

The impact of park trees on microclimate in urban areas

N. J. Georgi · K. Zafiriadis

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Abstract Trees in cities have an important positive effect on people's lives. One such positive effect is the amelioration of microclimate. The aim of this research is to assess the correlation between parameters that affect the microclimate of parks during the summer. We measured air temperature, relative humidity and solar radiation in the sun and shade of the trees in urban parks in Thessaloniki, Greece. The results indicate that: the air (A) temperature reduction percentage (dTAir%), air relative humidity increase (dTRh%), discontent index reduction percentage (DI%) (cooling effect) and solar radiation (L) percentage that passes through the trees' foliage to their shade creates an exponential function of $dA\% = a \cdot e^{-bL}$. These functions are also applicable to the limiting variation values of the parameters. If we use $L = 0$ (meaning Lightsh = 0, which is the case for an extremely dense tree), then the values that we expect from this particular parameter are the maximum possible. These maximum values are a characteristic feature of the parameter variation for this particular research area. These maximum values for the trees in the parks of Thessaloniki are: $\max dTAir\% \approx 24\%$, $\max dRh\% \approx 41\%$ and $\max dDI\% \approx 16\%$.

Keywords Air temperature · Relative humidity · Solar radiation · Thermal comfort · Shade trees

Introduction

Environmental variables that are important for human thermal comfort include solar radiation, temperatures of surrounding surfaces, air temperature, and humidity and wind speed

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(Herrington, 1978; Akbari and Taha, 1992). Urban trees can ameliorate these environmental variables by preventing solar radiation from heating the surrounding buildings and surfaces, cooling the air by evapotranspiration, and reducing wind speed (Akbari et al., 2001). Trees function, therefore, as natural 'air conditioners', at least with regards to the microclimate of the city (Rowntree, 1986).

The microclimate that was created under the tree foliage has been the subject of several research programmes. Measurements that were carried out in the suburbs of Sacramento, in areas where mature trees are found, showed that the air temperature under the tree foliage was 1.7 – 3.3°C lower compared with areas where there are no trees (Taha et al., 1988). In Miami, Florida, the average air temperature reduction during summer was 3.6°C in the shade of large trees (Parker, 1989). Similar research that was carried out in Sacramento and Phoenix showed that a 25% increase in the number of trees can reduce the temperature during the summer by 3.3–5.6°C (Akbari et al., 1992). In Bloomington, Indiana, Souch and Souch (1993) found that midday temperatures underneath the tree canopy were 0.7–1.3°C lower compared with non-shaded areas. However, other urban studies did not detect significant reductions in temperature in the shade of trees (Herrington et al., 1972; Plumley 1975; McGinn, 1982). Urban trees can also alter the solar radiation rates in shaded areas. Thayer and Maeda (1985) showed that certain deciduous trees help in the reduction of solar radiation rates from 25% to 50%, with an average reduction of 35%. Heisler (1982, 1984) showed that, during winter, certain species (such as *Platanus acerifolia* and *Quercus palustris*) reduce solar radiation rates in the centre of their shade by 54% and 37%, respectively.

The variation of microclimate conditions in the shade of trees depends on the tree species. Souch and Souch (1993) studied three different species, in different conditions (parks, gardens and streets). Their results showed a reduction in temperature and an increase in relative humidity under the trees' foliage. The three different species examined did not present statistically important differences in the reduction of temperature and increase of relative humidity, and no connection was found between the reduction of temperature and the natural characteristics of trees (height, width of foliage, thickness of trunk, etc.). *Acer saccharum* and *Juglans regia* presented lower temperatures than *Pinus radiata*. They also found similar results when comparing temperature with relative humidity of trees found in streets and parks. They found that the relative humidity was higher (ranging from 27% up to 33%) under the trees and did not seem to depend on tree species. The difference in temperature and humidity measured between different environments (parks or streets) was deemed to be more significant than the difference between tree species growing in the same environment.

Trees found in the urban environment prevent solar radiation from heating buildings, cool the area through their evapotranspiration, reduce wind speed and reduce the need to use air-conditioning systems (Dimoudi and Nikolopoulou, 2003). However, due to the reduction of vegetation in urban areas, the problem of the thermal island is continuously increasing (Herrington, 1978). The cool climate conditions that occur in small areas depends on how shaded these areas are (Dafis, 2001). According to Ferrante and Mihalakakou (2001), plants have a large effect on the microclimate. Trees and green areas help to cool cities and to save energy. The evapotranspiration that results from vegetation foliage reduces the temperature in urban areas. An important change in temperature (heat tolerance) occurs as a result of the trees' foliage, in combination with the direct solar radiation (Shashua-Bar & Hoffman, 2003). This study examined the geometry and direction of the streets, as well as how these factors affect climate. It also examined how the street is affected by the presence of trees that provide shade. The results of the measurements carried out in Israel showed that the solar radiation rates in the trees' shade were 10% lower than those in the open air (Givoni et al., 2003). Measurements carried out in the urban areas of Tokyo, around buildings at midday,

showed that the maximum variation in the average air temperature caused by green areas was 0.47°C (Shobhakar and Hanaki, 2002).

The objective of the present project is to study the relationship between factors that affect the ecological, functional and bioclimatic behavior of trees in the parks of Thessaloniki, Greece. Because there are several factors that affect the ecological and functional behavior of trees, there are many different indexes (climate, geometrical characteristics, type of soil, architecture and urban plan characteristics, direction and intensity of winds, etc.) that are available to quantify their impact. We believe that, in the present project, we should determine the values of the following parameters: (1) tree species, tree height, width of foliage, air temperature, relative air humidity and intensity of light (solar radiation).

Methodology

Site description

The research was carried out in the city of Thessaloniki, Greece, and, in particular, in the centre and eastern part of the city (Municipality of Thessaloniki, where almost 360,000 people live in an area of 1,780 hectares). The city of Thessaloniki is located in northern Greece and is the second largest city of the country. It is built near the sea at an elevation ranging from 0 to 100 m between Hortiatia Mountain and Thermaikos Bay, and is located 40° 37' N and 22° 37' E. The research area belongs to the Mediterranean Vegetation Zone called *Quercetalia pubescentis* (hilly, sub mountainous), subzone *Ostrio-Carpinion* and area *Coccifero-Carpinetum*. The vegetation found in the city's parks arose as a result of plantations. The city's climate favours the growth of trees. In addition to this, the city's temperature is high with a low relative humidity rate, whereas it enjoys many hours of sunshine from June until September.

Measurement of environmental parameters

The microclimate was measured for a number of different species of trees growing in the parks of Thessaloniki (Figure 1). Temperature, humidity and intensity of light were measured for individual trees in the sun and in its shade. We then calculated the difference in the value percentage of each parameter under the sun and in the shade of the tree. All measurements were carried out between July and August, to standardize weather conditions. It should be noted that measurements were not carried out in days of extreme weather conditions and, indeed, not during the time period from 13.00 to 15.00. Hot summer days were selected so that the difference in the measurements of temperature, humidity and intensity of light would be the maximum possible. The various species of trees that were selected for these measurements were those found in large numbers in the parks of Thessaloniki. From each species of tree, we chose those that presented a normal growth and had similar geometrical characteristics (height and width of foliage).

Air temperatures (°C), relative humidity percentage and solar radiation ($\mu\text{En}/\text{m}^2 \cdot \text{sec}$) were measured at a height of 1.5 m from the ground in the shade of trees and out of the shade under the sun (Figure 2).

The value of solar radiation percentage (%) or 'active solar radiation' absorbed or reflected by the tree ($d\text{Light}\%$) was calculated using the following formula:

$$d\text{Light}\% = 100 (\text{Light}_{\text{sun}} - \text{Light}_{\text{sh}}) / \text{Light}_{\text{sun}} \quad (1)$$



Fig. 1 Master Plan of Municipality of Thessaloniki. The (▼) triangle symbol indicates the parks where the measurements have been taken

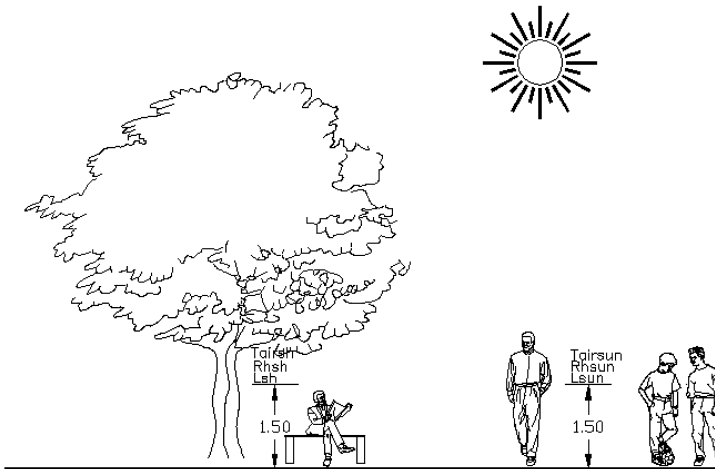


Fig. 2 The location at which air temperature, relative humidity (percentage) and solar radiation were measured

where *Light_{sun}* and *Light_{sh}* represent the solar radiation in the sun and shade, respectively. The value of $L = 100 - dLight\%$ gives the percentage of total solar radiation that filters through the foliage—that is, the energy (solar radiation) rate—which is not absorbed or reflected by the tree to the unit surface per sec. and finally manages to ‘pass through the tree’. This radiation affects both humans and materials (pavements, grass, asphalt, etc.) that are found in the shade of the tree.

Results

Elaboration of environmental parameters' measurements

The environmental parameters that were measured for the present research are shown in Table 1 (average measurement of 21 tree species). In this table, we show the results separately for each species of tree measured (294 trees belonging to 21 different species).

Measurements of the environmental parameters were carried out in the early afternoon hours (13.00–15.00) during the summer period. Although the weather conditions were almost similar, certain differences were observed. The air temperature during these days ranged between 29°C and 36°C, whereas the relative humidity ranged between 28% and 52%. Due to the difference in weather conditions, the use of difference (dif) in the parameters that were studied is not possible to present a statistically acceptable result. Therefore, we believed that it was necessary to study the difference percentage of the variation (reduction or increase) in the relevant parameter. The difference percentage is calculated as follows:

$$dTair\% = (Tairsun - Tairsh)/Tairsun \times 100 \quad (2)$$

$$dRh\% = (Rhsh - Rhsun)/Rhsun \times 100 \quad (3)$$

where:

$dTair\%$ = reduction percentage of air temperature in the shade of trees

$Tairsun$ = air temperature value in the sun

$Tairsh$ = air temperature value in the shade of the tree

dRh = increase percentage of the relative humidity in the shade of the tree

$Rhsh$ = relative humidity value of air in the shade of the tree

$Rhsun$ = relative humidity value of air in the sun

The species that were measured are shown in Table 2.

Evaluation of results of the discontent index measurement, as calculated using the values of the relative parameters

During the summer months and due to specific bio-climatic conditions (Balafoutis and Maheras, 1986; Giles et al., 1987) at this time of year in Greece, many people express a feeling of discomfort. The most convenient and common method to calculate the discomfort index in a place on a particular day at a particular time is by the discomfort index (DI) proposed by Thom (1959). This index is calculated from the air temperature and hydrometric parameters of the dewpoint temperature or the relative air humidity value. This index is used in many countries as a criterion of emergency protection measures, which need to be taken for the population when the value exceeds a certain limit (e.g. USA). Thom's discomfort index is calculated by the formula:

$$DI = TEM - 0.55 (1 - 0.01 HUM) (TEM - 14.5) \text{ } ^\circ\text{C} \quad (4)$$

where:

DI = Discomfort Index in °C (DI)

TEM = Air temperature °C.

HUM = Relative humidity (percentage) %.

Table 1 Elaboration of mean environmental parameters' measurements of park trees

PLANT	Height	Foliage	Tairsh	Tairsum	dTair %	Rhsh	Rhsum	dRh %	Lightsh	Lightsum	dLight %	L = 100 - dLight %	Dish	Disum	dDI %
Bpa	19.3	16.9	25.7	33.2	22.6	55.4	42.4	30.7	18.3	1013.3	98.2	1.8	23.0	27.3	15.8
Malb	6.8	5.0	28.7	34.5	16.8	62.8	49.9	25.9	21.7	1111.7	98.1	1.9	25.8	29.0	11.0
Caus	15.8	11.6	27.8	33.2	16.3	56.1	45.6	23.0	21.7	1100.0	98.0	2.0	24.6	27.6	10.9
Plsp	20.6	15.6	27.8	32.2	13.7	57.2	46.1	24.1	35.0	1090.0	96.8	3.2	24.7	27.0	8.5
Csil	6.4	5.2	27.7	30.7	9.8	58.7	47.6	23.3	35.0	1036.7	96.6	3.4	24.7	26.0	5.0
Lstyr	13.3	6.3	29.0	32.9	11.9	43.9	35.5	23.7	35.0	1008.3	96.5	3.5	24.5	26.4	7.2
Ahi	7.5	5.5	30.3	33.6	9.8	33.9	27.5	23.3	50.0	1150.0	95.7	4.3	24.6	26.0	5.4
Fam	19.5	10.0	28.8	31.9	9.7	51.1	42.2	21.1	45.0	1025.0	95.6	4.4	25.0	26.4	5.3
Aalt	14.7	9.3	30.0	32.5	7.7	52.3	44.8	16.7	51.7	1138.3	95.5	4.5	25.9	27.0	4.1
Uam	21.2	15.5	26.6	28.8	7.6	45.0	39.0	15.4	60.0	1100.0	94.5	5.5	22.9	24.0	4.6
Sjap	12.9	14.1	30.8	33.6	8.3	46.6	40.2	15.9	60.0	1071.7	94.4	5.6	26.0	27.3	4.8
Rps	12.0	7.5	30.0	32.3	7.1	55.7	48.4	15.1	60.0	1025.0	94.1	5.9	26.2	27.2	3.7
Lja	8.0	4.6	29.1	31.3	7.0	55.0	47.3	16.3	61.7	1018.3	93.9	6.1	25.5	26.4	3.4
Mpo	8.9	8.2	32.8	35.5	7.6	39.1	34.2	14.3	65.0	1066.7	93.9	6.1	26.7	27.9	4.3
Pbru	18.8	11.9	29.5	31.6	6.6	53.1	45.9	15.7	68.3	1073.3	93.6	6.4	25.6	26.5	3.4
Peer	9.8	7.2	30.2	31.8	5.0	60.2	52.1	15.5	73.3	1125.0	93.5	6.5	26.8	27.2	1.5
Ane	9.8	6.8	30.7	33.0	7.0	55.6	48.5	14.6	68.3	1046.7	93.5	6.5	26.7	27.8	4.0
Kpan	10.4	7.6	30.8	33.0	6.7	42.7	38.5	10.9	70.0	1036.7	93.2	6.8	25.7	26.7	3.7
Cbi	6.8	4.4	29.4	31.4	6.4	47.8	42.8	11.7	76.7	1046.7	92.7	7.3	25.1	26.1	3.8
Posp	21.9	10.1	30.9	32.9	6.1	46.1	42.0	9.8	85.0	1153.3	92.6	7.4	26.0	27.0	3.7
Aju	11.3	8.9	31.2	32.8	4.9	43.7	40.9	6.8	95.0	1138.3	91.7	8.3	26.0	26.9	3.3
Average			29.4	32.5	9.5	50.6	42.9	17.8	55.1	1075.0	94.9	5.1	25.3	26.8	5.6
St. Deviation			1.7	1.4	4.5	7.5	5.8	6.0	21.2	48.1	1.9	1.9	1.1	1.0	3.4

Information given in these tables is presented in columns as follows:

PLANT: Tree species, HEIGHT: Height of tree in m., FOLIAGE: Diameter of foliage in m., Tair: Temperature of air in °C, Rh: Relative humidity of air %, Light: Intensity of light or solar radiation $\mu\text{En}/\text{m}^2 \cdot \text{sec}$, sh, when the measurement is carried out in the shade; sun, when the measurement is carried out in the sun; dif: represents differences between the parameters of sun and shade for all environmental parameters (air temperature, relative humidity, solar radiation)

Table 2 Species that were measured, with their respective symbols

No	Symbol	Scientific name
1	Aalt	<i>Ailanthus altissima</i>
2	Caus	<i>Celtis australis</i>
3	Fam	<i>Fraxinus americana</i>
4	Ahi	<i>Aesculus hippocastanum</i>
5	Bpa	<i>Brussunetia papirifera</i>
6	Malb	<i>Morus alba</i>
7	Aju	<i>Albizia julibrissin</i>
8	Ane	<i>Acer negudo</i>
9	Kpan	<i>Keorleteria paniculata</i>
10	Cbi	<i>Catalba bignoides</i>
11	Uam	<i>Ulmus americana</i>
12	Lja	<i>Ligustrum japonicum</i>
13	Csil	<i>Cercis siliquastrum</i>
14	Lstyr	<i>Liquandambar styraciflua</i>
15	Plsp	<i>Platanus</i> spp.
16	Mpo	<i>Maclura pomifera</i>
17	Pbru	<i>Pinus brutia</i>
18	Pcer	<i>Prunus cerasifera</i>
19	Posp	<i>Populus</i> spp.
20	Rps	<i>Robinia pseudoacacia</i>
21	Sja	<i>Sophora japonica</i>
21	Hsy	<i>Hibiscus syriacus</i>

This index has also been used in Greece and has given satisfactory results (Balafoutis et al., 1998) when evaluating the discomfort that the largest sector of the population expresses. The use of the discomfort index represents the feeling of discomfort that certain, a few or many people of a group express when they find themselves in a certain area. To estimate the feeling of discomfort, certain limits were determined, which are shown in Table 3.

The discomfort index (DI) was calculated according to Equation 4 in the sun (DISun) and shade (DIsh) of the tree as follows (Figure 3):

$$DISun = Tairsun - 0.55 (1 - 0.01 RhSun) (Tairsun - 14.5),^{\circ}C \quad (5)$$

and

$$DIsh = Tairsh - 0.55 (1 - 0.01 Rhsh) (Tairsh - 14.5),^{\circ}C \quad (6)$$

Table 3 Discomfort index values (DI), in degrees celsius and discomfort feeling scale (Balafoutis et al., 1998)

Feeling of discomfort	DI [°] C
1 No discomfort	< 21
2 Discomfort expressed by < 50% of the population	21–24
3 Discomfort expressed by > 50% of the population	24–27
4 Discomfort expressed by the majority of the population	27–27
5 Discomfort expressed by all	29–32
6 Stages of medical alarm	> 32

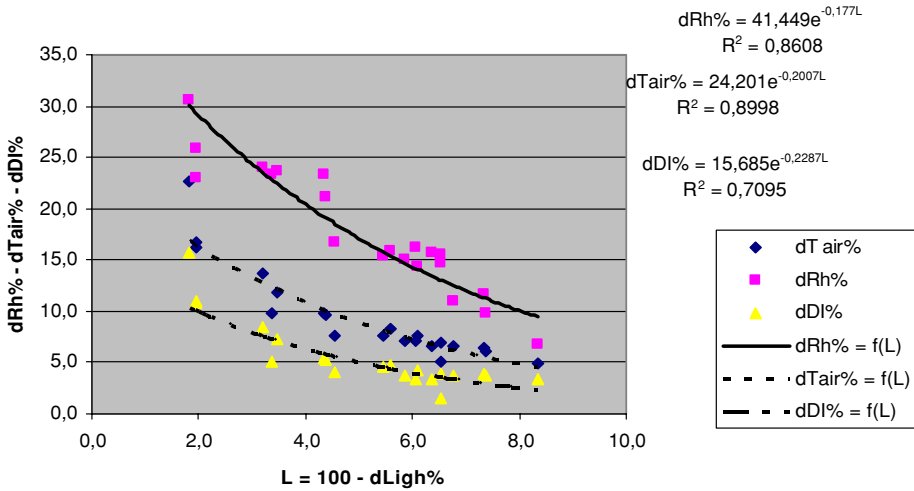


Fig. 3 Change of dRh%, dTair% and dDI% in relation to L%

where:

DISun and *DIsh* = discomfort index in the sun and shade, respectively, in °C

Tairsun and *Tairsh* = air temperature in the sun and shade, respectively, in °C

Rhsun and *Rhsh* = relative humidity percentage (%) in the sun and shade, respectively.

Table 1 presents the results of the aforementioned calculations and a reduction percentage of the discomfort index achieved in the shade of the tree. This value is symbolized by *dDI%* and is calculated by the formula:

$$dDI\% = (DISun - DIsh)/DISun \times 100 \tag{7}$$

The use of the discomfort index in the present study focuses on the comparison of the index expressed in the sun and shade of a tree and is intended to show how this index is reduced in the shade. Therefore, its use in the present research is not related to the discomfort expressed by people but the percentage of discomfort reduction achieved in the shade of a tree.

From each species of tree examined, we chose individuals that had similar or common general characteristics. This means that they had approximately the same growth and same geometrical characteristics (height and width of foliage). We also made an effort to use trees that were located in areas that presented no significant differences in microclimatic conditions. We also did not measure trees that were found in parks or were affected by extreme microclimate conditions of the area (e.g. trees located in very narrow streets, trees located in the shade of buildings, trees very close to the sea or affected by the sea breeze, etc.). We believe that the difference in the parameters examined was mainly due to the different kinds of trees and not the various conditions prevailing in the area where these trees were located.

Table 1 presents the average values of the trees' characteristics. The examination of the average and standard deviation of values, and the height and width of foliage, showed that each tree was indeed selected from types of trees that had similar characteristics (standard deviation: 0.3–2.2 for an average tree height (ranging from 5 to 20 m) and an average

foliage width (ranging from 3.0 to 17.0 m). We also present the results of measurements of different parameters and the reduction of parameters (temperature, humidity), as an average of these measurements. The results shown in Table 1 give the average of a large number of measurements carried out for trees of the same species and relatively similar dimensions. For each type of tree, we present the average result from 10 to 20 measurements. The examination of values in Table 3 shows that for all parameters measured, the typical deviation in relation to the relative average value is particularly low.

In the present study, we believed that we had to find a factor that represented the capacity of each species of tree to affect the microclimate in shade and open sunshine. Solar radiation (intensity of light) was thought to be the determinant factor of a system of leaves and branches of a particular tree canopy. The solar radiation factor of a dense tree canopy approaches the value of 0%, whereas for a tree which (theoretically) provides no shade, it approaches the value of 100%. The solar radiation in the shade of a tree ($L = 100 - dLight\%$) is a representative value that, in the present study, represents the species of tree fairly well as the purpose of the research is to study the relationship of the tree with the climatic conditions created in the air by the shade of trees.

Evaluation of the calculation of different parameters and their relationship with the species of tree

Changes in temperature, humidity and solar radiation as a correlative of tree species

The design of the correlation between the variables measured for this study takes into account the different values in the sun and in the shade, as a percentage reduction (%) associated with each species of tree. Each tree species was examined as a correlative of $L = 100 - dLight\%$, meaning the solar radiation percentage that each tree allows to pass through the system of leaves and branches. These changes were measured with least squares linear regression methods for each of the different types of analysis. In each case, we calculated the *coefficient of determination* (R^2). Following this, we checked whether this particular type of analysis is applicable to the limit values of the change in its variables (e.g. for 0% and 100%), so that it has a natural hypostasis.

Change of the air temperature reduction percentage (%) in relation to the species tree

Applying the least squares linear regression method for the values of $L = 100 - dLight\%$ and $dTair$, we reached the conclusion that their relationship is an exponential function of the following type:

$$dTair\% = a_1 \cdot e^{-b_1L} \quad (8)$$

where:

$dTair\%$ = the air temperature reduction in the shade as a percentage (%) of the value of air temperature in the sun.

$L = 100 - dLight\%$

a_1 and b_1 = parameters, the values of which depend on the climatic conditions of the research area

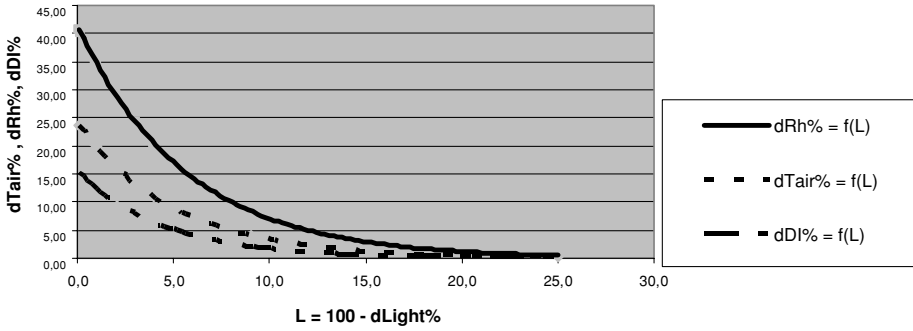


Fig. 4 Change of dRh%, dTair% and dDI% in relation to L% calculated with exponential function

For the values examined, the coefficient of determination follows:

$$dTair\% = 24.201 \cdot e^{-0.2007L} \quad R^2 = 0.8998 \quad (9)$$

Figures 3 and 4 present the graphic displays of the aforementioned mathematical ratio and variation curve calculated from Function 8.

Figure 5 shows the relationship between experimental and calculated rates from the above aforementioned function.

As L approaches 0, then $dTair\%$ approaches the value a ($a = 24,201$). This means that, in the case of a tree with extremely dense foliage ($Lightsh = 0$), the value $dTair\% = a_1$ is the maximum limit above which there can be no further temperature reduction percentage. For example, if the air temperature in the sun is 35°C , the reduction of temperature in the shade of a dense tree is not expected to exceed 8.5°C in the air. Conversely, when L approaches 100%, as in the case of an extremely thin foliage ($Lightsun = Lightsh$), then $dTair\%$ approaches a low value of approximately $dTair\% = 5 \times 10^{-8}$ for the air, which means it approaches $dTair\% = 0$. The value of constant b ($b = 0.2007$) represents the increase of $dTair\%$ with a reduction of L percentage (%) (negative sign of the exponent).

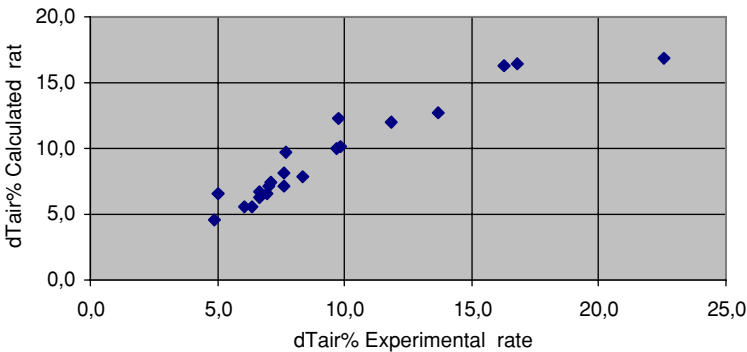
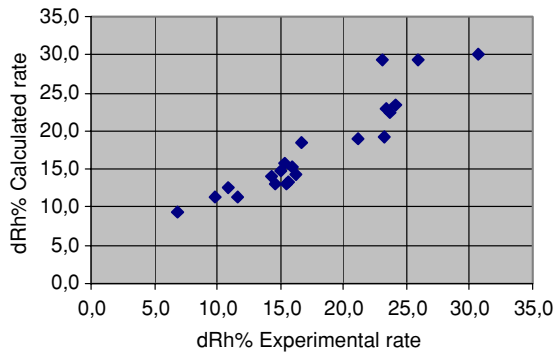


Fig. 5 The relationship between experimental and calculated rates of dTair%

Fig. 6 The relationship between the experimental and calculated rates of dRh%



Change in the increase percentage (dRh%) of relative air humidity correlative of the species of tree

Further applying the method of least squares linear regression for values of dRh% and $L = 100 - dLight\%$ results in the following exponential function:

$$dRh\% = a_2 \cdot e^{-b_2L} \tag{10}$$

where:

$dRh\%$ = increase of relative humidity percentage in the shade of trees, as percentage of the value of the relative humidity percentage in the sun.

a_2 and b_2 = parameters, the values of which depend on the climatic conditions of the research area.

For the observations from this study, Function 10 can be expressed as:

$$dRh\% = 41.449 \cdot e^{-0.177L}, R^2 = 0.8608 \tag{11}$$

Figures 3 and 4 present the graphical displays of the aforementioned mathematical ratio and variation curve calculated from the aforementioned function. Figure 6 shows the relationship between the experimental and calculated rates from the above aforementioned function.

When the value of L approaches 0 (which is the case for a very dense tree foliage, $Lightsh = 0$), then $dRh\%$ approaches the value of a (meaning that $dRh\%$ results in 41.449%). This value of $dRh\%$ is the maximum limit over which it is not possible to expect any further percentage increase of the relative humidity in the shade of the tree.

The value of parameter b_2 ($b_2 = 0,177$) represents the percentage rate of the relative humidity in the shade of the tree, with an increase of the value of L (meaning the increase of the tree’s density). When the value of L approaches 100 (in the case of sparse foliage), then the value of $dRh\%$ approaches $9 \times 10^{-7}\%$. This means that the value of $dRh\%$ approaches 0.

Change of ratio $dRh\%/dTair\%$ versus tree species

From the functions $dRh\% = f_1(L)$ and $dTair\% = f_2(L)$ examined in the previous chapters and with divisions of parts, we obtain the following:

$$dRh\%/dTair\% = 1.713 \cdot e^{0,0237L} \tag{12}$$

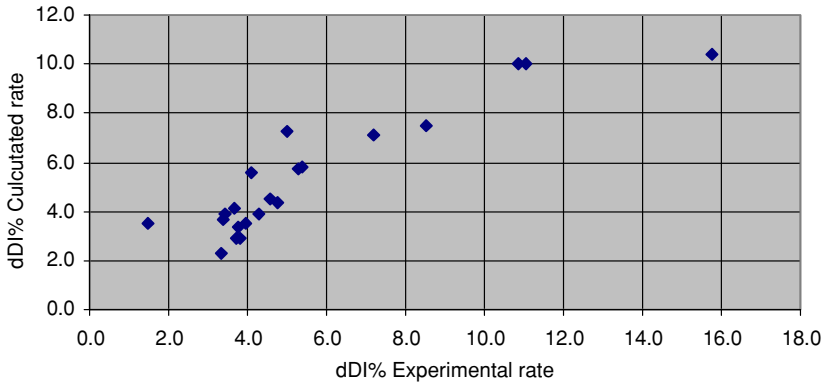


Fig. 7 The relationship between experimental and calculated rates of dDI%

If L approaches 0 (which is the case for a tree with extremely dense foliage), the value of $dRh\%/dTair\%$ approaches 1.713. This means that the value of 1.713 is a minimum variation limit for this ratio. If, for example we have $dTair\% = 10\%$, then the increase percentage of the relative humidity in the shade is expected to be at least $1713 \times 10\% \cong 17\%$.

Change in the discomfort dDI% index versus tree species

Applying the least squares linear regression method for values $dDI\%$ and $L = 100 - dLight\%$, we obtained the following exponential function:

$$dDI\% = a_3 \cdot e^{-b_3L} \tag{13}$$

where the values of a_3 and b_3 depend on the climatic conditions of the research area.

The function of the values examined in Equation 13 are:

$$dDI\% = 15.685 \cdot e^{-0.2287L}, R^2 = 0.7095 \tag{14}$$

Figures 3 and 4 present the graphical displays of the mathematical ratio and variation curve calculated for Equation 14. Figure 7 shows the relationship between experimental and calculated rates from Equation 14.

When L approaches 0, then the value of $dDI\%$ approaches the value of parameter a_3 , meaning $dDI\% = 15.685\%$. The value $dDI\% = 15.685\%$ is a maximum limit over which we expect no further reduction percentage of the value of $dDI\%$ in the shade of the tree. The value of parameter b_3 ($b_3 = 0.2287$) represents the increase percentage of $dDI\%$ with a reduction of the value of L . This ratio is much larger than the variation ratio of $dTair\%$ and the relative humidity percentage $dRh\%$. When L approaches 100% (in the case of an extremely sparse foliage), then the value of $dDI\%$ approaches a small value of approximately $dDI\% = 2 \times 10^{-9}$. This means that it practically approaches $dDI\% = 0$.

Comparison of the variation of dTair%, dRh% and dDI%, versus L

Figure 4 shows the variation of $dTair\%$, $dRh\%$ and $dDI\%$, versus the value of L , as calculated with the liner regression functions used previously. The more the value of L is reduced, the

more the distance between these three curves increases, whereas the more the value of L is increased, the closer the three curves come to be united (as, for an ultimate $L = 100$, they approach 0). This means that for very dense trees, the percentage values of $dDI\%$, $dTair\%$ and $dRh\%$ differ widely, whereas the more sparse the tree's foliage is (L value is increased), the more the values of these parameters are similar, reaching almost the same limit value of 0 for $L = 100$.

The difference in e exponents in these three functions has the following meaning: For one particular variation of L (e.g. an increase of L , meaning a reduction of the tree's density), the reduction ratio of $dRh\%$ is lower than the reduction ratio of $dTair\%$, which is lower than $dDI\%$. For example, if the value of L is increased from $L = 0$ to $L = 10$, which is the case in a very sparse foliage, then:

The value of $dDI\%$ will be reduced from 15.685 to 1.593 (90% reduction)

The value of $dTair\%$ will be reduced from 24.201 to 3.252 (87% reduction), and

The value of $dRh\%$ will be reduced from 41.449 to 7.060 (83% reduction)

This means that the increase percentage of the relative humidity will be lower than the temperature reduction percentage and this will be lower than the reduction percentage of the discontent index.

Discussion and conclusion

Our measurements of air temperature, relative humidity and solar radiation in the sun and in the shade of park trees in Thessaloniki, Greece, suggest that the relationship between reduction in air temperature ($dTair\%$), increase in relative air humidity ($dRh\%$), increase in the discontent index ($dDI\%$) and the solar radiation that passes through a trees' foliage to its' shade, results in the following exponentials:

$$\boxed{dA\% = a \cdot e^{-\beta L}} \quad (15)$$

where:

A = the parameter examined:

$Tair$ = air temperature in °C

Rh = relative humidity%

DI = discontent index °C, calculated with Thom's formula:

$$DI = Tair - 0.55 (1 - 0.01 Rh) (Tair - 14.5)^\circ\text{C} \quad (16)$$

$dA_1\%$ = % variation of the parameter value in the shade of the tree, in relation to the parameter value in the sun.

$dTair\%$ = $100 (Tairsun - Tairsh) / Tairsun$

$dRh\%$ = $100 (Rhsh - Rhsun) / Rhsun$

$dDI\%$ = $100 (DISun - DIsh) / DISun$

$L = 100 - dLight\%$

$dLight\%$ = $100 (Light\ sun - Light\ sh) / Light\ sun$

$Lightsun$ and $Lightsh$ = the solar radiation value in the sun and in the shade in $\mu\text{En}/\text{m}^2 \cdot \text{sec}$

a and b = parameters (fixed), the values of which depend on the climatic conditions and characteristics of the research area, as well as the kind of parameters measured (air temperature, or relative humidity, or discontent index).

All equations of this type, studied for a large number of trees in the parks of Thessaloniki, describe with sufficient accuracy, the experimental data of the present project. Equation (15) is applicable for parameter limit values with sufficient accuracy. If in equation (15) we use the value $L = 0$ (meaning $Lightsh = 0$, in the case of an extremely dense tree canopy), then the values $dA\% = f(0) = a$ are the maximum limit values that we could obtain from this particular parameter. These maximum values are the characteristic quantities of the variation of a parameter for this particular research area. These maximum values for the trees in the parks of Thessaloniki are: $maxdTair\% \approx 24\%$, $maxDRh\% \approx 41\%$ και $maxDDI\% \approx 16\%$. These maximum values that were determined for the parameters studied (air temperature, relative humidity percentage and discontent index) are consistent in magnitude with the results of other studies examining similar climatic characteristics during the summer (Oke, 1974; Plumley, 1975; Herrington and Plumley, 1976; Foster, 1978; Parker, 1983; Heisler, 1985; Heilman et al., 1989; Parker, 1989; Heisler, 1990; Zajicek and Heilman, 1991; Kjelgren and Clark, 1992).

The value of parameter β in the previous equations represents the variation ratio of the parameter value with the increase in the value of L . The largest variation level is obtained by the value of the *discontent index* $dDI\%$, followed by $dTair\%$ and $dDRh\%$.

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