Climate change and built environment - the role of urban greenery as a mitigation strategy in Greek urban areas

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Abstract. Extreme thermal conditions and heat waves, as a result of global warming, have increased in recent years. Especially in the Mediterranean area, cities face higher temperatures during summer months which severely affect thermal comfort and citizens’ well-being. In this context, this study aims to evaluate the role of urban greenery as a mitigation strategy and focuses on its effect towards the improvement of the urban microclimate and thermal comfort under extreme summer conditions. To this aim, a typical square, located in Athens, Greece, has been chosen as a case study. The microclimatic conditions are evaluated for its present state and after an increase of 20% of soil surface and 30% of trees, while both current (i.e., 2020) and future summer climatic conditions (for the year 2060) are examined. It was also proposed that all the soil surfaces would be covered in grass. The potential air temperature, mean radiant temperature and surface temperature are analysed by simulation means, using the ENVI-met microclimate simulation tool. The results of this study showed that increasing the vegetation ratio inside the study area contributes to considerably lower surface temperatures, while a significant reduction on mean radiant and air temperature at the pedestrian level is also achieved, forming better microclimate conditions. Urban greenery is an important factor for healthy and resilient cities. Its presence can provide lower temperatures in the pedestrian level during summer months, reforming the microclimate. The outcomes of this study can be used by urban planners and stakeholders to improve environmentally urban areas, mitigate the results of climate change, and create resilient cities.

1. Introduction
Climate change has a major impact on the urban built environment both with respect to the buildings’ performance and the formation of the outdoor and indoor thermal comfort conditions, but also regarding the higher probability of confronting extreme events such as heat waves [1]. Regarding the Mediterranean region, it has been found highly susceptible to changes in climate and it is expected to become warmer and drier with an increased frequency of extreme weather events, such as heat waves and extreme precipitations [2]. Undoubtedly, the increased urbanization along with the ongoing climate change and the accompanying rising temperatures and extreme heat waves are considerable determinants of human thermal comfort and well-being; urban areas, already experiencing the negative consequences of the heat island effect, will bear the burden of these harsher heat events due to global warming. In fact, the different thermal and absorbent (non-reflective) properties of building materials [3] in combination with the reduced evapotranspiration due to plant deficiency and the anthropogenic
production of heat, as well as the atmospheric pollution, enforce the increase of temperature in the urban fabric[4]. The impact of the urban heat island, compounding the warming due to climate change is gradually growing and, thus, it is of imperative importance to assess techniques and strategies that will contribute towards the mitigation of these effects and the adaptation of the built environment to the new conditions, advancing urban resilience and sustainability.

Towards this direction lies the objective of this study. It aims to evaluate via simulation means the ability of street trees to act as an effective measure against the increased outdoor air, surface and mean radiant temperature of urban areas, caused due to the climate change, while promoting the public health and the well-being of the citizens. The effect of street trees on the improvement of the outdoor thermal environment has been revealed in many previous scientific studies. Indicatively, the results of a recent literature review have shown that the addition of street trees inside the canyons of urban areas, may result in a reduction of the peak ambient summer Tair between 0.20 °C and 5.0 °C [5], having also a prominent effect on the outdoor thermal comfort regulation [6] and filtering of particulate pollutants [7]. In terms of buildings’ energy efficiency, previous studies suggest a considerable reduction on the peak cooling energy demand due to solar radiation interception and the evapotranspiration effect [8].

In this context, this study aims to evaluate via simulation means, the role of trees on the improvement of the microclimatic conditions of an urban square, under hot summer conditions, both for the present and the future climate. Firstly, microclimatic simulations with the ENVI-met model are conducted for the current state of the square, considering an extreme summer day of the present and the future climate. After the identification of the problematic parts of the square, being highly prone to human thermal discomfort, the mitigation potential of additional trees is examined, both for the current and the future climate projections. The study is organized in the following way: Section 2 describes the case study area, whereas the methodological approach is given in Section 3. The results of the study are given in Section 4 and Section 5 summarizes the main findings of the research.

2. Case study area
A typical square in the area of Ilioupoli, Athens, has been selected for the purposes of this study, located at 5 km southeast from the center of Athens (latitude 37°98’N, longitude 23°72’E). The google earth image of the investigated square is shown in Figure 1. According to the Köppen climate classification [9], Athens is characterized by a hot-summer Mediterranean climate with warm, dry summers and mild wet winters. July and August are the driest months with the first one being also the warmest, whereas January is considered as the coldest month. The broader area of the case study square, extending to 20.250m² has mixed land uses and it is characterized by low urban density. The surrounding buildings are generally four floors high, while there are also detached houses of one or the ground surface materials of the examined square, they comprise of concrete pavement, granite pavement (single stones) and only a small part is covered with loamy soil with vegetation. The optical and thermal characteristics of the pavements are provided in the following sections. To provide a more

Figure 1. Aerial photos indicating the case study area, the 2 distinguished zone A and zone B. detailed analysis and better describe the characteristics of the examined area, the square has been divided
in 2 zones (see Figure 1); the first zone (i.e., Zone A) is expected to present more degraded thermal environment under hot summer conditions since there are only a few planted trees of low height and the biggest part is covered by mineral, rough materials. On the other hand, Zone B is characterized by a higher presence of vegetation, comprising both by mature trees that create important zones of shade but also grass and bushes.

3. Methodology and tools
As already mentioned, the aim of the study is to numerically evaluate the role of trees on the improvement of the microclimate parameters that considerably affect summer thermal comfort of the pedestrians (i.e., air, surface and mean radiant temperature) both for the present-day and the future climate projections. To this aim, microclimate simulations are conducted with the ENVI-met microclimate model (a) for an extreme summer day of 2020 (i.e., current climatic conditions) and b) for an extreme summer day in 2060 (i.e., future projections). At a first step, the stochastic weather generator Meteonorm is employed to create the hourly weather datasets for the years 2020 and 2060. At a second step, the generated weather datasets are organized and processed to define the hottest summer day (i.e., the day with the highest dry bulb temperature) for the years 2020 and 2060, which will be then used for the microclimate simulations with the ENVI-met model.

3.1. Meteonorm weather generator and definition of the simulation days
Meteonorm is a widely applied tool for climate data generation [10]. Apart from its extensive climatic database for multiple points around the world, it also offers the option of spatial interpolation for areas without any historical climatic records. Meteonorm can generate typical years with hourly resolution for any site, whereas its latest versions can also be used for climate change studies. More precisely, Meteonorm uses general circulation models under the fourth IPCC assessment report (AR4) for the climate change and it can create future weather files according to different IPCC emission scenarios (B1, A1B and A2) for intervals of 10 years between 2010 and 2100 [10]. In this study, the Meteonorm version 7.2 has been used to generate: (a) an hourly typical weather dataset for the current period for the city of Athens (i.e., 2020) and (b) an hourly, future weather file for the B1 emission scenario, for the year 2060. After the generation of the 2 weather datasets, the respective hourly climatic data were statistically processed to identify the day with the highest dry bulb temperature. It is for these two extreme summer days that the ENVI-met microclimate simulations will be performed. Both for the year 2020 and 2060, a day of July has been identified as the warmest with the daily Tair average values reaching 32.9 ºC and 33.6ºC in 2020 and 2060 correspondingly.

3.2. ENVI-met microclimate simulations
ENVI-met is a prognostic, three-dimensional, grid-based microclimate model, designed to simulate complex surface-vegetation-air interactions in the urban environment. Based on the fundamental laws of fluid dynamics and thermodynamics, it can simulate the diurnal cycle of major climatic variables, such as air and soil temperature and humidity, wind speed and direction, radiative fluxes etc., with a typical horizontal resolution from 0.5 m to 5.0 m and a time step of 1–5 seconds [11], while the simulated time period usually varies between 24 h and 5 days[12]. The model contains (a) the one-dimensional (1D) boundary model, used for the initialization of the simulation and the definition of the boundary model conditions, (b) the 3D core model, consisting of 3D cells that represent different elements, such as buildings, vegetation or atmosphere. A detailed overview of the model’s characteristics and limitations is provided in [11] and [5].

3.2.1. Simulation scenarios. As previously mentioned, the impact of urban greenery on the improvement of the outdoor thermal environment is here evaluated both for the present-day and the future climatic conditions. For each examined period 2 scenarios are assessed, involving the microclimatic parameters of the study area in its current state and after planting additional trees. Given
that there is already significant vegetation presence in Zone B of the square, the proposed interventions mainly involve the area of Zone A.

The examined scenarios are the following:

- Scenario A: current state of the square, climatic conditions for the year 2020
- Scenario B: increase of the natural surfaces and trees by 20% and 30% respectively in zone A, climatic conditions for the year 2020
- Scenario C: current state of the square, climatic conditions for the year 2060
- Scenario D: increase of the natural surfaces and trees by 20% and 30% respectively in zone A, climatic conditions for the year 2060

3.2.2. Model and simulation setup. The main input parameters for the microclimate simulations with the ENVI-met model involve (a) the area input file, generated through a graphic interface and representing the geometrical characteristics of the study area and (b) the configuration file, containing the meteorological boundary conditions of the simulations. For the generation of the model’s geometry and the representation of the case study area of a set of 50 × 45 × 30 grids has been adopted for the x, y and z axis with a resolution of 3.0 m; two nesting grids have been also placed around the main domain area, to reduce the boundary effects and assure the numerical model’s stability. The ground properties of the nesting grids are those of concrete pavements to approximate in a realistic way the surfaces on the boundaries of the study area. The plan of the area input files of the current state of the square and after the addition of trees is shown in Figure 2.i and Figure 2.ii respectively. It has to be mentioned that planting configuration of the proposal has been done so as to achieve the maintenance of adequate free open space for the citizens, while also assuring an important part of shaded areas, protected by solar radiation in summer.

After the evaluation of base case model, the natural surfaces have been increased by 20% and the number of trees has been also increased by 30%. The tree types have been selected so as to present high tolerance to drought and extreme temperatures, whereas their maintenance needs are also low. The selected species include the *Citrus Aurantium* and the *Cercis Siliquastum*, which are commonly found in the urban areas of Mediterranean cities. The Leaf Area Density [13] of the considered tree species and the respective geometrical characteristics are shown in Table 1, while Table 2 summarizes the thermal properties of the ground surfaces.

Finally, the input boundary conditions for the simulation days, for the current and future period are shown in Table 3. As previously mentioned, the respective data are derived by Meteonorm weather generator and concern the warmest summer day for the year 2020 and 2060. A total number of 4 simulations have been performed with the ENVI-met model, one for each scenario previously presented. At this point it has to be mentioned that, due to limitation of resources, a detailed evaluation of the ENVI-met model using on-site measurements was not possible.

![Figure 2](envisetup.png)
Table 1. Leaf Area Density and geometrical characteristics of the considered trees.

| Tree type           | LAD (m$^2$/m$^3$) | Height (m) | Crown diameter(m) |
|---------------------|-------------------|------------|-------------------|
| Citrus Aurantium    | 2.0               | 4          | 3                 |
| Cercis Siliquastum  | 1.5               | 10         | 11                |

Table 2. Thermal properties of ground surface materials [14].

| Material           | Emissivity | Solar reflectance | Volumetric heat capacity $C_p$ (J/m$^3$K) | Thermal conductivity $\lambda$ (W/mK) |
|--------------------|------------|-------------------|------------------------------------------|-------------------------------------|
| Asphalt            | 0.90       | 0.10              | $2.1 \times 10^6$                        | 0.7                                 |
| Concrete tiles     | 0.90       | 0.30              | $2.1 \times 10^6$                        | 1.5                                 |
| Soil               | 0.95       | 0.20              | $3.0 \times 10^6$                        | 1.5                                 |

Yet, the model has been widely validated by the scientific community [5]; moreover, the aim of the study is to comparatively assess the role of urban greenery on the outdoor thermal environment, rather than to establish absolute values. For the purposes of the current research, the model can be considered as a reliable tool for microclimate simulation.

Table 3. Initial meteorological conditions for ENVI-met simulations.

| Initial meteorological conditions | 2020 | 2060 |
|----------------------------------|------|------|
| Wind speed measured in 10m height (m/s): | 2.50 | 0.10 |
| Wind direction (deg):             | 90.00 | 90.00 |
| Roughness length at measurement site: | 0.010 | 0.010 |
| Min. and max. temperature of atmosphere (°C) | 27.30 (min.), 32.00 (max.) | 27.50 (min.), 39.30 (max.) |
| Min. and max. relative humidity in 2m (%) | 29.00 (min.), 52.00(max.) | 31.00 (min.), 58.00(max.) |

4. Results

The estimated air temperature ($T_{air}$) at 1.5m from the ground level during the two warmest time steps of the selected simulation day of 2020 (i.e., at 12:00 and at 16:00 p.m.) both for the current state of the square and after the addition of trees is shown in Figure 3. Regarding the present conditions, the estimated $T_{air}$ at noon fluctuates between 34°C and 36.8°C with the highest values being reported in the unshaded areas and the lowest in the shaded parts of both Zone A and B of the square. In fact, the high surface temperatures of the unshaded ground surfaces contributed to an increased heat transfer through convection, leading thus to high $T_{air}$ values of the adjacent air layer. The addition of trees has led to a reduction of the estimated $T_{air}$ at noon by 0.30 °C to 0.80°C, mainly due to the intense solar radiation interception and the cooling through evapotranspiration. Moreover, even if additional grass areas have been considered for zone B, the highest modifications are still reported in the center of Zone A, where the number of trees has been significantly increased, resulting thus to the creation of more areas under shade. A similar tendency is also reported for the simulated $T_{air}$ in the afternoon when the addition of trees contributed again in a reduction of the estimated $T_{air}$ by 0.20°C to 0.80°C.

To continue, Figure 4 depicts the estimated air temperature ($T_{air}$) at 1.5m from the ground level at 12:00 and 16:00, for the selected simulation day of 2060 both for the current state of the square and after the addition of trees. Regarding the present morphological conditions, the estimated $T_{air}$ at noon varies between 34°C and 37°C, with the highest values being again reported in the unshaded areas of both Zone A and B of the square. The additional vegetation resulted in a peak $T_{air}$ reduction 0.27°C and 0.20°C at 12:00 and 16:00 pm respectively. At this point the following remark should be done: as it can be seen, the $T_{air}$ values of the two simulation days do not substantially vary in spite of the climate change and the expected higher $T_{air}$ values. This is attributed to the selection approach of the simulation days. More
precisely, the identification of the simulation day for both current and future periods, has been based only the parameter of Tair, without accounting for the relative humidity and wind speed. As a consequence, potential wind gusts or extremely calm conditions, considerably affecting the Tair distribution have not been into account. Still, the aim of the study is to perform a comparative analysis on the vegetation effect, rather than provide absolute values and thus, the simulations have been further processed.

Figure 3. Estimated Tair values at 1.5m for selected simulation day of 2020 at (i) 12:00 and (ii) at 16:00 p.m., for the current state (Scenario A), after the addition of trees (Scenario B).

Figure 4. Estimated absolute Tair values at 1.5m for selected simulation day of 2060 at (i) 12:00 and (ii) at 16:00 p.m., for current state (Scenario C), after the addition of trees (Scenario D).

To continue, the estimated mean radiant temperature (Tmrt) at 1.5m from the ground level at noon and 16:00 p.m., for the selected simulation day of 2020 and both for the current state of the square and after the addition of trees is shown in Figure 5. As it can be seen, both for the present and the future climatic conditions, the highest Tmrt values are noticed in the unshaded parts of the examined square and more precisely in areas covered by concrete pavement. For both examined periods, peak Tmrt values
exceed 75°C, indicating areas of high risk regarding the pedestrians’ thermal comfort. For the simulation day of 2020, the addition of vegetation, especially in the areas of Zone A, contributed to a considerable reduction of the Tmrt up to 14.0°C and 29.5°C at 12:00 and 16:00 p.m. respectively, while lower Tmrt differences have been found for the areas being already in shade, either by the existing trees foliage or by the building volumes. From one hand, the creation of the dense shading shield by the newly added trees, has led to a high reduction of shortwave radiation reaching the ground (as it is directly absorbed by the foliage) and on the other hand both short-wave reflection and long-wave emission are considerably attenuated, leading thus to reduced Tmrt values. The same tendency is also noticed for the future simulation period, during which the addition of trees resulted again in a considerable reduction of around 27°C in the areas of Zone A, being hence forward in shade. The obtained results are in line with the reported findings in previous literature reviews, examining the cooling potential of urban greenery [5].

Figure 5. Estimated Tmrt values at 1.5m for selected simulation day of 2020 at (i)12:00 and (ii) at 16:00 p.m., for the current state (Scenario A), after the addition of trees (Scenario B).

Figure 6. Estimated Tmrt values at 1.5m for selected simulation day of 2060 at (i)12:00 and (ii) at 16:00 p.m., for the current state (Scenario A), after the addition of trees (Scenario B).

5. Conclusions
This study evaluated the potential of urban greenery to improve the outdoor thermal environment of an urban square in Athens, Greece under hot, summer conditions, both for the current and future climatic conditions. The obtained simulation results highlighted the significant contribution of vegetation on the regulation of mean radiant temperature, the parameter than strongly influences the outdoor, human thermal comfort; high Tmrt reductions of 27°C have been estimated for the current and future climatic conditions. On the other hand, the effect of vegetation of the reduction of the Tair was of lower importance as the peak estimated values did not exceed 0.8°C. This finding is in line with the results of other previous studies, emphasizing that the cooling influence of additional greenery inside the urban
areas can be rather minor during daytime, given the high surface densities and anthropogenic heat release [15]. The additional vegetation in urban squares could be thus combined with other mitigation measured such as fountains and sprinklers, enhancing the evaporative cooling. Finally, the results of this research can be used to improve urban planning, giving a better understanding of the distribution of urban greenery in the open spaces of the urban fabric and contribute to cities’ resilience.

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