological Variables	
Daily Values[1]	**15.07.2010**
Average air temperature (°C)	31.6
Minimum air temperature (°C)	27.4
Maximum air temperature (°C)	38.4
Average wind Speed ($m.s^{-1}$)	2.5
Average relative humidity (%)	45

[1]Source: Environmental Research and Sustainable Development, National Observatory of Athens (www.meteo.noa.gr/).

The total simulation duration was set to 24 hours. Additional information regarding the model simulation as well as the surface materials, plants, and built infrastructure that were used in the digitisation of the area can be found in the work of Koletsis et al. (2019). To assess the effect of the examined urban-trees on thermal sensation, the PET index was chosen. The BioMet ENVI-met tool (ENVI-met/BioMet 2019) was applied to calculate the PET. For the purpose of this paper, the PET Mediterranean thermal sensation scale (Table 3) was used to evaluate the thermal conditions of the square. The ENVI-met results represent values at 1.4 m above ground surface.

3. Results

The hourly air temperature (Tair, °C), PET (°C), and mean radiant temperature (Tmrt, °C) values were calculated at all the examined trees per tree type and were averaged separately to produce overall Tair, Tmrt, and

PET that represent each tree type at pedestrian height (1.4m). The cooling effect of the examined tree types is estimated in relation to the reference point (treeless point over grass) (Figure 2). Table 4 presents the minimum, maximum, and average air temperature, mean radiant temperature and PET values among the examined cases.

Table 3. Thermal sensation classification.

PET (°C)		
Original scale[1]	**Mediterranean scale**[2]	**Thermal sensation**
<4.0		Very cold
4.1-8.0	less than 0.7	Cold
8.1-13.0	0.7 to 5.2	Cool
13.1-18.0	5.2 to 14.8	Slightly cool
18.1-23.0	14.8 to 23.8	Neutral
23.1-29.0	23.8 to 31.2	Slightly warm
29.1-35.0	31.2 to 39.1	Warm
35.1-41.0	higher than 39.1	Hot
>41.0		Very hot

[1]Source: Matzarakis and Mayer (1997); [2]Source: Pantavou (2014)

Table 4. Average, Maximum and Minimum Air temperature (Tair), Mean Radiant Temperature (Tmrt) and Physiologically Equivalent Temperature (PET) values at the reference point and the three examined tree types.

Reference point			
	Tair (°C)	Tmrt (°C)	PET (°C)
Maximum	35.5	81.0	56.5
Minimum	27.9	20.4	23.6
Daily average	31.7	50.2	40.0
Average (09:00-18:00)	**33.3**	**75.1**	**52.5**
$Tree_{LowLAD}$			
	Tair (°C)	Tmrt (°C)	PET (°C)
Maximum	35.1	74.6	55.6
Minimum	28.0	21.7	24.4
Daily average	31.7	43.8	38.4
Average (09:00-18:00)	**33.0**	**65.2**	**49.9**
$Tree_{MediumLAD}$			
	Tair (°C)	Tmrt (°C)	PET (°C)
Maximum	34.9	69.4	50.5
Minimum	27.6	22.1	24.4
Daily average	31.3	43.7	37.3
Average (09:00-18:00)	**32.7**	**63.4**	**47.7**
$Tree_{HighLAD}$			
	Tair (°C)	Tmrt (°C)	PET (°C)
Maximum	34.7	64.1	48.9
Minimum	27.1	23.2	24.7
Daily average	31.0	39.6	36.0
Average (09:00-18:00)	**32.6**	**56.5**	**44.8**

Abbreviation: LAD, leaf area density.

As far as it concerns the air temperature, the daily average cooling effect of $Tree_{LowLAD}$ was negligible, whereas in $Tree_{MediumLAD}$ and $Tree_{HighLAD}$, it was 0.3 °C and 0.7°C, respectively (Figure 2a). As presented in Table 4, the effect of $Tree_{LowLAD}$ and $Tree_{MediumLAD}$ increased slightly with solar intensity and became more evident between 09:00 LST and 18:00 LST, whereas it remained the same at $Tree_{HighLAD}$. The maximum air temperature was obtained at 16:00LST. The maximum daily air temperature was observed at $Tree_{Low\ LAD}$ and the minimum at $Tree_{High\ LAD}$, at 06:00LST.

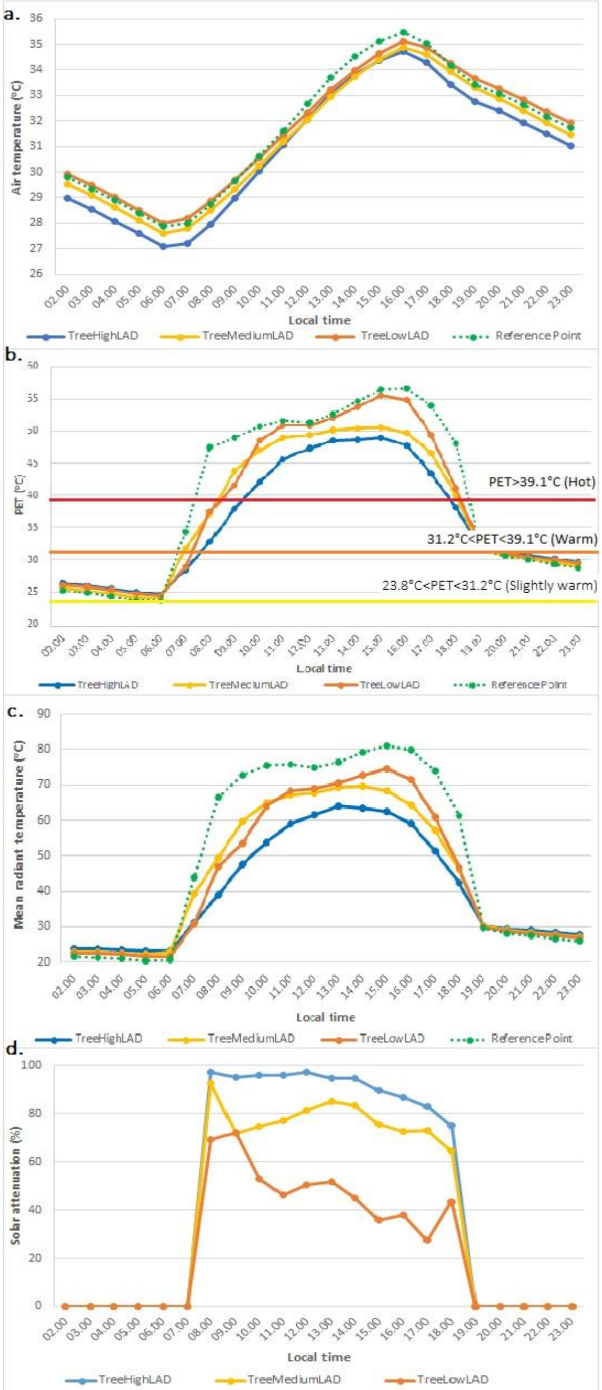

Figure 2. The effects of the examined tree types on a. air temperature, b. PET, c. mean radiant temperature, and d. solar attenuation.

Figure 2b shows the PET evolution in each examined tree type. Despite the positive effect of trees, the average daily PET lies within the 'warm' category at all the examined cases, while 'hot' thermal conditions prevail from 09:00 LST to 18:00 LST. At these hours, the average difference between the reference point and the $Tree_{LowLAD}$, $Tree_{MediumLAD}$, and $Tree_{HighLAD}$ varies at 2.6 °C, 4.8°C, and 7.6 °C, respectively. The maximum PET difference, 6.9°C, between $Tree_{LowLAD}$ and $Tree_{HighLAD}$ is obtained at 16:00 LST. From 02:00 LST to 06:00 LST and from 19:00 LST to 23:00 LST, the three tree types present negligible differences in PET. At these hours, $Tree_{Medium\ LAD}$ induces slightly lower PET than the other two tree types.

The presence of tree canopies significantly reduces the mean radiant temperature at each tree type, with the highest reduction observed at $Tree_{HighLAD}$ (Figure 2c). Comparing the three examined tree types, the maximum mean radiant temperature is observed at $Tree_{LowLAD}$ at 15:00 LST and the minimum at $Tree_{High\ LAD}$ at 05:00 LST. The maximum hourly mean radiant temperature difference among the three examined tree types is 12.5°C (between $Tree_{HighLAD}$ and $Tree_{Low\ LAD}$), observed at 16:00 LST.

Figure 2d shows the hourly solar attenuation. The shading effect was estimated by calculating the difference in the hourly direct shortwave radiation between the reference point and each tree type. The daily average solar attenuation was estimated at 49%, 77%, and 90% for $Tree_{LowLAD}$, $Tree_{MEDIUMLAD}$ and $Tree_{HighLAD}$, respectively. These results imply a significant contribution of dense vegetation to solar radiation attenuation.

4. Conclusions

This study examined the thermal conditions that obtained at Syntagma Square given the three types of vegetation with different LADs, namely $Tree_{LowLAD}$, $Tree_{MediumLAD}$, and $Tree_{HighLAD}$. The results revealed that, leaf area density of the tree canopies can have a significant influence on the microclimate. Compared with a treeless reference point, the magnitude of the cooling effect increases with LAD, particularly during midday and early afternoon. More specifically, the average PET reduction at $Tree_{HighLAD}$ during the warmer hours of the day (09:00LST – 18:00LST) was 7.7 ºC and the daily average air temperature reduction, 0.7ºC. Despite the fact that the trees provided improvements in the outdoor thermal environment, all the examined tree types exhibited average daily biometeorological conditions corresponding with the 'warm' category of PET thermal sensation scale.

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