LAI and Albedo Measurements Based Methodology for Numerical Simulation of Urban Tree's Microclimate: A Case Study in Egypt

Fahmy M., El-Hady H, Mahdy M.

Abstract—Urban trees foliage has a significant role on modifying its microclimate thermal conditions. In this concern, both of the leaf area density (LAD) and the Albedo affect the tree heat budget. Consequently, the modeling and simulation process that take place to assess the tree's thermal performance within urban environments have to be considered crucially. The database of the numerical simulation tool used, ENVI-met V4.0, does not have plants of different climatic regions that is why LAD and Albedo have to be generated to represent a specific plant. Therefore, a developed methodology to assess trees microclimatic thermal performance is presented in this work by introducing local urban trees to the simulation tool through the measurements of Leaf Area Index (LAI) which is a derivative of LAD, Albedo, and the canopy geometrical parameters. To apply this methodology, three common trees have been used in a local site near Alexandria, Egypt. According to the results, modeling trees foliage on a measurements' basis showed a better state of thermal performance, whether in terms of the pedestrian's thermal comfort (represented by the Predicted Mean Vote, PMV) or the mean radiant temperature (Tmrt) in comparison to the thermal performance results using the empirical modeling methodology proposed by (Fahmy et al., 2010), in order to assess the microclimate modifications that a tree can do within its urban built environment, in addition to generate a numerical database for the Egyptian trees starting with the selected trees' species.

Index Terms— Albedo, Albero, ENVI-met, LAD, LAI, Tree foliage, Urban Simulation

1 Introduction

As an important urban passive cooling elements with a key role in the different urban environments' thermal interactions, urban trees have to be considered in the procedure of modeling their environments as part of assessing these interactions through simulations[1-4]. A variety of tree geometrical variables have to be known to generate a three dimensional canopy representation with botanical properties to study a tree heat budget and its role in modifying microclimates conditions. The canopy shape, height and foliage content affect the amount and angular distribution of the received radiation by the density and spatial distribution of the trees. LAD, LAI and Albedo are conceptual environmental canopy modeling parameters for studying trees' heat exchanges with the outdoor environment which appear in terms of evapotranspiration and shading [5-7]. That is why trees' thermal performance and role in modifying their microclimates differs from a tree to another [8].

On the other hand, the lack of information about the different properties of the various kinds of trees (age, kind, geometric shape, and botanical properties...etc) increases the complexities which prevents architects and urban designers from conducting simulations with appropriate trees inputs, that is why some empirical inputs and assumptions might take place[9]. Therefore, this work aims to model the foliage of urban trees using measurements of LAI and Albedo using the numerical database of the CFD package ENVI-met 4.0 and its trees modeling tool Albero to assess the thermal effects of selected Egyptian urban trees.

Albero is ENVI-met V4.0 plants database plug-in which is used as a platform for a foliage modeling parameters in 3D by introducing leaf area density (LAD) and Albedo. It supports the user with data management, plant generation and modification graphical user interface to design functional 3D vegetation and directly integrates it into ENVI-met V4.0 modeling and simulation process but only for the default trees of the software database which doesn't include local Egyptian ones. On the other hand, As LAD needs LAI values to be generated, Fahmy ea al., (2010) suggested that LAI should equal 1 in order to have a solid shade on the ground at peak time, and also used the default Albedo of the database, [7]. This solved the problem of how to generate LAD without having measured data for LAI as LAD values depend on LAI values in addition to not having a measured data for Albedo. However, in this methodology the canopy foliage concluded is not real to some extent as both LAI and Albedo were empirical. That is why this work is presented; to model and simulate local trees foliage thermal performance within their urban environments on a measurements basis for its foliage rather than on empirical foliage.

2 Methodology

To assess trees role in modifying their urban environments' thermal performance, a four main milestones methodology

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International Journal of Scientific & Engineering Research Volume 7, Issue 8, September -2016
ISSN 2229-5518

was applied. First, field measurements of Albedo and LAI and observations of the trees geometry, second, digitizing and recomputing the tree initial measurements, modeling the selected local trees numerically to be added to the simulation tool and finally modeling and simulation of the urban site selected to assess trees within its built environment.

Field measurements for Trees foliage Albedo could have been introduced to the data base of the simulation tool but to generate the LAD values needed for modeling trees foliage, a proposed methodology, fig 1, has been developed in order to introduce the local trees foliage to the simulation tool through LAI measurements mainly and Albedo secondarily. After that, 3 simulations for a selected urban site were conducted once for the base case, once more using the assumed LAI=1 that could build a tree numerically according to Fahmy et al. (2010) and finally using the LAD values generated from the measured LAI according to the exerted work in this paper.

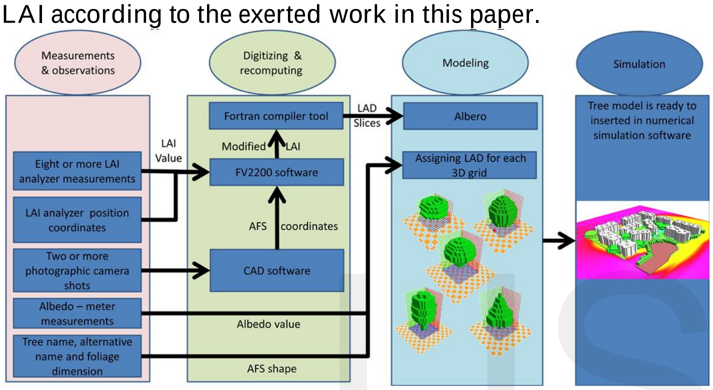

Fig 1 Methodology of generating LAD values to simulate a single (isolated) tree in meteorology numerical simulation software

2.1. Tree field measurements and observations

In this milestone, Albedo measurements were done using a 2 back to back CMP21 second class high temperature pyranometer as Albedometer manufactured by Kipp and Zonen fig 2, 27 Albedo-meter shots (3 measurements x 3 plants x 3 attempted trails) were taken by this device.

72 LAI shots (8 measurements x 3plants x 3attempted trials) for the Leaf area Index (LAI), fig 3, values were taken using LAL2200c plant canopy analyzer fig 4, where eight or more readings and shots are required for a single tree in order to obtain a more accuracy for LAI results and correspondingly more accuracy LAD even before recomputing LAI. Sky condition and scattering correction are very important factors in the process of measuring the LAI factor for a single tree, even more than for a canopy or a forest. The height and the distance of LAL2200c measuring console position from the tree trunk and the coordinates of tree canopy outline should be recorded in separate sheets as it will be used afterwards in the LAI software called FV2200 to recompute (refine) the initial measurements of LAI.

Fig 2 Albedo measurements use 2 back to back CMP21 second class high temperature pyranometer as Albedometer manufactured by Kipp and Zonen

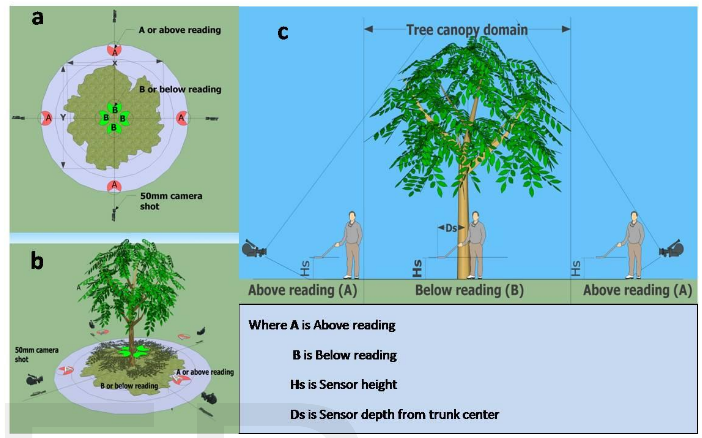

Fig 3 (a) Tree layout showing the locations of required 8 readings around single tree,(b) Perspective view showing camera shots related to A and B readings and (c) Profile view showing the required Hs and Ds as important inputs in LAL2200c plant canopy analyzer .

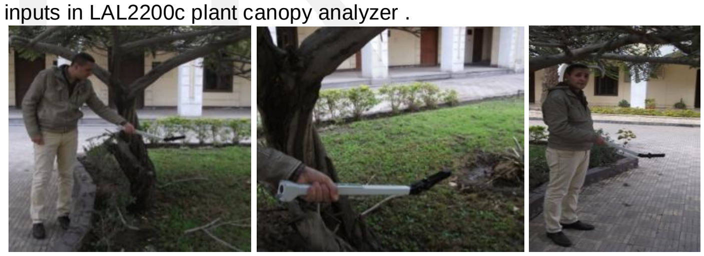

Fig 4 Using LAL2200c plant canopy analyzer in field measurements

2.2 Digitizing and recomputing tree measurements

Digitization process is needed in order to draw the tree profile which in turn is needed to recompute (refine) the initial LAI measurements. Therefore, two or more photographic camera shots were needed (with non-special lenses) for each modeled tree, depending on the tree canopy's profile and its ratio in the x and y axis as shown in fig 5. Using an object with a known height or a scale-meter beneath the tree trunk will facilitate the scaling process when using the photographic camera shots in CAD programs to obtain the Averaged Foliage Shape (AFS). It worth mentioning that the use of a 50 mm lens camera will help in minimizing the predicted small errors, which may occur due to the user accuracy in CAD program when scaling the tree's photo [10].

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ISSN 2229-5518

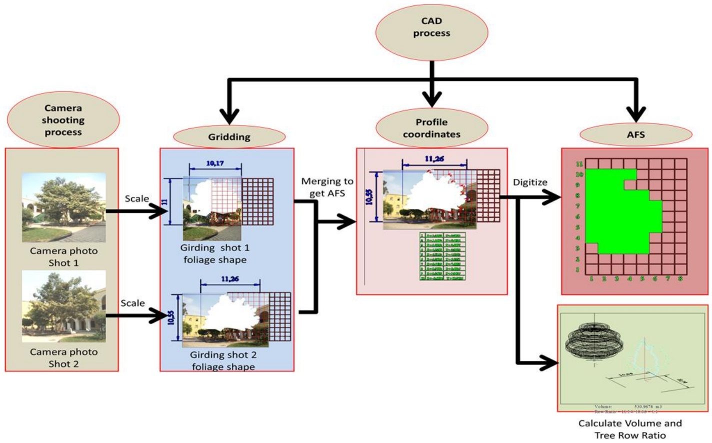

Fig 5 Using camera shoots with scale-meter to gridding and digitizing tree Averaged Foliage Shape (AFS) by CAD software

A minimum of 1x1m grid is required for the AFS digitizing drawing, to get tree foliage profile and estimate the AFS coordinates in x and z axis as shown in fig 5.

Calculating the AFS volume and Row Ratio (x to y ratio in the plan view) will help us to validate the foliage shape in both CAD and LAI software (FV2200).

Using FV2200 software of the LAI2200 to refine measurements, LAI values were recomputed after editing the initial measured LAI by inserting the captured tree profile coordinates in order to increase the accuracy through the digitized tree profile (tree crown section) and Row Ratio (tree horizontal plan). Fig 6 indicates the following information:

(1) Half profile (vertical cross section) of AFS coordinates.
(2) The (x, z) coordinates of the LAI2200 sensor beneath trunk.
(3) The type and orientation of the view cap used in measurements.
(4) Row ratio (x to y ratio in the plan view).

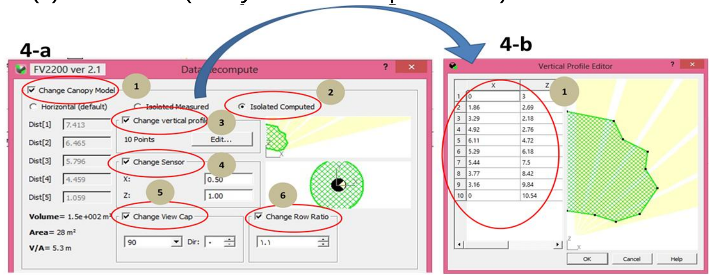

Fig 6 Interface of FV2200 tool used to recompute initial LAI measurements.4-a showing the required steps to refine initial LAI measurements, where 4-b showing vertical profile inserted coordinates.

After refining LAI measurements in FV2200 software, a new LAI of the selected tree has now been generated with extra aaccuracy and will be used in LAD calculations by a Fortran compiled tool for the empirical equation Eq.1 suggested by Lalic and Mihailovic (2004), [11].

Later, LAD results will be built in Albero, the trees 3D modeling tool of ENVI-met V4.0, and added to ENVI-met V4.0 plants database to represent the 3D canopy and trunk of these trees when modeling the case study environment and hence, trees can be simulated.

$$LAD = Lm \cdot \left(\frac{h - zm}{h - z}\right)^{n} \cdot \exp\left[n\left(1 - \frac{h - zm}{h - z}\right)\right] \qquad (1)$$

Where h is the total height of the tree in meters, zm is the canopy height at which LAD is the maximum, i.e. Lm (m), z is the height of LAD slice in meters and $n = 6$ if $0 \geq z \geq zm$, and 0.5 if $zm \geq z \geq h$.

3 CASE STUDY DESCRIPTION

3.1 Site analysis

This study examines the urban form of a residential quarter neighborhood in New Borg El-Arab, Alexandria, Egypt as a case study. The site was inaugurated in 1988 and is seen as the natural extension of Alexandria, as well as one of the most important industrial areas in Egypt.

New Borg El Arab City has major development plans underway and the city is expected to grow substantially in the future, multiplying the current population many times over. The current Strategic Master Plan for New Borg El Arab City was approved in 2013 by the New Urban Communities Authority (NUCA) and the General Organization for Physical Planning (GOPP) as presented in fig 7. It shows the existing and proposed land uses for the city until the year 2032. The current population is approximately 100 000 inhabitants, which is expected to grow to 750 000 inhabitants by 2032.

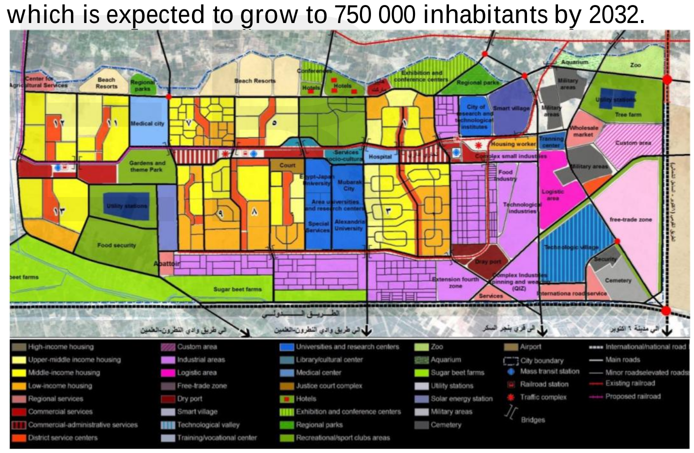

Fig 7 Approved strategic master plan for New Borg El Arab city for 2032[12]. Red circle added to the figure show the case study position

New Borg El-Arab weather is characterized by a mild climate; it prevails as the Mediterranean climate which is characterized by hotness in summer with, mild and rainy Winter fig 8. Table 1. Winter in New Borg El-Arab city extends through December, January and February where the maximum temperature ranging between 12°C and 18°C, and exposed to many severe thunderstorms, hails and heavy rains. The summer extends through the months of June, July and August and temperature ranging between 25°C and 30°C. In spring and sutumn the maximum temperature reaches 22°C, except during the wind waves of “khamasin” which raises the temperatures (in the Spring season) up to 32°C, fig 9, Table 2 .

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Fig 8 (a) Highlighted in red the geographical location of the research area, edited from Google maps for New Borg El-Arab, Alexandria. It shows that the location is still empty and surrounding sites is still under construction. (b) The final layout design designed by the Egyptian armed forces.

TABLE 1
Land use percentage for New Borg El-Arab, Alexandria, Egypt

Usage	Area (m^2)	Percentage (%)
Residtial	19298	45.38
Services	3499.97	8.23
Green Area & Pedstrain pathes	3906.06	9.2
Internal Asphalt road and parking	8830.24	20.76
Entrances and external roads	6986.7	16.43
Total	42020.97	100 %

TABLE 2
Geographical data for New Borg El-Arab, Alexandria, Egypt case study

	1st corner point	2nd corner point	3rd corner point	4th corner point
Long. & Lat.	30° 49' 51.203" N	30° 49' 47.887" N	30° 49' 53.011" N	30° 49' 55.664" N
	29° 32' 5.583" E	29° 31' 59.79" E	29° 31' 55.792" E	29° 32' 1.953" E
Altitude	63 m	65 m	66 m	64 m
Location Time Zone	EET(Eastern European Time)UTC/GMT +2 hours			
WMO Station	623601 (HEBA) at Borg El-Arab International Airport			

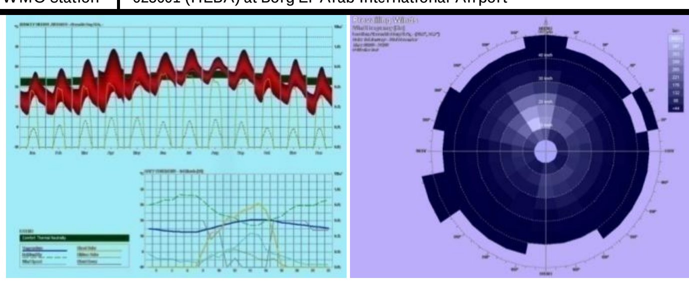

Fig 9 Monthly average meteorology for New Borg El-Arab, Alexandria. It based on 30 years records of WMO Station no. 623601 at Borg El-Arab International Airport. [13].

3.2 Selected Trees

Three of the most common trees used in the Egyptian urban environment were selected to verify the proposed methodology fig 10. Measurements took place on the 21st of July as the maximum hot day of the summer in the case site, analyzed by ECOTECT2010 Weather Tool [13], to ensure the solar altitude is the maximum which in turn generates the maximum shading plot under the tree crown. Albedo measurements is presented in Table 3 whereas LAI measurements before and after recomposing by the FV2200 tool of LAI2200c canopy analyzer as well as the calculated LAD values are presented in table 4 after applying the methodology.

Fig 10 Left; Ficus Nitida tree and a close look to its foliage. Middle, Cassia Nodosa tree and Right is Cassia Leptophylla tree

TABLE 3
Average readings for the three selected trees

Measured Data	Horizontal Global Radiation w/m²			Horizontal Diffused Radiation w/m²			Albedo			
Measured Tree	Reading (1)	Reading(2)	Reading 3	Reading 1	Reading 2	Reading 3	Reading 1	Reading 2	Reading 3	Average
Ficus Nitida	820	815	900	75	74	80	0.091	0.091	0.089	0.090
Cassia Nodosa	830	840	870	71	70	75	0.086	0.083	0.086	0.085
Cassia Leptophylla	960	703	840	80	61	72	0.083	0.087	0.086	0.085

4 Simulation

ENVI-met as a numerical Computational Fluid Dynamics (CFD) microclimatic model is capable of simulating the built environment (surface-air-plant) thermal interactions based on the fluid dynamics and heat transfer fundamentals, solar movement and vegetation databases and it proofed reliable usage in the scope of environmental impact assessment [14]. Its fourth version had a large improvement since its third version in terms of the new graphical user interface, heat budget calculations, databases, modeling and output data extraction tools.

In order to assess the influence of different LAI and Albedo of the tree on its thermal performance and in turn the modifications might occur in its microclimate , the case study has been simulated once as built (base case), once more with empirical trees modeled with LAI equals 1 and the default Albedo of ENVI-met plants database and finally simulated with the same pattern of trees of the second simulation but modeled with measured and recomputed LAI in addition to the measured Albedo, fig 11. Models of the three simulations had the same configurations for buildings arrangement, outdoor finishing materials, soil layers and weather conditions.

Simulations took place on the 21st of July for 12h from 6.00am local solar time (LST) to 6.00pm LST using input data shown in table 5. To ease discussion of results, the model of base case is assigned as C1, the model that used LAI of 1 is C2, and the model that used measured LAI is C3.

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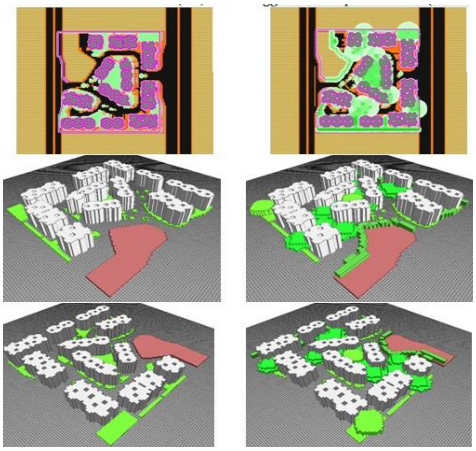
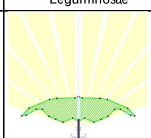
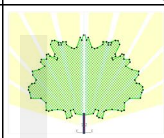
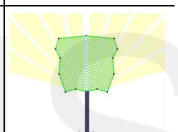


Fig 11 **left** 2D and 3D visualization for the three models of C1, and C2, C3 at **right**

TABLE 4

Selected trees geometrical variables, Measured LAI and computed LAD.

Tree name / Specifications	Cassia Nodosa			Cassia Leptophylla			Ficus Nitida		
Alternative name	Pink shower			Gold Medallion			Indian Laurel		
Family	Leguminosae			Fabaceae or, bean family			Moraceae		
Foliage Shape									
Total tree height	5 m			12 m			3 m		
Maximum LAD height	4 m			8 m			2 m		
Foliage height	3 m			9 m			2 m		
Foliage Albedo									
ENVI-met default Albedo	0.18			0.18			0.18		
Measured Albedo	0.085			0.085			0.090		
LAI (Leaf Area Index) m^2/m^2	Assumed	Measured	Recomputed	Assumed	Measured	Recomputed	Assumed	Measured	Recomputed
	1	3.4	1.61	1	3.18	4.79	1	3.98	3.95
LAD(Leaf Area Density)									
At 1.00m	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
At 2.00m	0.0	0.0	0.0	0.0	0.0	0.0	0.27	1.07	1.07
At 3.00m	0.24	0.86	0.39	0.03	0.12	0.182	0.86	3.44	3.41
At 4.00m	0.62	2.19	1.00	0.05	0.17	0.264	0.0	0.0	0.0
At 5.00m	0.74	2.62	1.20	0.08	0.25	0.384	0.0	0.0	0.0
At 6.00m	0.0	0.0	0.0	0.11	0.36	0.547	0.0	0.0	0.0
At 7.00m	0.0	0.0	0.0	0.15	0.48	0.734	0.0	0.0	0.0
At 8.00m	0.0	0.0	0.0	0.17	0.56	0.843	0.0	0.0	0.0
At 9.00m	0.0	0.0	0.0	0.17	0.54	0.824	0.0	0.0	0.0
At 10.00m	0.0	0.0	0.0	0.15	0.48	0.723	0.0	0.0	0.0
At 11.00m	0.0	0.0	0.0	0.07	0.25	0.376	0.0	0.0	0.0
At 12.00m	0.0	0.0	0.0	0.00	0.0	0.000	0.0	0.0	0.0

5 RESULTS AND DISCUSSION

Output data was extracted, Leonardo2014 which is tool within the ENVI-met V4.0 package, at 1.5m above ground level (agl) to justify the middle height between 1.2m-1.8m agl at which pedestrian is affected by the microclimate of an urban canyon[15]. Extracted output data includes outdoor PMV to represent a cumulative microclimate condition that a pedestrian might face under the effect of trees in addition to a set of climate parameters that a tree might affect. These parameters include air temperature (T_a), relative humidity (RH), direct shortwave radiation (SW_{Dir}), diffused shortwave radiation (SW_{Diff}), reflected shortwave radiation (SW_{Ref}), mean radiant temperature (T_{mrt}) and Predicted Mean Vote (PMV). Outputs were averaged at 1.5m above ground level (agl) to represent the whole outdoor urban spaces of the site and ease the comparison between the simulations rather than to have output at only one point of a selected urban canyon. The built in averaging tool (map script) of Leonardo2014 analyze each produced color schematic map, and compute the average value for each climatic parameter.

Table 5

Inputs of simulation parameter value

No.	Parameter	Value
1	Number of main area grids	x=175,y=175 & z=30
2	Nesting grid around main area	3
3	Soil profile for all grids (main, nesting)	Sandy soil
4	Grid size	x=1,y=1 & z=1
5	Vertical grid generation	Equidistance
6	Walls material	Brick wall: thickness=0.3 m, absorption=0.6, reflection=0.4 emissivity=0.9, specific heat=840, thermal conductivity=0.3 density=1000
7	Roof materials	Reinforced concrete thickness=0.2 m ,absorption=0.7, reflection=0.3 emissivity=0.9, specific heat=840, thermal conductivity=1.3 density=2000
8	Simulation Time	21-7-2015 starts from 06:00 AM ends at 06:00 PM for 13 hours
9	Start wind speed at 10m height	1 m/s
10	Start wind direction	355^{o} from north
11	Air roughness length	0.01
12	Initial temperature of atmosphere	27.78 ^{o}C
13	Initial specific humidity of atmosphere	13.511
14	Initial relative humidity of atmosphere	67 %

Fig 12 to 18 show the meteorological parameters generated from the three simulations output data sets.

Results indicate that using a measured LAI and Albedo in numerical modeling and simulation conclude an acceptable outdoor climatic conditions and comfort levels in terms of the reduction in PMV at the third case in comparison to the sec-

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ISSN 2229-5518

ond one. By the rise of solar altitude at the start of simulation at 6.00am LST, the common trend of output curves was increasing until the noon time after which the curves values of meteorological parameters as well as PMV tend to decrease until reaching the sun set time. Ta has been reduced from C1 to C3 by about 1.5° and the difference between Ta C2 and C3 is 0.5° owed to the dense trees used of which the least difference of LAI is 0.61 more of the Cassia Nodosa. RH increased in C1 compared to C2andC1 for the same reason. The more density added to the trees canopies over the empirical value of 1 in addition to the extra effect of the measured Albedo (0.085, 0.085 and 0.090 for the three trees respectively) revealed more evapotranspiration, incident radiation reflection and absorption and shading effects and in turn revealed more alleviation or cooling effect to the surrounding conditions. This explains why SWDir values showed reductions from C1 and C2 to C3 by considerable amounts. Differences of SWDir between C1, C2 and C3 were 185w/m2 and 160 w/m2 respectively. A smaller amount of differences was recorded for SWDiff, SW Ref but it didn't affect the considerable reductions of Tmrt and in turn PMV. Tmrt of C1 was 65.75 C° at 02:00pm, C2 was 62.32C° and C3 was 60.31C°. Tmrt reductions between C1, C2 and C3 were 6.2° at 10.00LST, 4.1° at peak time and about 6.2° early evening at 3.00pm LST.

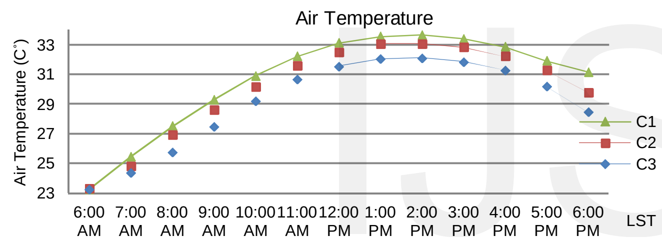

Fig 12 Air temperature comparisons between different cases

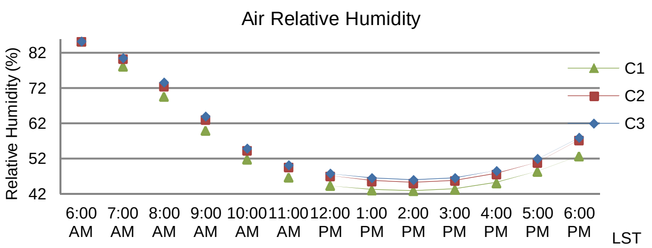

Fig 13 RH comparisons between different cases

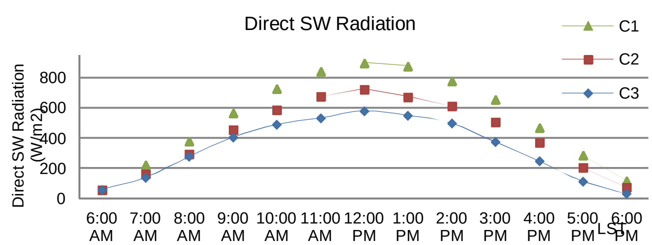

Fig 14 SW$_{Dir}$ comparisons between different cases

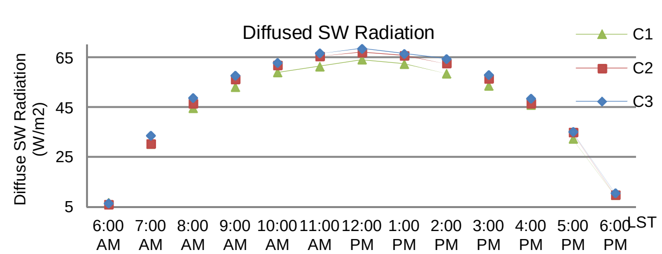

Fig 15 SW$_{Diff}$ comparisons between different cases

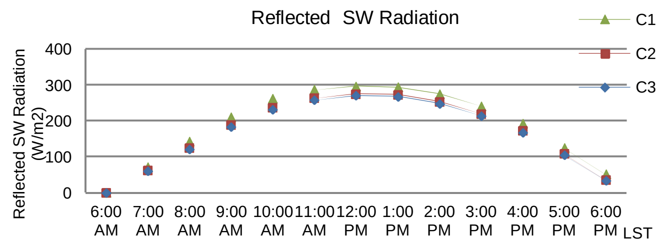

Fig 16 SW$_{Ref}$ comparisons between different cases

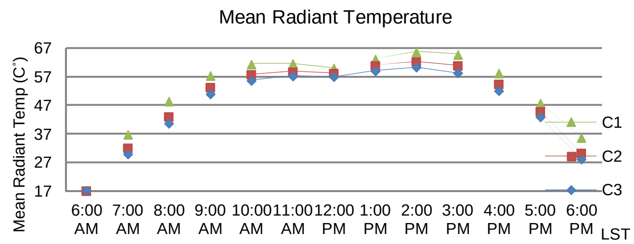

Fig 17 T$_{mrt}$ comparisons between different cases

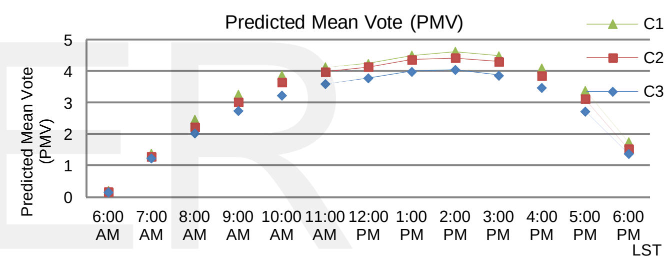

Fig 18 PMV comparisons between different cases

PMV results proofed the hypothesis; the more dense trees canopies (owed to the measured and recomputed canopies), the more comfortable PMV levels. Differences of PMV results increase during the morning hours till noon and starts to decrease by evening hours, it recorded 4.63 for C1, 4.43 for C2 and 4.05 for C3 at 2.00pm LST.

Fig 19 to 21 show thematic maps extracted from the simulation outputs using Leonardo2014 for different meteorological and comfort parameters of C1, C2 and C3 respectively.

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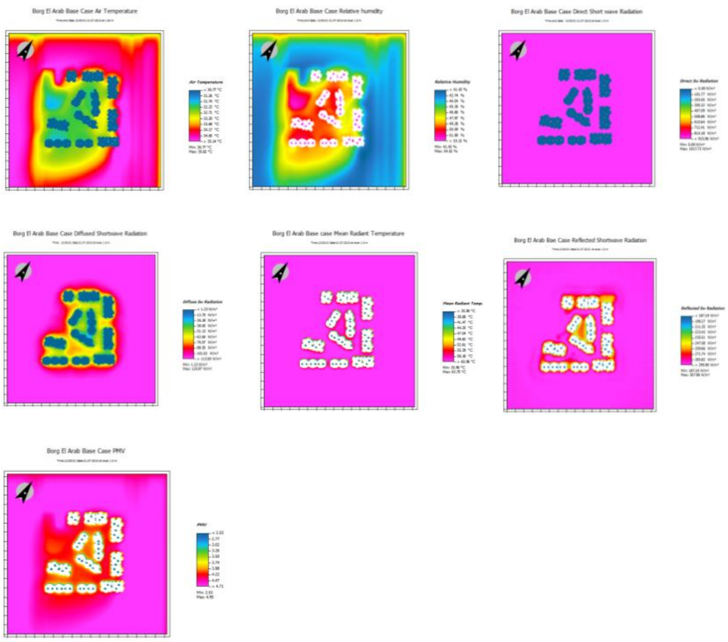

Fig 19 Output thermal maps of C1

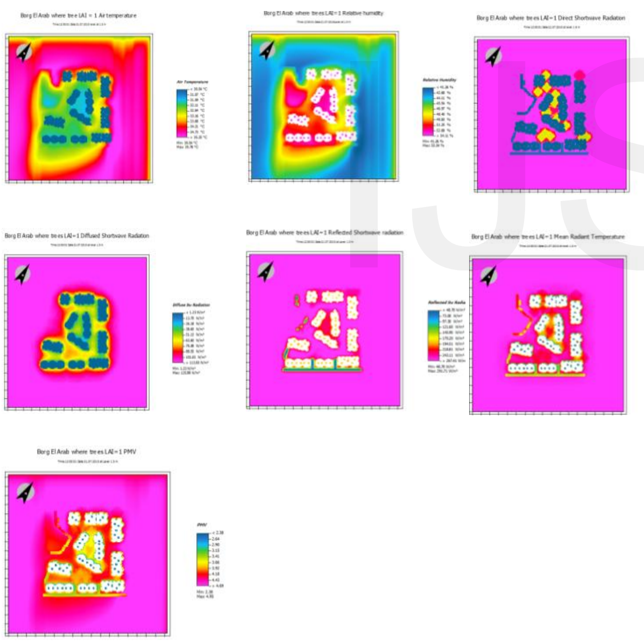

Fig 20 Output thermal maps of C2

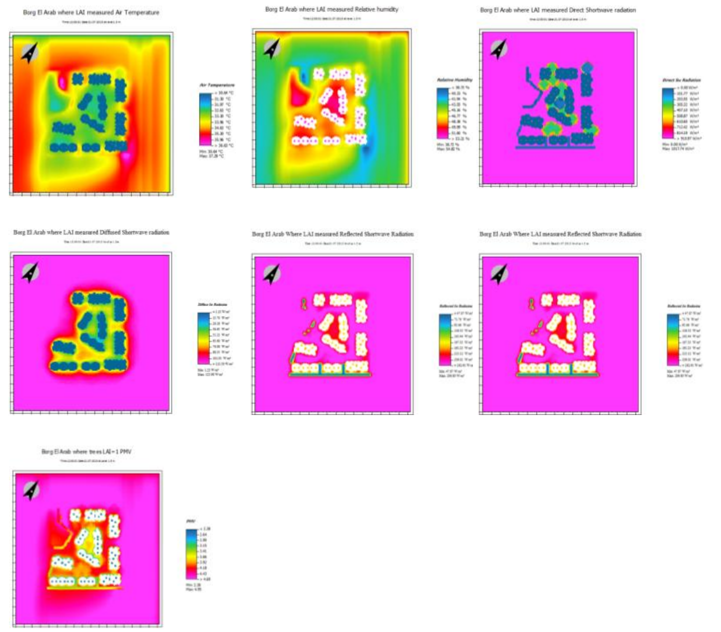

Fig 21 Output thermal maps of C3

6 Conclusion

This paper discussed, modeled and simulated the micro-climatic passive cooling effects of urban trees on a foliage parameters' measurements basis within its urban environment using ENVI-met V4.0 for a residential quarter neighborhood in New Borg El-Arab, Alexandria, Egypt. A new methodology utilized the measurements of LAI and Albedo and canopy geometrical parameters of three common Egyptian urban trees to numerically model and simulate the site base case (without trees), the site with empirical trees using LAI of 1 and the site with trees modeled using measurements. The methodology used measured LAI and Albdeo to generate LAD values of each tree and model and simulate its canopy in Albero which is the trees modeling tool in ENVI-met V4.0.

Results show that foliage measurements of trees concluded more dense and radiation reflective trees which revealed more evapotranspiration, incident radiation reflection and absorption and shading effects; i.e. more cooling effects. In this work both meteorological and comfort outputs of the case used trees modeled after measurements were better than those of the empirical trees. This not only proofs that urban trees is an important urban passive design element in hot regions as literature tells, but also proofs that enhanced modeling of urban trees affect the results expected of such microclimatic cooling hypotheses. Moreover, it offers a better way to construct a numerical data base for simulating the thermal effects of trees.

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