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The greening of a square in comparison to high albedo tiles replacement - the case of Georgios I square, Patras, Greece

Kotsiris, George, Charalampopoulos, Ioannis, Androutsopoulos, Andreas, Kavga, Aggeliki

Ph.D. associate Scientist, Department of Agriculture, University of Patras, Greece
Lecturer of Laboratory of General and Agricultural Meteorology, Agricultural University of Athens, Athens, Greece
Researcer of Centre for Renewable Energy Sources & Saving (CRES), Pikermi 19009, Greece
Assistant Professor of Department Agriculture, Laboratory of Greenhouse Technology & Biometeorology, University of Patras, Greece

ABSTRACT: The use of high albedo materials in urban open spaces has been spread aiming the environmental upgrading and improvement of thermal comfort conditions. However, is this the best option, when planting the open space is possible? The study deals with this subject by comparing three scenarios at Georgios I square, in the city of Patras in Greece, simulated with the ENVImet bioclimatic software. In the first scenario (reference case), was simulated the existing situation of the square. In the second scenario, high albedo tiles applied in the whole area of the square. In the third scenario the greening of the square increased from 3% to 21.4%. Calculations of various environmental parameters and the PMV thermal comfort index were carried out and spatial temperature distribution maps and diagrams were produced for the scenarios comparison. The results showed that high albedo tiles indicated no positive impact on thermal comfort, mainly due to the mean radiant temperature increment. On the other hand, the greening of the square decreases 2.7 ^{o}C or 7.4% the avarage air temperature during the day and decreases 1.5 value in thermal scale or 48% the thermal discomfort of the open space.

KEYWORDS: Urban open spaces; greening; high albedo materials; thermal comfort

I. INTRODUCTION

In contemporary cities, the covering of open spaces with hard infrastructure, with high thermal capacity, the loss of green space and the increase of heat release from citizen activities have significantly increased the urban ecological footprint (Oke, 1998; Lee and Sharples, 2008) resulting to a negative impact on the quality of life (Nastos and Kapsomenakis, 2015).

The thermal balance of cities is affected by the increased absorption of solar radiation. Additionally, heat is accumulated and released in the urban environment resulting in higher urban ambient temperatures compared to the surrounding urban environment, a phenomenon known as 'Urban Heat Island effect (UHI)'. (Oke, 1982; Landsberg, 1982; Santamouris, 2007*).* Under the growing of an unfavourable urban environment, the assessment of citizens thermal comfort in open spaces became necessary (Nikolopoulou and Lykoudis, 2007; Fröhlich and Matzarakis, 2013) in order to develop plans to confront this effect.

According to Santamouris (2014) in order to confront the urban warming, two mitigation and adaptation technologies are proposed: 1. Increasing the solar reflectance through the use of materials with high solar reflectance, (and high thermal emittance) to keep surfaces cool (Stathopoulou et al., 2009; Akbari, 2016). 2. Increasing the evapotranspiration. This may be achieved through the intensive use of urban greenery like urban parks and green roofs and also through the use of water-permeable pavements.
The effect of green vegetation in urban environment has been extensively pinpointed (Wilmers, 1990; Hoyano, 1988; Bowler et al., 2010) and achieving thermal comfort in open spaces through greenery has been adequately studied

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(Charalampopoulos et al., 2013; 2015; 2017), while Jung et al. (2005) studied the UHI in correlation with urban greening.

The use of high albedo materials seems to be the available approach in cases where the planting of open spaces is impossible, for example, the streets, partially the pedestrian streets, sloping roofs with tiles and even small sidewalks. However, what is the proper option, in terms of environmental upgrading and thermal comfort, when planting of open spaces is possible? The aim of this study is to investigate this question in a specific open area case: the Georgios I square in the city of Patras, Greece (refer to Figure 1).

Fig. 1 George I square 3D Axonometric (Received from Google earth).

II. METHODOLOGY

Georgios I square is the biggest in the city, but with the less green cover in Patras. High buildings, most at 27 meters surround a flat area consisted of paving, plants and asphalt street. A study for the reconstruction of it was carried out and three scenarios were simulated by the use of the ENVImet software (Bruse and Fleer 1998; Bruse, 2004). First, the existing situation of the square (here forth referred as EXIST scenario) was simulated. In the second scenario, high albedo tiles are applied in the whole square area, here forth referred as ALBEDO. In the third scenario, the greening of the square increased from 3% to 21.4%, here forth referred as GREEN. Data received from 24th of July, the hottest month of the year. The day selected represents with a good approach the whole month. The average air temperature of 24th was 27.2 ^{o}C while the monthly mean was 27.1 ^{o}C, the higher air temperature was 30.1 to 30.9 ^{o}C and the lower 24.7 to 24.1 ^{o}C, respectively. The wind direction of 24th was SW, as the dominant direction of the month and the rain was zero mm, as happened on 28 of the 31 days of the month (www.meteosearch.meteo.gr). Taleghani and Berardi (2018), in a similar simulation of an open space in Toronto, used data from one day, 28th of July 2005.

A. PARAMETERS THAT DETERMINE THE MICROCLIMATE IN URBAN OPEN SPACES

The study of the urban open spaces microclimate, in relation to the human thermal comfort factors could define the basic parameters of sustainable design (Giatrakos et al., 2009; Nikolopoulou and Lykoudis, 2007). Based on these parameters, a set of bioclimatic indexes can be calculated to evaluate the thermal comfort of the open spaces users (McGregor et al., 2002; Thorsson et al., 2004; Nouri et al., 2018; Charalampopoulos et al., 2019a; 2019b).

The parameters used, which are also diagrammatically presented in the present study, were: the air temperature (Ta), the surface temperature (Ts), the Mean Radiant Temperature (MRT), the relative humidity (%RH) and the global solar irradiation (I_G), that is received as output from ENVImet sofware (Bruse and Fleer, 1998; Bruse, 2004) while produces spatial temperature distribution maps. Salata et al. (2016) support that the mean radiant temperature, wind velocity and air temperature are the three micrometeorological variables that most affect outdoor thermal comfort in the Mediterranean area.

The determination of comfort conditions in outdoor urban environments was of great interest during the last decade (Orosa et al., 2014). However, quoting environmental parameters alone does not reveal the effect of the microclimate on open space users and their thermal sensation. For this reason, some appropriate thermal comfort indices were also used.

B. THERMAL COMFORT

According to standards ISO 7730 (2005) and ASHRAE 55-2017, thermal comfort is the condition of mind that expresses satisfaction with the thermal environment or a person feels thermally neutral. Thermal comfort is a microclimate criterion and can be defined operationally as the range of climatic conditions considered comfortable and acceptable (Givoni, 1998). In order to form a perception of the environment of the square to users' thermal sensation and mainly, to compare different mitigation and adaptation scenarios, the comfort index Predictive Mean Vote (PMV) was also calculated by ENVImet.

C. PMV INDEX

PMV (Predictive Mean Vote) is an index that expresses the quality of the thermal environment as a mean value of the votes of a large group of people on the ASHRAE (2017) seven-point thermal sensation scale (+3 hot, +2 warm, +1 slightly warm, 0 neutral, -1 slightly cool, -2 cool, -3 cold). This average vote is associated with the equilibrium thermal balance of the human body, which includes basic environmental parameters such as air temperature, relative humidity, air velocity, mean radiant temperature, and personal parameters such as activity and clothing. Moreover, PMV is the independent variable for the index PPD (Predictive Percentance of Dissatisfied) forming the model PMV-PPD. So, if the vote is ±1 means that 80% of people are thermally comfortable.

Actually, PMV index has a solid base in the indoor environment but not in an open space (Fanger, 1970). These parameters do not include shortwave radiation and assume still air and steady-state conditions. The outdoor spaces present a more complex environment. So, there is a general consensus that the metric of PMV is not suitable for outdoor comfort analyses. But even if used for outdoor conditions, it cannot be used in the same way. If the PMV is in the range from ± 1, it could not be supported that 80% of people are feeling comfortable, as PMV–PPD model predicts. People tolerate much more extreme conditions when they are outdoors because the range of adaptability with clothing and metabolic rate is much greater and other factors such as physiological adaptation to the local climate conditions (acclimatization), behavioural and social adaptation (rules, norms and values), expectations and preferences occur (Humphreys and Nicol, 2018).

However, the PMV was adapted to outdoor spaces after the parametrization of the radiative fluxes performed by Jendritzky et al. (1979) while Golasi et al. (2016) study revealed that the PMV presented a good level of sensitivity, with a total percentage of correct predictions of 32.3%. Lately, a study supported that PMV index cannot describe the comfort during summer but it can predict the increase or decrease of the comfort votes quite realistically (Tsitoura, 2019).

D. ENVI-MET SOFTWARE

In order to evaluate of the case-specific scenarios, the ENVI-met software was used for microclimate simulations and climate parameters calculations (Bruse and Fleer 1998; Bruse 2004). ENVI-met is a typical raster based simulation

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software with high parameterisation ability. ENVI-met is a three-dimensional microclimate model designed to simulate the surface-plant-air interactions in an urban environment with a typical resolution down to 0.5m in space and 1.5 sec in time. The atmospheric solver of ENVI-met includes a full 3D Computational Fluid Dynamics (CFD) numerical analysis (Bruse and Fleer, 1988). ENVI-met is a well-documented software established as a valid simulation tool (Elnabawi et al., 2013) for academic and operational research. It has been widely used in studies for pedestrian thermal comfort (Ozkeresteci et al., 2003; Ali-Toudert and Mayer 2006; Taleghani and Berardi, 2018), affect of thermal comfort (Müller et al., 2013; Fröhlich and Matzarakis, 2013), UHI mitigation (O'Malley et al., 2015) and urban planning (Chen and Wong, 2006; Bowler, et al., 2010; Jeong et al., 2015).

E. SPACE MODELLING THROUGH ENVI-MET

The first task was to set the space to be tested. This includes the location, the horizontal and vertical dimensions of the architectural environment, the surface materials and the vegetation size, kind, distribution and percentage of green areas.

The simulations were carried out for George I square at 38^{o} 14' N latitude and 21^{o} 44' E longitude. The domain simulated is organized as a 120*80*30 grid, to x, y and z axes respectively, where every grid-cell is 2*2 meters (refer to Figure 2). The grid includes: a. the flat open space that is composed of paving, plants and asphalt street, with a total area of 12.300 m^2, hereinafter referred to as square, and b the surrounding buildings, the most of which are equipped with a concrete roof and have a height ranging between 15-27 m, and 10 nesting grids around the main area.

Moreover, in the EXIST scenario; the paving was formed from open scale-grey marble with a reflectivity of 0.3. In the ALBEDO scenario; the paving was simulated by shining granite with a reflectivity of 0.8. In the GREEN scenario, the existing paving green area was increased from 3% to 21.4% in terms of m^2. No other change was simulated between the three scenarios.

In the existing situation of the square, there are 95 trees considered 3 m high with light dense foliage of 4 m^2. In the GREEN scenario, some 165 trees of 15 m high with dense foliage of 16 m^2 were considered.

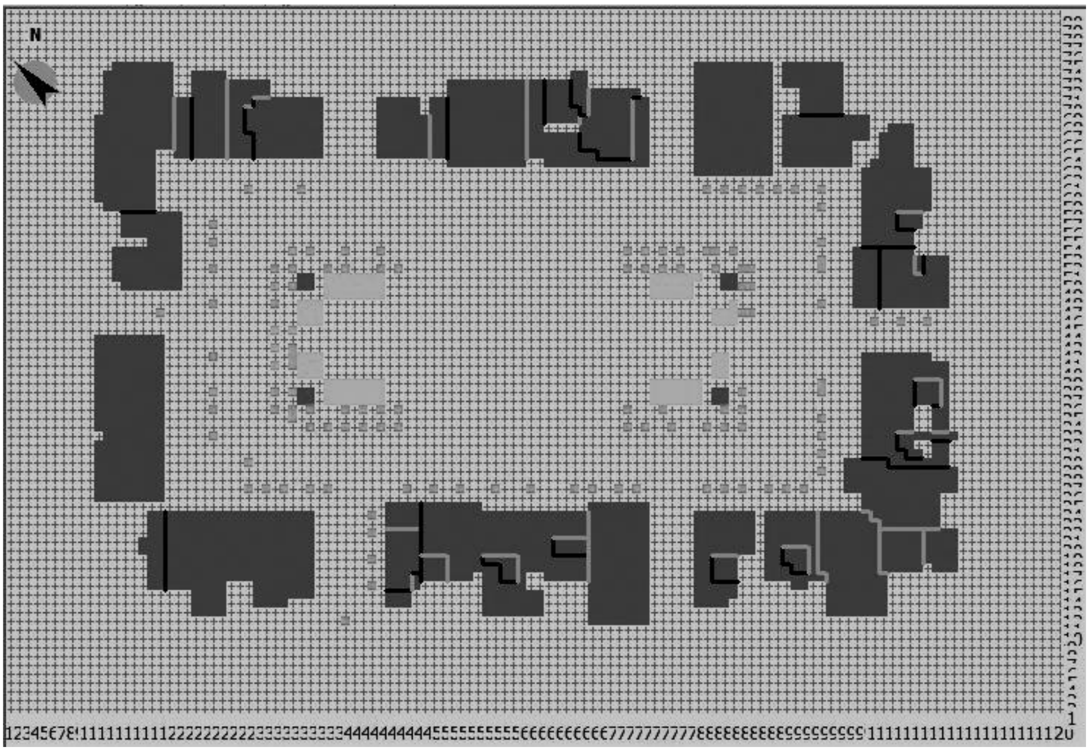

Fig. 2 George I square modelling with ENVImet. Dark grey depicts the buildings that surround the square.

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F. INPUT DATA AND CONFIGURATION FOR THE ENVI-MET CALCULATIONS

Being a prognostic model, ENVI-met requires only initial values to run. The initial conditions were formed by meteorological data for wind speed and direction, relative humidity and air temperature taken from the National Meteorological Service station (http://www.hnms.gr/emy/el/climatology/climatology_city?perifereia=West%20Greece&poli=patra) of Patras, for 24th of July 2017. In parallel, meteorological data for all days of July received by the National Observatory of Athens (www.meteosearch.meteo.gr).
Configuration details are: save model state each 60 min, wind speed in 10 m above ground 3 m/s, wind direction SW, initial temperature atmosphere 301 K, relative humidity in 2 m, 50%.

III. RESULTS AND DISCUSSION

A. OUTPUTS

Using an additional software, named Extract, the values for daily diurnal means of radiant temperature (MRT), air temperature (Ta), surface temperature (Ts), relative humidity (RH), wind speed (V) and global irradiation (I_G) were calculated at a height of 1.6 meters, for the 24th of July.

Furthermore, using a spreadsheet, the values were modified to .xls files and diagrams. From the received data, the average values were calculated for the grid cells that represent the square. Twelve average values every two hours and throughout the day are listed below presenting the fluctuation of MRT, Ta, Ts, RH, AirWind, I_G, and in the same way the thermal index PMV.

B. MRT FLUCTUATION

The Mean radiant temperature has become a widely used metric for outdoor thermal comfort that helps to capture the effect of incoming solar radiation on the street pedestrians (Guo et al., 2020). The greening of the square (GREEN scenario) reduced the MRT dramatically during sunlight in comparison with both ALBEDO and EXIST scenarios and also showed the lowest values during the night. The average daily reduction was 38% and 34%, respectively.

At the same time, the ALBEDO scenario presented the higher values, especially during sunlight (see figure 3). It is shown that the placement of high reflectivity tiles in the square seems to increase heat stress factor.

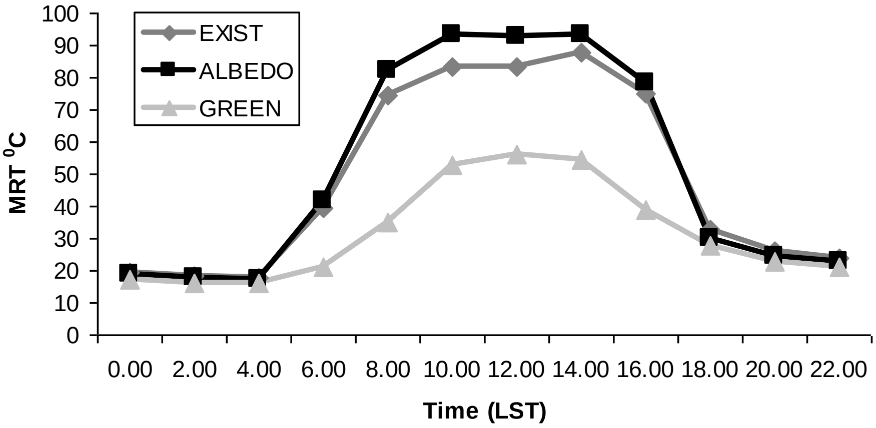

Fig. 3 MRT fluctuation during the 24th July 2017, at 1.6 m height, for the three scenarios.

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In order to have a more detailed picture spatial temperature distribution maps were produced for MRT (figures 4,5,6) at 14.00, using LEONARDO, an add of ENVImet software. All maps were produced in the same thermal scale from 314 to 379 Kelvin degrees.

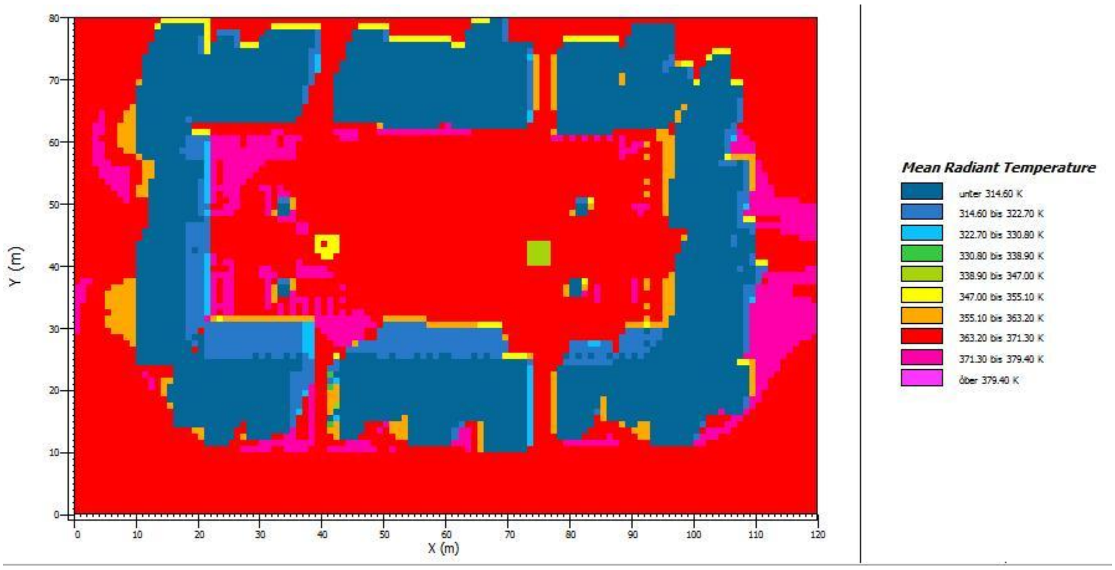

Fig. 4 MRT spatial distribution map during the 24th July 2017, at 1.6 m height in 14.00, for the existing scenario (EXIST). The dark blue color indicates buildings.

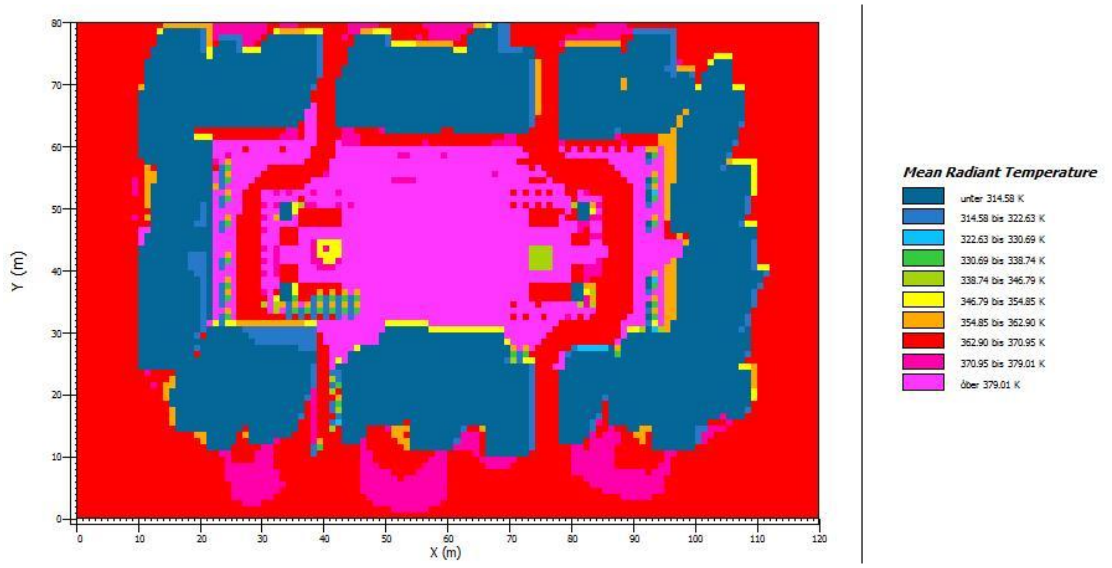

Fig. 5 MRT spatial distribution map during the 24th July 2017, at 1.6 m height at 14.00, for the scenario with high albedo tiles set (ALBEDO). The blue color indicates buildings.

It can be seen that after the placement of high albedo tiles in the square, the calculated MRT shifted a step up on the thermal scale, from red to dark pink. In red color remain the asphalt covered streets.

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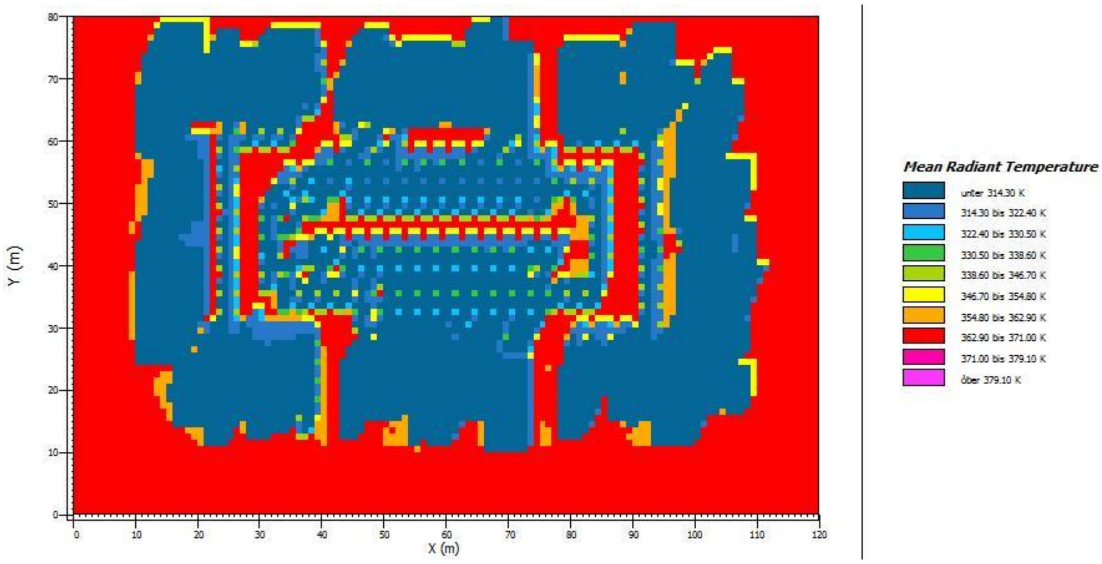

Fig. 6 MRT spatial distribution map during the 24th July 2017, at 1.6 m height at 14.00, for the scenario of square greening (GREEN). In blue color the buildings and the planted square are pictured. In light blue the trees.

It's apparent that after square greening, the calculated MRT shifted many steps down the thermal scale, from red to blue. Only the asphalt-covered streets remained in the red.

C. AIR TEMPERATURE DISTRIBUTION

The greening of the square (GREEN scenario) reduced significantly the air temperature throughout the day and also helped to cool the environment during the night. The daily average reduction was 2.7 and 2.3ºC or 7.4% and 7.5% in comparison with the EXIST and ALBEDO scenarios, respectively (refer to figure 7). The ALBEDO scenario presents a very similar fluctuation to the EXIST scenario, with an advantage of 0.44ºC in daily average terms and 0.7ºC at 14.00, the hottest time of the day. These results are similar with Taleghani's and Berardi's results (2018), who by increasing the albedo of the square from 0.1 to 0.3 and 0.5, achieved to cool off the main square in Toronto 0.5 and 1.0ºC at 15:00, respectively.

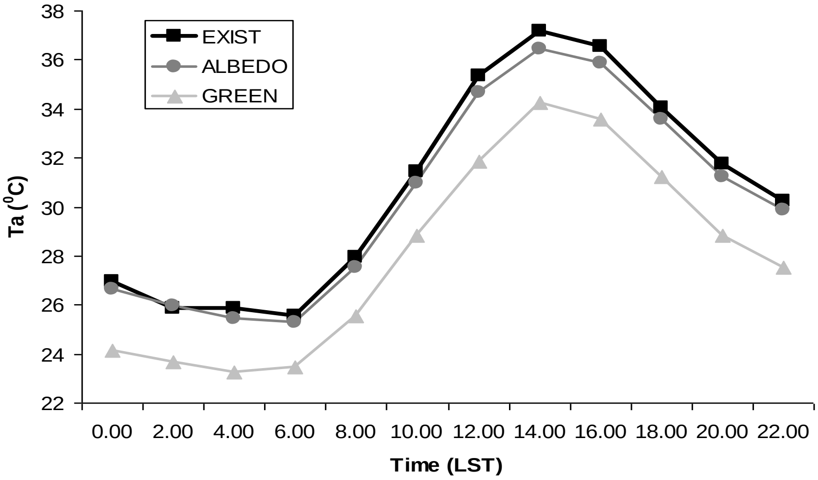

Fig. 7 Air temperature fluctuation during the 24th July 2017, at the height of 1.6 m, for the three scenarios.

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D. SURFACE TEMPERATURE FLUCTUATION

In both ALBEDO and GREEN scenarios, the mean surface temperature was significantly decreased. The daily average reduction was 5.7 and 6.6ºC in comparison with the EXIST scenario, respectively. ALBEDO scenario presents a slight advantage in comparison with GREEN at midday hours; 1.7ºC between 12.00 to 14.00, while the opposite is observed during the night; 1.9 between 22.00 to 6.00 (see figure 8). The daily average difference between EXIST and ALBEDO scenarios was 0.9ºC.

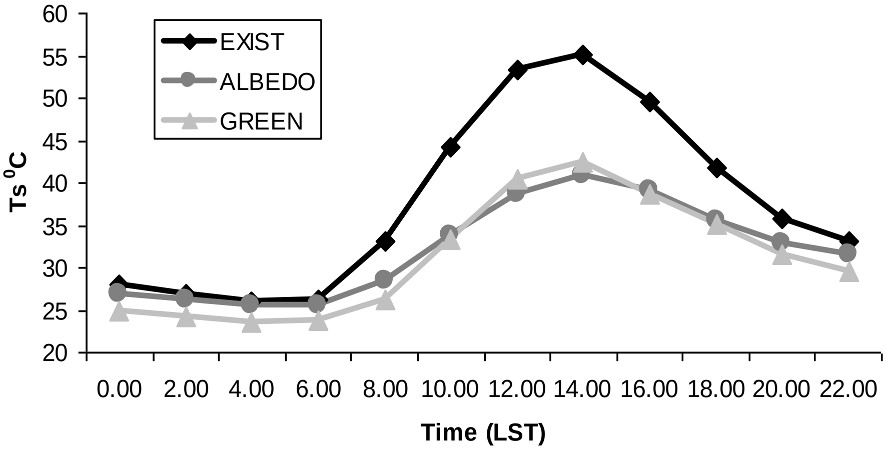

Fig. 8 Surface temperature fluctuation during the 24th July 2017, for the three scenarios.

E. RELATIVE HUMIDITY

The GREEN scenario, as expected, because the evapotranspiration of the trees causes a drastic increase in relative humidity. In the ALBEDO and EXIST scenarios, the RH fluctuates similarly (refer to figure 9). The daily average values for GREEN, ALBEDO and GREEN scenarios were 46.1%, 34.3% and 32.2%, respectively.

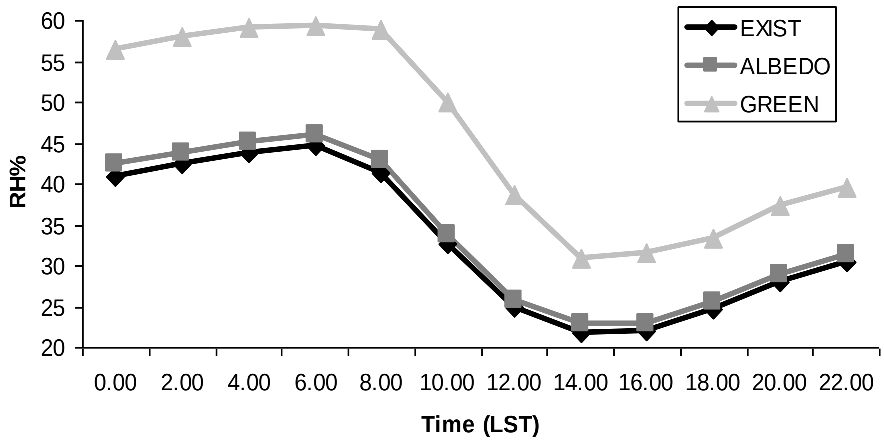

Fig. 9 Relative humidity fluctuation during the 24th July 2017, for the three scenarios.

F. GLOBAL SOLAR IRRADIATION FLUCTUATION

One more drastic change caused by the greening of the square is the reduction of the incident global irradiation, as a result of shading from the foliage of the trees (see figure 10). The average sunlight day values for GREEN, ALBEDO and EXIST scenarios were 338, 949 and 953 Wm^{-2}, respectively.

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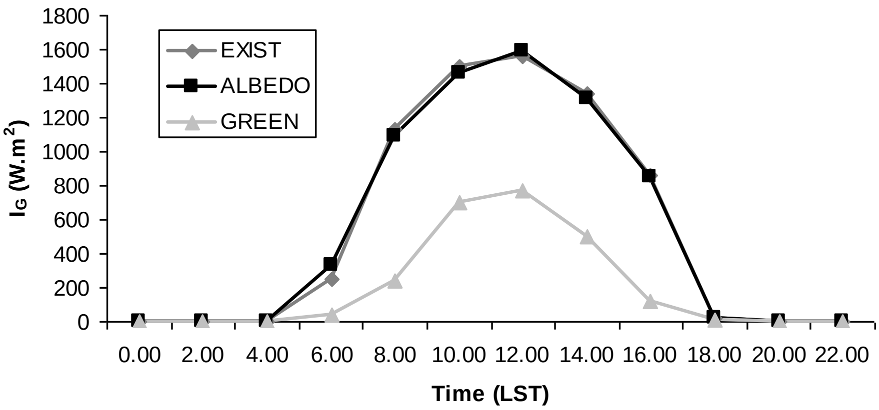

Fig. 10 Global Irradiation fluctuation during the 24th July 2017, for the three scenarios.

From the above findings regarding the changes in microclimatic parameters for each scenario studied the following results are drawn:

The greening of the square (GREEN scenario) has a significant positive effect in the air temperature (Tair), the mean radiant temperature (MRT), the surface temperature (Ts), the relative humidity (RH), and the total incident irradiation (I_G), in comparison to placing high albedo tiles (ALBEDO scenario) and even greater effect when compared to the existing situation. The placing of high albedo tiles (ALBEDO scenario) in comparison with the EXIST one, only the MRT was slightly decreased, and did not affect significantly the rest of the microclimate parameters (I_G, Tair, RH). The only positive result was the decrease in the surface temperature (Ts) in comparison with EXIST scenario.

Another finding is that, under the circumstances studied, the ALBEDO scenario cannot contribute to mitigate the Urban Heat Island (UHI) phenomenon, because it did not cool the environment during the night, in terms of MRT, Tair and RH. The reduction of Ts provides small differences when compared with the existing situation (EXIST scenario) during the night and with the GREEN scenario, both night and day.

G. PMV INDEX

The values of the predicted mean vote (PMV), for each of the three scenarios calculated with Rayman software, are in accordance with the results of the microclimatic parameters found through the simulation with ENVI-met. In Figure 11, the variation of the PMV for every scenario is presented and can be seen that the ALBEDO scenario led to a worse environment, in the specific open space, in terms of thermal comfort, while GREEN scenario drastically improved the mean daily PMV, 1.5 value in thermal scale or 48%.

Moreover, it can be seen that many values lie out of the PMV thermal boundaries. However previous works have shown that under unbearable thermal conditions, PMV values lie over the ASHRAE-55 thermal scale (Kenawy, et al., 2010; Assael, et al., 2010; Tsitoura et al., 2014). Moreover, as claimed in the guide of the ENVI-met software “the PMV value is a function of the local climate and it can also reach values above or below these limits”.

Generally, the PMV index overestimates the prediction of the thermal dissatisfied level in open spaces, as explained in PMV section of Methodology chapter. However, the validity of using the PMV index in qualitative comparisons was supported from Salata (2016), who indicated that ENVI-met can give a satisfying approximation of the qualitative trend of the PMV examining different thermal stresses and microclimatic conditions, thus giving the possibility to compare different urban configurations. He also refers that at midday hours during summer in Rome, the PMV provided by ENVI-met reported high values (between 5 and 6) and the rest hours the PMV values that were estimated through questionnaires that complying to ISO 10551 (1995) have a good correspondence with a mean deviation of about 0.76 PMV which was calculated by ENVImet.

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At the present study using the PMV index to compare three different urban configurations it was found that the thermal environment of the specific square is unbearable during a sunlight day, for the scenarios EXIST and ALBEDO. Only the GREEN scenario seems to moderate the thermal stress for a long time period during the day, when between 8 p.m.-6 a.m. the PMV represents slight warm conditions of thermal scale, and close to hot between 12:00 and 14:00, when slightly exceed the thermal scale (Figure 11). At the early morning hours, between 0:00 to 4:00 the thermal environment is assessed as comfortable for every scenario.

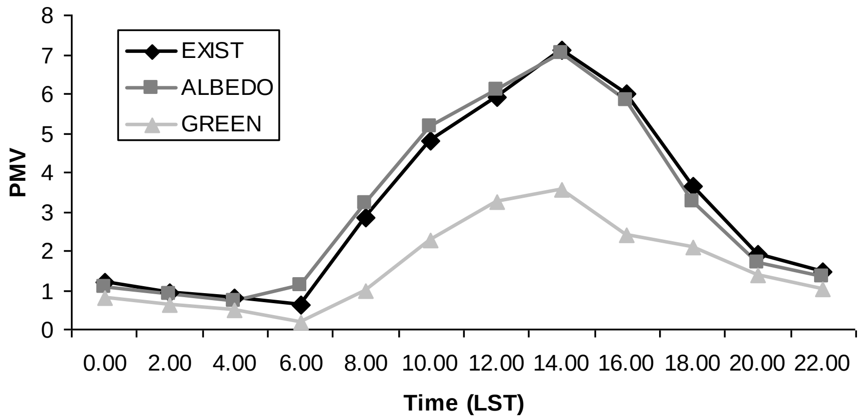

Fig. 11 PMV values in the 24th of July 2017, for the three scenarios.

IV. CONCLUSION

A square in the Mediterranean city of Patras was selected to study its potential to achieve acceptable outdoor comfort conditions. The square is surrounded from high rise buildings, constructed by conventional materials and covered with trees only in 3% of the total square area. The scenarios studied were the existing situation (EXIST scenario), the replacement of the existing pavement with high albedo tiles (ALBEDO scenario) and the greening of the specific open space by planting trees and increasing the green space from 3% to 21.4% of the total square area. The conclusions of the study were the following:

- During a typical warm summer day (the 24th of July), which is representative for the regional microclimate conditions of the whole month, the studied area acts like a heat trap
- Only the GREEN scenario could improve drastically the microclimate parameters, the thermal comfort and mitigate the thermal stress
- The simulated scenario ALBEDO ended up in an aggravated human environment, in terms of thermal comfort and heat stress
- The ALBEDO scenario’s negative impact is mainly attributed on the increase of the mean value of the Mean Radiant Temperature
- The positive impact of the GREEN scenario to the thermal environment is based on the drastic reduction of the total incident Solar Irradiation and the mean radiant temperature, the intense raise of Relative Humidity and the significant reduction of Air and surface Temperature
- The ALBEDO scenario, under the circumstances studied, can not contribute to mitigate the Urban Heat Island (UHI) phenomenon, because it does not cool the environment during the night, in terms of MRT, Tair and RH. The reduction of Ts provides small differences when compared with the existing situation (EXIST scenario) during the night and the GREEN one during both night and day
- The PMV index can be used to evaluate the thermal comfort of an open space, in order to have a qualitative trend or to compare different scenarios of different urban configurations. However, the excessive values, which are witnessed at midday, can not be quantitatively evaluated because they are not covered by a corresponding thermal scale. Further investigation is needed to effectively correlate the sensations out of the thermal comfort scale and the actual magnitude of thermal discomfort observed.

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A study with clearly distinct interventions was necessary to understand the individual effects of each other. Furthermore, more complicated scenarios are needed to be simulated, which can combine plants, pop-up water sprinklers, cool materials, in order to constitute the integrated tools, able to confront such unbearable urban thermal conditions.

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AUTHOR'S BIOGRAPHY

Kotsiris A. George- Ph.D. on Landscape Architecture, Department of Horticulture, Agricultural University of Athens. M.Sc. of Department: Cities and Buildings Environmental Planning, Hellenic Open University of Patras. Associate Scientist at Technological Universities last 20 years. Manager in Landscape projects in private sector. More than 20 publications on international journals and conferences, 106 citations according Scopus review.