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Microclimate modification by urban shade trees – an integrated approach to aid ecosystem service based decision-making

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Abstract

Since microclimate regulation is one of the most important services of vegetation that is directly perceived by urban population, many studies aimed to evaluate and map this service on different spatial scales. Most of the investigations focused on the modification of only one parameter, namely the reduction of air temperature. However, it is important to state that thermal sensation, health and well-being are influenced by more atmospheric parameters, including air humidity, wind velocity and the three-dimensional short- and long-wave radiation environment as well. This necessitates the assessment of the modification effect of urban vegetation on the thermal components separately. With the above mentioned objective, this paper presents the initial results of a microclimate investigation series carried out in Szeged, South-East Hungary. Systematic on-site measurements were carried out with a pair of special human-biometeorological stations on 20 clear summer days of 2015 in order to reveal the small-scale climate regulation potential of single trees in urban environment. Five healthy, mature trees were selected for the analysis, without the disturbing (additional shading) effect of any other trees or artificial objects. We compare separately the median values of the main thermal parameters – air temperature, relative humidity, as well as the short- and long-wave radiation components from the upper and lower hemisphere – measured under the canopy of the trees, and in the sun. Our results demonstrate that all of the five investigated tree specimens have significantly greater impact on the components of the radiation budget, while the modification of air temperature and humidity is rather small. Inter-species differences seem to be small in the warmest hours of the day, and may be attributed to the dimensional and canopy-characteristics. During the development of ecosystem service indicators it would be advisable to use integrated human-biometeorological indices which take into account all meteorological parameters that influence considerably human thermal comfort.

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Keywords: climate regulation, urban trees, temperature, humidity, radiation components, clear summer days

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1. Introduction

In the light of the excessive level of urbanization as well as the predicted effects of climate change [1] the need for climate conscious urban planning strategies is greater than even before. Regional climate models project more intense, more frequent and longer-lasting heat stress periods for Central-Europe [2, 3] that will likely lead to increased mortality [4, 5], especially among heat-sensitive population groups like infants and elderly people [6, 7]. Recent studies report that summertime heat stress may increase much more in cities than in rural and natural areas [8, 9]. Since many urban environments can be characterized with microclimates that result in high levels of heat stress in the warmer periods of the year, there is an emerging need for adequate adaptation and mitigation strategies in urban landscape planning [10, 11]. Such strategies, as well as the related local (governmental) decision making, have a significant role in settlement management all over the world [12]. The specific steps of their implementation can influence either only the built environment, e.g. through ensuring adequate ventilation [13], adopting high-albedo materials [14, 11] or also the establishment of water bodies [15] and the green surfaces through planting and maintaining urban trees and other types of vegetation [14].

Urban vegetation is a fundamental element in urban planning with high climate regulation potential, i.e. a capability to reduce heat stress in summer and optimize human comfort conditions [14]. Ecosystem services provided by green areas include, among others, carbon sequestration, energy saving and the recreational value of urban parks as well [16]. A well-planned system of smaller and larger vegetated areas offers important ecological services and several other functions that may be perceived by citizens to a different extent. Some investigations demonstrated that urban population are primarily aware of cultural services, and they perceive few of the supporting and regulating services directly [17, 18]. Microclimate regulation by trees belongs to the latter category, since the attendance of outdoor urban spaces and individuals' behaviour in these areas are obviously influenced by the existing microclimatic differences: people in outdoor environments generally seek to find the most comfortable places in terms of thermal conditions [19, 20]

The environmental assessment methodology of green areas, in addition to many scientific results about various planning processes at a regional-scale, is expected to become more important. According to the recent communications of the European Commission [21], every regional development programs, being of national or international level, have to serve the development of green infrastructure. This document emphasized that urban green areas are important elements of the green infrastructure. Assessments of ecosystem services and investigations of their spatio-temporal differences are usually based on appropriate indicators. In scientific investigations, these indicators are used to characterize complex socio-environmental factors and processes in a simple manner, and to describe the state of ecological integrity [22]. Besides, in order to help planning integrate the concept of ecosystem services in practice, simple and sound indicators are necessary, and, as far as possible, taking into consideration the effects of land use intensity [23]. Development of several indicators has been in progress all over the world relating to the investigation of urban ecosystems [24]. There are detailed reviews about the usage of indicators developed according to service-categories [25]. Other studies assessed several types of services with different indicators [26]. However, there is an emerging need for integrated indicators that assess many types of services with only one measure; a couple of studies have already adopted such indicators [27, 28].

Because climate regulation is one of the most widely acknowledged services of urban vegetation, many studies evaluated it on different spatial scales. There are simple, generally applicable indicators for the purpose of impact assessment at urban-scale planning processes [29]. Intra-urban differences may be evaluated through Urban Morphology Types [30], while Vegetation Structure Types may be useful for small-scale spatial planning [31]. Earlier investigations focused primarily on the air temperature reduction capacity of vegetation (see for example the detailed review work by Bowler [32], as well as the works of Bastian [33] and McPhearson [34]). However, it is important to state that thermal sensation, health and well-being are influenced not only by air temperature, but other atmospheric parameters too. The so-called thermal parameters include air temperature, air humidity, wind velocity, as well as short- and long-wave radiation flux densities from the environment which affect the human energy budget [35, 10]. Earlier studies have demonstrated that the sensitivity of people regarding the different components of outdoor thermal environment is different [36, 37, 38].

Green areas in cities are capable of modifying all thermal parameters. Vegetation management – especially urban forestry – contributes significantly to the mitigation of the urban heat island via evapotranspiration. Evapotranspiration is the sum of evaporation and transpiration. Evaporation means water vaporization into the air from different wet surfaces (soil, canopy interception, and water surfaces), and transpiration is the process of water movement through a plant converting water into vapour and releasing it into the atmosphere through the stomata. These processes cool the immediate environment and increase the level of air humidity [14]. It is widely known that vegetation enhances the intensity of evaporation [39]. This intensity can be assessed via remote sensing [40] and the evaporative cooling can be calculated through different models [41]. Shading by trees – provided by single trees, clusters of trees or urban forests – may decrease air temperature and reduce considerably the solar radiation income of the ground and other surfaces in the shade [39, 40, 41]. It is important to note that the reduced amount of direct radiation under the tree canopy means mitigated thermo-physiological strain [42, 43, 44].

In spite of the great number of field measurements and model simulations regarding the climate regulation services of urban trees, i.e. investigations of their modifying effect on individual thermal parameters, there is a considerable lack of knowledge regarding the relative magnitude of these modifications. It would be important to know which parameters are modified to a greater or lesser extent by planting and maintaining urban trees. Besides, there are only isolated studies about the inter-species differences regarding the climate regulation potential of urban trees. These attributes can be examined on the level of individual trees.

The above mentioned facts necessitate evaluating the modification effect of urban trees on the atmospheric parameters separately, in order to improve the general assessment of ecosystem services provided by urban vegetation and thus to promote the development of ecosystem service indicators. This requires the simultaneous measurement of many atmospheric parameters under the same meteorological background conditions. In line with the mentioned general goals, this paper presents the results of a long term Hungarian measurement campaign investigating the small-scale climate modification potential of single shade trees in the warmest hours of the day in summer. Small-scale meteorological conditions influence directly the perception of human thermal comfort [10, 14]. Specifically, we set the targets of this study as follows:

- looking for significant modifications in microclimate parameters resulted by the trees,
- ascertain the relative impact of trees on the different climate parameters,
- comparison of different trees regarding their climate regulation potential,
- discussion of the obtained results from the viewpoint of ecosystem service indicator development.

2. Measurements in Szeged

A systematic measurement series was organized in Hungary aiming to analyze the small-scale impact of single, mature trees on different climate elements in an urban environment. Our investigations took place in the city of Szeged (46°N, 20°E), the regional centre of the Southern Great Plain in South East Hungary. Szeged is the third most populated city of Hungary with more than 162,000 permanent residents, and an area of 281 km^2. Land-use types in the city vary from the densely built-up inner city to the detached housing suburban areas.

Based on the 1971–2000 climate normal period, the sunshine duration is 1978 hours per year, the annual sum of precipitation is 489 mm and the mean temperature is 10.6°C. Monthly mean temperature values are around 20°C during June, July and August with maximum temperatures above 25°C (Table 1). According to Fábián, Matyasovszky [45] the middle and the southern part of the Carpathian-basin are dominated by the hot summered and mild wintered *Cfa* in Köppen climate classification system. The time series of annual spatial mean temperatures shows a quasi-constant rise and intense oscillations in the distribution of precipitation can be observed through these years.

There are some important attributes making Szeged very interesting from the viewpoint of meteorological investigations. Being already one of the warmest cities in Hungary, the urban climate of Szeged may be affected very intensively by the general warming tendencies predicted for the Carpathian Basin (e.g. by [45, 46, 47]). It should also be highlighted that Szeged is spread on a flat area without considerable topographical differences (78-85 m above sea level), which allows small-scale meteorological results to be generalized [39].

In the frame of a systematic measurement series in 2015, several micro-climate parameters were measured, which influence the human energy budget, and thus directly affect human thermal sensation and the perception of thermal comfort (Table 2). As basic factors, air temperature – T_a [°C] and relative humidity – RH [%] were recorded under mature urban trees as well as in nearby sunlit sites (Fig. 1). Beside these parameters, short- and long-wave radiation flux densities were also recorded; separately from the upper and lower hemisphere – K_u, K_d, L_u, L_d [W/m^2].

Table 1 Climate data in Szeged for the period of 1971–2000: monthly averages of maximum, mean and minimum temperatures, as well as precipitation. Source: Hungarian Meteorological Service

Month	*T_a-max [°C]*	*T_a-mean [°C]*	*T_a-min [°C]*	*precipitation [mm]*
Jan	*2.8*	*-0.8*	*-3.8*	*24*
Feb	*5.7*	*1.2*	*-2.6*	*23*
Mar	*11.6*	*5.9*	*0.5*	*25*
Apr	*16.9*	*10.8*	*5.2*	*40*
May	*22.4*	*16.3*	*10.3*	*51*
Jun	*25.5*	*19.2*	*13.0*	*68*
Jul	*27.7*	*20.8*	*14.3*	*53*
Aug	*27.6*	*20.8*	*14.0*	*56*
Sep	*23.3*	*16.4*	*10.3*	*37*
Oct	*17.2*	*11.0*	*5.6*	*35*
Nov	*8.9*	*4.7*	*1.2*	*38*
Dec	*4.1*	*0.9*	*-2.0*	*39*

Table 2 Investigated parameters and their relation to thermal discomfort in summertime conditions (based on [35])

Notation	*Parameter*	*Influence on the thermal budget of the human body, and thus on thermal discomfort*
T_a [°C]	air temperature	High T_a means greater convective heat gain for the human body. The possibility of heat stress and discomfort increases with rising T_a above the surface temperature of the human body (with a typical value of 33°C) .
RH [%]	relative humidity	The effect of humidity depends on T_a; in the case of high T_a, high RH causes thermal discomfort and increases the possibility of heat strain because it obstructs latent heat loss by evaporative cooling (i.e. obstructs the vaporization of sweat from the body surface).
K_u [W/m^2]	short-wave (solar) radiation from the upper hemisphere – global radiation	Short- and long-wave radiation flux densities mean sensible heat gain to the human body. Generally in summer, when T_a is high, greater magnitude of radiation heat gain is the primary cause of thermal discomfort and heat stress.
K_d [W/m^2]	short-wave (solar) radiation from the lower hemisphere – reflected radiation	
L_u [W/m^2]	long-wave radiation from the upper hemisphere – atmospheric counter radiation	
L_d [W/m^2]	long-wave radiation from the lower hemisphere – emitted radiation from the ground	

We used two special (tailor-made) human-biometeorological stations for the purpose of these measurements; both of them equipped with Vaisala sensors (WXT-520) and Kipp & Zonen net radiometers (CNR-1 and CNR-4). The accuracy of T_a-measurements is ±0.3°C at 20°C (±0.25°C at 0°C), and it is ±3% in the case of RH in the 0–90% domain (±5% if RH falls between 90 and 100%). We conducted simultaneous measurements with the two stations that recorded one-minute averages in the case of all parameters. One of the stations was placed under carefully selected urban trees (selection criteria are detailed in the next paragraph), at a distance of two meters on the northern side of the tree trunk. The other station measured simultaneously at the same place, in an open point fully exposed to direct solar radiation during the measurement interval.

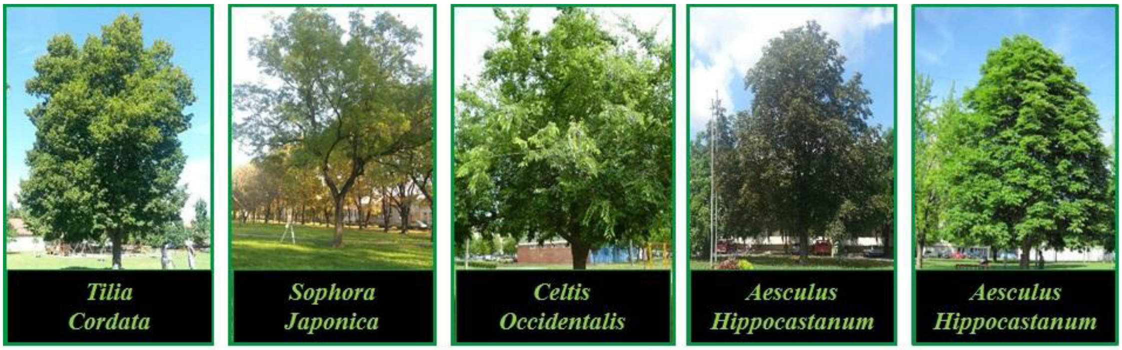

Fig. 1. Photos about the investigated trees

The ground cover had to be the same in the measurement sites under tree and in the sun, in order to avoid the albedo-influence on the obtained values of reflected radiation – K_d (Tables 2-3). Using telescopic legs, the sensors were placed at 1.1 m height above ground level. This height corresponds to the centre of gravity of a standing European man, the most frequently applied standard subject in outdoor thermal comfort investigations [10, 43, 44]]. Following the instructions of the manual of the net radiometers, we took special care about the horizontal levelling and their orientation to South.

Before the micrometeorological measurement campaign, thorough field surveys were conducted in the urbanized areas of Szeged aiming to select appropriate trees and study locations. The main criteria were to find healthy adult tree specimens without the disturbing effect of other natural or artificial landscape elements [48, 40, 41], in order to ensure that other trees or buildings do not influence the recorded parameters significantly during the measurement period (typically from 10 am to 4.15 pm). Besides, the selected trees were to stand in a park or a square with considerable amount of open sunny locations too, in order to facilitate the nearby 'in the sun' measurements. Moreover, we sought to represent those species that are frequently planted in Hungarian towns as street trees or park trees. Finally, five specimens were selected for the purpose of our investigations (Fig. 1, Table 3):

- one *Tilia cordata* (small-leaved linden),
- one *Sophora japonica* (pagoda tree),
- one *Celtis occidentalis* (common hackberry),
- and two *Aesculus hippocastanum* (horse-chestnut) with different dimensional characteristics.

Table 3. Dimensional characteristics of the selected trees

	T. cordata	*S. japonica*	*C. occidentalis*	smaller *A. hippocastanum*	larger *A. hippocastanum*
height [m]	15.5	12	9	13.5	15
trunk height [m]	2.5	3	1.8	2.5	2
canopy diameter [m]	9	12	14	9	10
trunk diameter [cm]	70.5	75	70	57	78
surface cover	concrete – grass	grass	grass	grass	grass

Table 4. Measurement days in 2015 under the selected tree specimens

T. cordata	*S. japonica*	*C. occidentalis*	smaller *A. hippocastanum*	larger *A. hippocastanum*
30-May-2015	29-May-2015	03-Jun-2015	02-Jun-2015	01-Jun-2015
06-Jul-2015	03-Jul-2015	05-Jul-2015	01-Jul-2015	02-Jul-2015
01-Aug-2015	06-Aug-2015	23-Jul-2015	22-Jul-2015	21-Jul-2015
31-Aug-2015	01-Sep-2015	29-Aug-2015	28-Aug-2015	27-Aug-2015

The microclimate measurements were carried out on 32 days in the vegetation period of 2015. Each day, the instruments were installed 10-20 min prior to the dedicated measurement interval in order to allow sensors to stabilize. For the purpose of this study we selected only those data that were recorded on clear summer days between 10 am and 4.15 pm. As a result, each tree will be represented with four measurement days in the analyses (Table 4).

Data analyses were performed within the statistical software SPSS. We were looking for significant small-scale climate modification effects of trees, as well as significant differences among the investigated specimens by using paired sample test. Since neither of the microclimate parameters had normal distribution, we performed the non-parametric Wilcoxon test (signed-rank test). The climate-regulation potential of the investigated trees was compared using distributional statistics of the measured parameters. Accordingly, the results were illustrated in the form of box-plot diagrams. The boxes indicate the spread of the sample as interquartile range (IQR), containing the middle 50 percent of values between the lower and upper quartiles (Q1, Q3. Similarly to [39], we defined the trees' climate regulation impact as differences between the medians of the measurement locations 'under tree' and 'in the sun'. Median values were used instead of arithmetic means, because the latter is very sensitive to outlier values, which may cause problems especially in the case of short-wave radiation.

3. Results

First we consider all data without disaggregation by the investigated trees, meaning 7520 data pairs originating from parallel 'in the sun' – 'under tree' measurements. Wilcoxon test proves that urban trees result in significant (0.000) modification in the case of all parameters (Table 5). However, the strength of the regulation effect differs among the investigated microclimate elements (Fig. 2).

Table 5. Results of the non-parametric Wilcoxon test looking for significant differences between 'under tree' and 'in the sun' groups

Parameters	Z	Asymp. sig. (2-tailed)	Note
T_a [°C]	-73.854	0.000	based on positive ranks when 'T_a under tree' > 'T_a in the sun'
RH [%]	-64.489	0.000	based on negative ranks when 'RH under tree' < 'RH in the sun'
K_u [W/m^2]	-75.102	0.000	based on positive ranks when 'K_u under tree' > 'K_u in the sun'
K_d [W/m^2]	-75.104	0.000	based on positive ranks when 'K_d under tree' > 'K_d in the sun'
L_u [W/m^2]	-75.107	0.000	based on negative ranks when 'L_u under tree' < 'L_u in the sun'
L_d [W/m^2]	-75.104	0.000	based on positive ranks when 'L_d under tree' > 'L_d in the sun'

Fig. 2.a-b illustrates that one may expect only slight modification in the case of the basic microclimate parameters of T_a and RH. The presence of single mature trees reduced T_a averagely by 0.6°C and increased RH by less than 2% (Fig. 2.a-b,). The increased relative humidity and the systematic cooling demonstrate that the enhanced evapotranspiration and the shading effect take place even on the small-scale level of one shade tree. It must be emphasized however that the distribution of values measured in the sun and under the tree are very similar in the case of T_a and RH. On the contrary, the distribution of short- and long-wave radiation components from the upper and lower hemisphere is obviously different at the two measurement points (Fig. 2.c-f).

The middle 50% of the global radiation values, i.e. K_u in the sun, fell between 687 and 856 W/m^2 signalling strong solar radiation on the 20 investigated days (Fig. 2.c). The mean and median K_u are 750 and 771 W/m^2, respectively. The transmitted radiation is considerably lower; the foliage reduced K_u averagely by 691 W/m^2. The corresponding difference between the medians is even higher: 709 W/m^2. These results indicate that single shade trees can be characterized with a transmissivity of about 8% in the 10 am – 16.15 pm period on clear summer days. The IQR of K_u in the shade is only 47 W/m^2 wide compared to the corresponding IQR of 169 W/m^2 in the sun.

K_d represents the short-wave radiation from the lower hemisphere, i.e. the solar radiation reflected from the ground. Likewise in the case of K_u, the presence of shade trees altered the distributional characteristics of K_d to a great extent (Fig. 2.d). However, the absolute value of this modification, i.e. the reduction in reflected radiation is rather small compared to K_u.

Long-wave radiation from the lower hemisphere (L_d) means the emitted radiation from the ground, and its magnitude depends on the surface temperature and material characteristics that influence emissivity. If the ground surface is not shaded by any natural or artificial object, it may be warmed up to a great extent. In the case of our study which was conducted on clear summer days, the strong solar radiation was able to heat up the ground surface. As a consequence, the middle 50% of L_d values in the sun ranged between 505 and 580 W/m^2. The corresponding 'under tree' IQR spread between 446 and 488 W/m^2 (Fig. 2.f). These results demonstrate that the presence of mature shade trees reduce solar income (K_u) and thus lower the radiation flux densities from the ground – K_d and L_d.

However, we can see a slight increase in the amount of L_u, i.e. the long-wave radiation flux density from the upper hemisphere. Standing at an unobstructed site, L_u originates from the atmosphere – therefore it is referred as atmospheric counter radiation – and its value is usually much lower than that of L_d. (Very simply: the ground surface is warmer, therefore it is able to emit more radiation.) Clouds, that would increase L_u due to their higher emissivity, did not interrupt our measurements on the selected summer days, thus the middle 50 percent of L_u values fell between 394 and 433 W/m^2 at the sunny location (Fig. 2.e).

Under the trees however, the greatest part of L_u (downward long-wave radiation) originates from the tree crown instead of the far and cool sky dome. In other words, the foliage acts as a heat radiator and it results in greater long-wave income from the upper direction. Indeed, our results show somewhat greater L_u under tree than in the sun (Fig. 2.e). Besides, since the surface temperature of the tree crown is much closer to the surface temperature of ground under the tree, the L_u and L_d values are more similar to each other in the case of the shaded measurement point (Fig. 2.e-f).

In the following we examine the differences among the investigated trees regarding their climate-regulation potential on clear summer days. The results are illustrated in the form of box-plot diagrams (Fig. 3-4). The broader boxes of *T. cordata* and *S. japonica* signal that the measurement days of these trees covered wider range of thermal conditions in terms of T_a and RH (Fig. 3). However, this fact has not influenced the systematic cooling and humidifying effect which can be observed in the case of all shade trees. The T_a and RH modification potential was never greater that 1°C and 2%, respectively. The greatest T_a reduction was observed in the case of *S. japonica* (median values reduced by 0.8°C), followed by *C. occidentalis* (0.7°C).

It is worth mentioning that these trees have the widest canopy diameter (see in Table 3). Less cooling potential was shown by the smaller *A. hippocastanum* (0.4°C), which had the narrowest and smallest canopy among the investigated trees. In the case of relative humidity, the tendencies are the opposite: we can see slight systematic increase in RH under each tree (Fig. 3). This may be caused by the increased evapotranspiration, but we have to take into account the fact that RH depends negatively on T_a. (Therefore clearer picture could be obtained if we used an absolute measure of humidity).

In terms of global radiation (K_u), the measurements occurred under very similar radiation conditions in the case of all trees (see the yellow boxes on Fig. 4.a). The middle 50 percent of K_u values in the sun fell between 700 and 900 W/m^2 in every cases, with medians of about 750–800 W/m^2. The transmitted radiation was significantly lower in the case of each tree: the medians decreased by more than 90% compared to the unobstructed value of K_u. The relative modification by the larger *A. hippocastanum* was especially great – 98% (Table 6). The IQR range was quite narrow under the trees, indicated by the green boxes on Fig. 4.a.

This is especially true for the two *A. hippocastanum*. Note that the distribution of transmitted radiation is characterized by several outlier values. These outliers were caused by the direct sunbeams reaching the ground occasionally, depending on the sun elevation, and canopy-structural characteristics. (As previously mentioned, because of these outliers the comparison of medians is recommended instead of the usage of mean values.) Analytical results indicate that *S. japonica* is characterized with the highest transmissivity, i.e. the least effective shading from the viewpoint of solar radiation reduction (Fig. 4.a). K_u decreased by 681 W/m^2 in the case of this specimen.

The greatest reduction (in absolute manner) was found in the case of *T. cordata* (741 W/m^2), followed closely by the larger *A. hippocastanum* (735 W/m^2) and *C. occidentalis* (727 W/m^2). The lower K_u-reduction potential of *S. japonica* may be attributed to its sparse canopy structure and small leaves that intercept lower amount of incoming global radiation. It is worth mentioning that relative modification reached almost 90% in the case of this specimen too (Table 6).

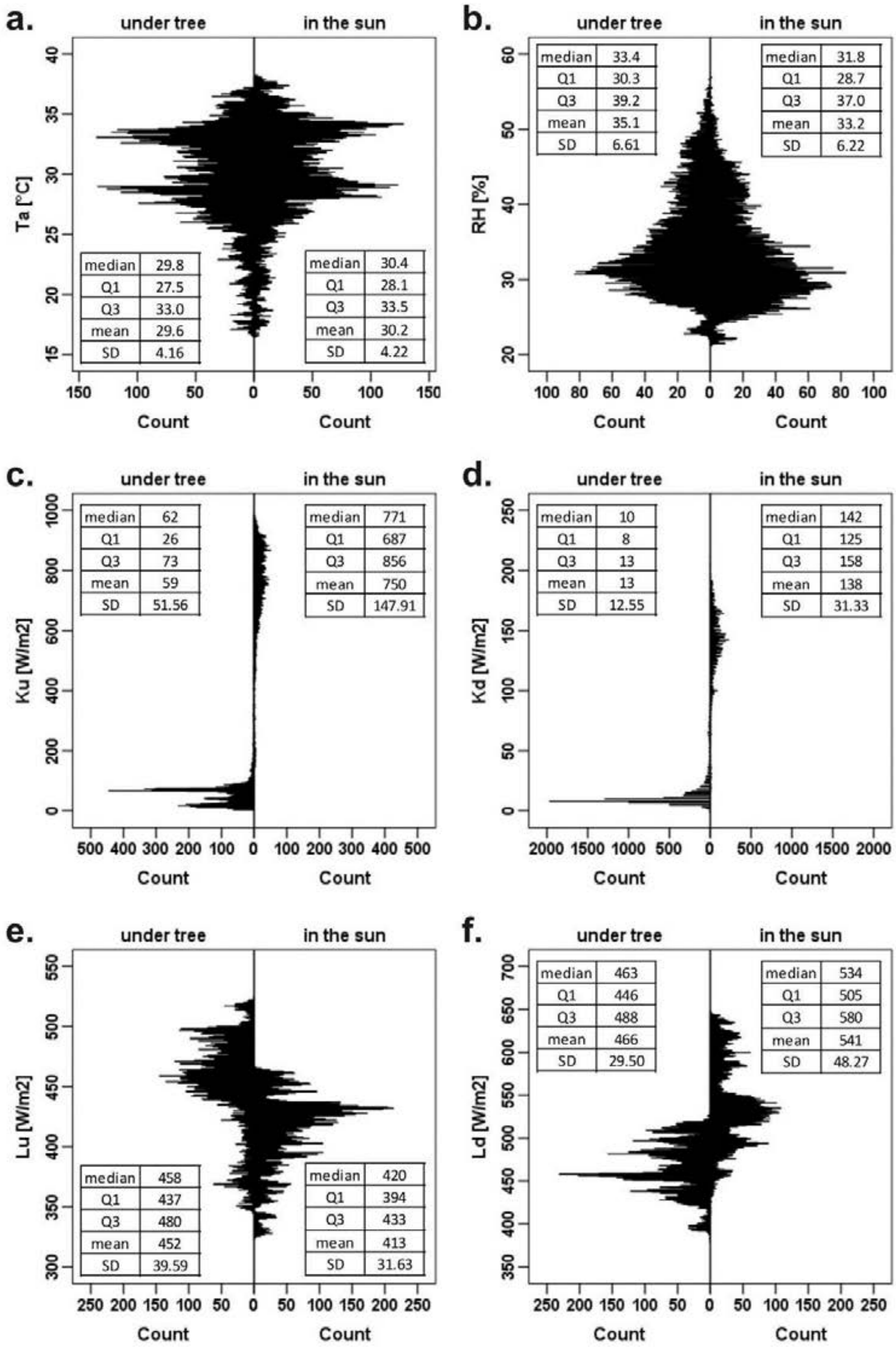

Fig. 2. Bean plots and the main distributional statistics of the measured parameters under tree and in the sun (Q1: first quartile, Q3: third quartile, SD: standard deviation)

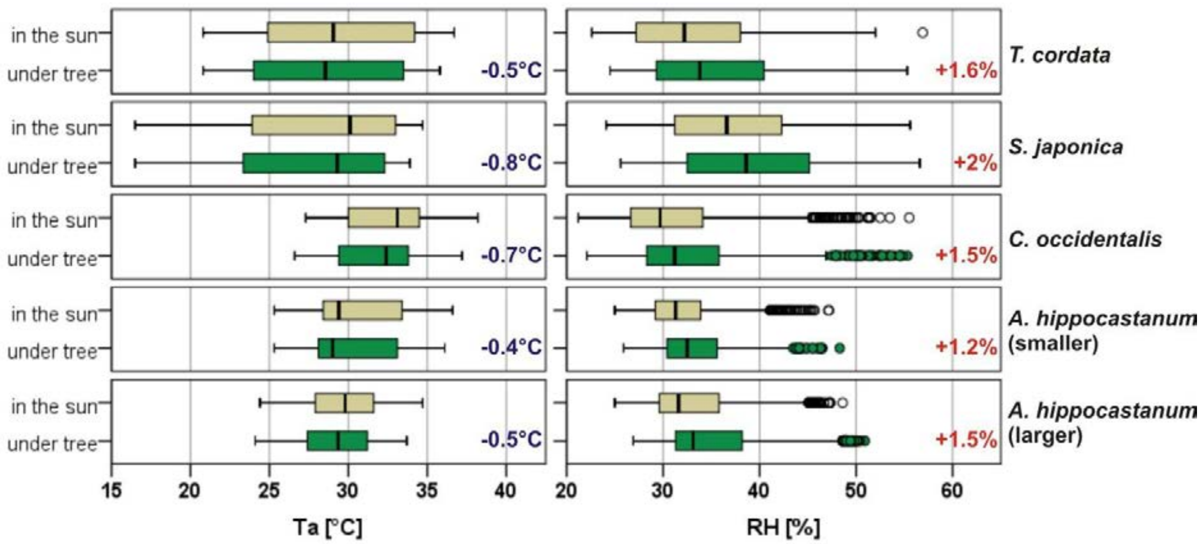

Fig. 3. Box-plot diagrams of 'under tree' and 'in the sun' air temperature and relative humidity, split by the investigated tree specimens (Blue and red values in the left bottom corner indicate the change of the median values)

As a consequence of the reduced short-wave radiation from the upper hemisphere (K_u), the amount of reflected radiation from the ground (K_d) decreased as well (Fig. 4.b). K_d values at the sunny location were somewhat lower in the case of *T. cordata* than those in the other trees, which may be related to the different surface cover (see Table 3). The relative modification of K_d by shade trees compared to the values in the sun seems to be very effective (91–95% reduction), however, in absolute value it reached only 110–146 W/m^2 (Table 6, Fig. 4.b).

The absolute and relative modifications were less pronounced in the case of the long-wave radiation components. The presence of shade trees decreased L_d by 95 W/m^2 in the case of *T. cordata*, and by 56 W/m^2 in the case of *C. occidentalis*. The corresponding decrease in relative manner was 16% and 10%, respectively (Table 6, Fig. 5.d). As mentioned earlier, the tree crown resulted in somewhat greater long-wave radiation from the upper hemisphere (L_u). However, the increase did not exceed 70 W/m^2 even in the case of 'the most effective radiator' *C. occidentalis* (Table 6, Fig. 5.c).

Table 6. Absolute and relative modification of the measured radiation components by trees, compared to the values measured in the sun. (Based on the median value of parameters)

	Radiation parameter	*T. cordata*	*S. japonica*	*C. occidentalis*	smaller *A. hippocastanum*	larger *A. hippocastanum*
Absolute modification [W/m^2]	K_u	-741	-681	-727	-714	-735
	K_d	-110	-131	-136	-146	-134
	L_u	25	29	67	44	38
	L_d	-95	-61	-56	-71	-62
	Sum	-889	-811	-865	-897	-891
Relative modification [%]	K_u	-94%	-89%	-95%	-91%	-98%
	K_d	-92%	-91%	-94%	-94%	-95%
	L_u	6%	7%	16%	11%	9%
	L_d	-16%	-12%	-10%	-13%	-12%
	Sum	-48%	-45%	-46%	-47%	-48%

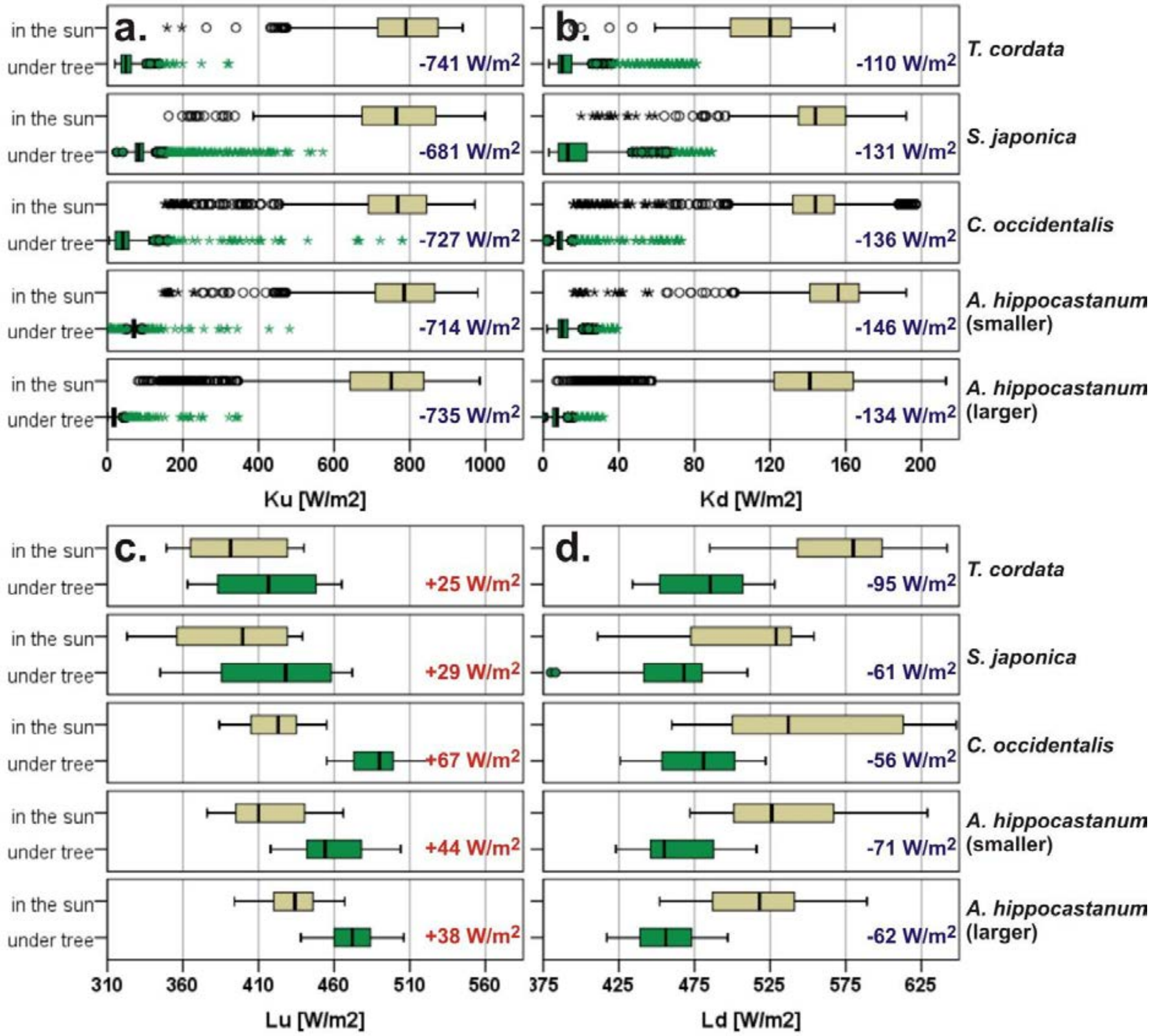

Fig. 4. Box-plot diagrams of short- and long-wave radiation flux densities from the upper and lower hemisphere under tree and in the sun, split by the investigated tree specimens (Blue and red values in the left bottom corner indicate the change of the median values)

The greater L_u emitting potential of *Celtis* may be attributed to its wider tree crown, denser canopy structure, as well as the shorter trunk height which meant that the base of its crown is closer to the measurement height (see Table 3). Although the investigated *S. japonica* has similar canopy diameter, its foliage is less dense and it consists of smaller leaves. Thus we may suspect that it is not able to absorb as much shortwave radiation – and heat up to the same extent – as *C. occidentalis*. Table 6 contains also the overall modification effect on the radiation budget of a man staying under the different trees ('Sum'). It is noticeable that the impact of tree crown on the radiation components is greater in the short-wave domain (at least 90%) than in the long-wave domain (for up to 16%), and the K_u reduction determines the final regulation potential in absolute manner. However, because the original values of L_u and L_d play a very important role in the radiation budget (see the yellow markers on Fig. 5), and these components were changed by trees only slightly (green markers on Fig. 5), the relative modification of the radiation Sum is less than 50% (Table 6).

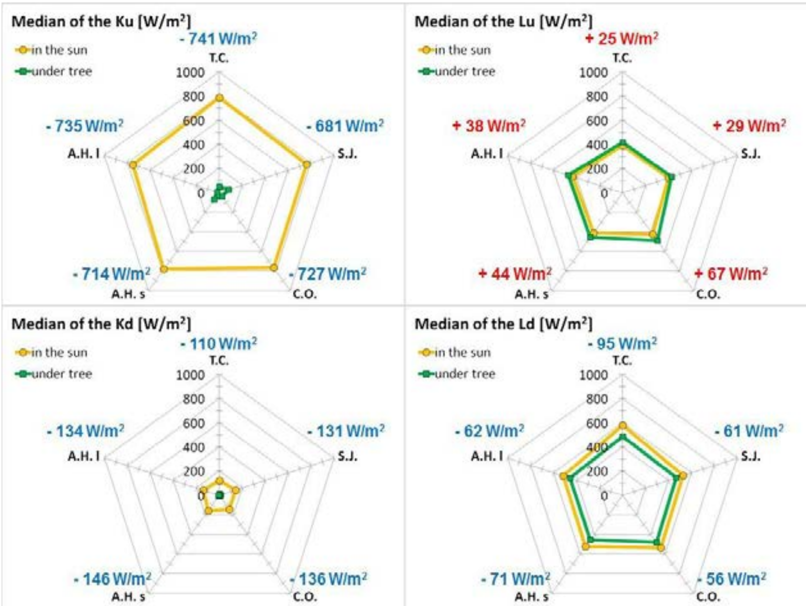

Fig. 5. Summary about the modification of radiation components by *T. cordata* (T.C.), *S. japonica* (S.J.), *C. occidentalis* (C.O.), and the smaller and larger *A. hippocastanum* (A.H.s, A.H.l)

Discussion and outlook

We found only slight differences in basic microclimate parameters between the measurement locations under trees and in the sun: the general level of T_a-reduction remained below 1°C, and the increase in RH did not exceed 2%. Our results evinced that all of the five investigated tree specimens had significantly greater impact on the components of the radiation budget.

Under Central-European climate conditions, extreme heat stress at street level is usually the effect of intensive solar radiation and the resulted positive radiation budget of pedestrians (eg. [49, 50]). Several earlier studies demonstrated that 3D radiant environment plays a key role in forming outdoor heat stress on warm, sunny days, and that long-wave radiation components have greater impact on the magnitude of the evolved radiation load (e.g. [10, 43, 44]). Our results indicate however that the trees' modification effect is greater in the short-wave domain. Basically, the tree crown reduced the amount of short-wave radiation reaching both the body and the ground from the upper hemisphere (K_u). As a consequence, short-wave flux densities reflected from the ground decreased as well (K_d). Besides, the ground surface was not able to heat up so much under the tree because of the reduced short-wave income. Consequently, the ground surface emitted less radiation in the long-wave domain, meaning reduced L_d. Overall, the effect of lowered K_u, K_d and L_d flux densities under the tree more than compensated for the slight increase in the long-wave radiation from the upper hemisphere (L_u). Inter-species differences seemed to be small in the warmest hours of the day (10 am – 16.15 pm), and these may be attributed to the dimensional and canopy characteristics of the investigated trees.

In general, the aim of this paper was to lay the foundation of later indicator development, through a comparative analysis focusing on the micro-scale climate regulation service of single shade trees. Our results emphasize the need to incorporate some parameters referring to the radiation environment, and the trees' effect on that, when developing ecosystem service indicators. The mean radiant temperature (T_{mrt}) is an integrated human-biometeorological index that expresses the effect of 3D radiation environment on the human body [51]. T_{mrt} involves several short- and long-wave radiation flux densities and express their impact on the body in degree Celsius. Several outdoor thermal comfort studies evinced that T_{mrt} is the most important parameter that impacts human thermal sensation in warm and sunny conditions, and it is an appropriate index to express the efficiency of different shading alternatives, i.e. shading by artificial and natural landscape elements [52]. Lindberg, Grimmond [53] worked out the methods for mapping T_{mrt} at micro-scale level, and by using a complex human-biometeorological index instead of air temperature, other criteria of suitable ecosystem service indicator can be also fulfilled [54]. In this study the inter-species differences proved to be small, and it is not easy to take them into consideration during assessments at local-scale. However, the shading capacity of different trees is useful information at the level of single trees and together with other species-specific information it can be used to assess a full spectrum of ecosystem services of urban vegetation. In our experience, the tools and methods of measurement (mobile meteorological stations) applied in this study proved to be adequate, and seem suitable for examining the climate-altering capacity of other species as well. Data collection is fairly labor-intensive because several measurement days are needed in order to determine species characteristics. However information directly usable in public space design can be obtained by these tree-level methods. For example, on the basis of short-wave transmissivity (shading capacity) species can be ranked, categorized and fit into different criteria-systems. These can facilitate decisions on various aspects of urban tree planting, and be incorporated into toolkits crafted for such purposes (e.g. [55, 56]), which could be generically used in different climate zones.

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