Microclimate regulation potential of different tree species: transmissivity measurements in Szeged, Hungary

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1. Introduction

Heat stress mitigation capacity of urban trees is widely acknowledged and makes these natural landscape elements very important in the field of climate conscious urban planning (Sashua-Bar and Hoffmann 2000, Bowler et al. 2010, Erell et al. 2011, Sashua-Bar et al. 2011). Many studies based on micrometeorological measurements and/or model simulations (e.g. Mayer 2008, Mayer et al. 2008, Égerházi et al. 2013, 2014) have proven already that shading, i.e. the reduction of direct solar radiation is the most effective way to moderate summer heat stress among Central European climatic conditions. Shading potential of trees is described usually by their transmissivity values (or solar permeability), i.e. by the proportion of solar radiation transmitted through the foliage (Cantón et al. 1994, Konarska et al. 2014).

On the one hand, although the transmissivity depends on the leaf density, orientation of the leaves, and other tree crown-related characteristics influenced by the health conditions and the annual foliation cycle, microclimate simulation studies usually set this attribute default in the case of all trees. However, by the usage of SOLWEIG model (Lindberg et al. 2008, Lindberg & Grimmond 2011) there is a chance to alter this parameter (Konarska et al. 2014). In order to facilitate urban landscape planning it would be important using transmissivity values that characterize appropriately the trees planted frequently as street and park trees in a given geographical region. On the other hand, despite the importance of thermal stress reducing effect of shade trees, the number of relevant studies with practical outcomes is very low in Hungary, and there is a lack of information about the shading and bioclimate-regulation capacity of them in Hungarian towns.

The aforementioned ideas motivated our research team to analyze the yearly transmissivity changes of Hungarian urban trees. The shading effect is planned to be investigated in two interrelated methodological steps:

1. on-site microclimate and radiation measurements under selected tree specimens,
2. micro scale model simulations with the SOLWEIG model.

The measurement based transmissivity values of typical Hungarian tree species are planned to be integrated into the second step, i.e. the radiation and micro-bioclimate modeling. In that way we could promote the work of Hungarian landscape designers to simulate the bioclimatic effect of differently vegetated (different extent, different species) recreation areas, moreover to simulate the micro-bioclimatic effect of vegetation in the different seasons according to the foliation-defoliation process.

Here we present the main experiences from the first year of the long-term Hungarian transmissivity-measurement series that started in 2014.

2. Methods

A systematic radiation measurement series was organized in Szeged (Southeast-Hungary) to analyze the yearly changes of four tree species used frequently in Hungarian towns as street trees or park trees. These are:

- Small-leaved linden (*Tilia cordata*)
- Pagoda tree (*Sophora japonica*)
- Common hackberry (*Celtic occidentalis*)
- Horse-chestnut (*Aesculus hippocastanum*).

To calculate the species-dependent transmissivity values, we measured the global radiation (total short-wave radiation from the upper hemisphere; sum of direct and diffuse solar radiation) at two locations:

- G_{trans} [W/m^2] is the transmitted solar radiation measured in the shade of the selected urban tree,
- G_{act} [W/m^2] is the actual value of global radiation measured in a reference station (inner-city weather station) free from sky obstruction.

Transmissivity is calculated then as the ratio of these values (G_{trans} / G_{act}).

In order to select the ideal tree specimens and locations for the investigations more field trips were conducted before the actual microclimate measurements. The main criteria were to find healthy and adult individuals in the case of all investigated species without the disturbing effect of other natural or artificial landscape elements, i.e. to ensure that other objects do not influence significantly the recorded parameters during the measurement period (typically from 10 am to 4 pm). Appropriate small-leaved linden and pagoda tree were found on a square within 1 km aerial distance from the reference station (***Table 1***). The common hackberry stands by a little lake over 2 km distance and the selected horse-chestnut specimen is on another square within almost 1.1 km. However, during the first summer period it turned out that this tree has been attacked by the horse-chestnut leaf miner (*Cameraria ohridella*) that causes earlier defoliation. Ensuring the continuous measurements a new, healthy horse-chestnut individual was selected on another square in almost 2.5 km distance (***Table 1***).

Table 1. Main dimensional characteristics of the investigated urban trees in Szeged, Hungary.

Species	Small-leaved linden	Pagoda tree	Common hackberry	Horse-chestnut I	Horse-chestnut II
Distance from roof-pyranometer [m]	740	945	2260	1140	2450
Full height [m]	15.5	12	9	15	13.5
Trunk height [m]	2.5	3	1.8	2	2.5
Canopy diameter [m]	9	12	14	10	9
Trunk diameter [cm]	70.5	75	70	78	57

2 micrometeorological stations, equipped with Kipp&Zonen net radiometers (CNR1 and CNR4), were used to record G_{trans} values under the selected trees. (The comparability of the two pyranometers of these net radiometers was tested on a cloudy and a totally clear summer day, and the average differences between the measured G values were only 10.14 and 3.8 W/m^2 on the 2 days, respectively. All data considered, the differences ranged from -35 to 50 W/m^2 and were not bigger in absolute value than 25 W/m^2 in more than 80% of the cases.) The sensors were placed 2 m distance from the North side of the tree trunks, taking care for the right orientation, height and leveling. Pyranometers were 1.1 m above ground level which corresponds to the gravity center of an adult European man, usually applied standard subject in outdoor thermal comfort investigations (Mayer 2008, Mayer et al. 2008).

The reference Kipp&Zonen pyranometer, measuring the G_{act} values necessary for the transmissivity calculations, is located on the top of the four-storey height building of the University of Szeged. It is run by the Hungarian Meteorological Service and records 10-minute mean values of global radiation. To be consistent with this temporal resolution, the measured G_{trans} values with 1-minute resolution were also averaged.

The investigations in 2014 lasted from June to November to determine not only the inter-species differences, but also the yearly changes of transmissivity induced by the autumn defoliation **(*Table 2*)**. After the first four measurement days, parallel measurements under the canopies of two different tree species were organized at the same time allowing the comparison of their solar permeability with respect of the very same meteorological background conditions.

Table 2. Measurement days and intervals in 2014 (dark-colored days were selected for the analyses).

Date	**Small-leaved linden**	**Pagoda tree**	**Common hackberry**	**Horse-chestnut**	**sky conditions**
27-Jun-2014		10:10 – 17:20			cloudy
1-Jul-2014	10:10 – 17:30				overcast
2-Jul-2014			9:50 – 18:10		cloudy
4-Jul-2014				10:10 – 17:40	clear
24-Jul-2014			9:40 – 18:10	10:10 – 16:50	cloudy
25-Jul-2014	9:40 – 17:50	10:00 – 17:40			cloudy
28-Aug-2014	10:00 – 16:50	10:20 – 16:30			cloudy
9-Sep-2014			9:50 – 17:20	10:10 – 17:00	mostly clear
18-Sep-2014	10:00 – 16:30	10:20 – 16:10			mostly clear
29-Sep-2014	10:00 – 16:30	10:20 – 16:10			clear
30-Sep-2014			9:40 – 16:40	10:00 – 16:20	clear
28-Oct-2014			10:10 – 15:00	10:40 – 14:50	clear
4-Nov-2014	10:00 – 14:50	10:20 – 14:30			clear

3. Results

3.1 Seasonal change of the foliage

As clear sky conditions occurred most frequently in the case of horse-chestnut, the annual effect of foliation status on solar permeability is presented on the example of this species. ***Fig. 1*** illustrates the daily curves of global radiation, transmitted radiation as well as the calculated values of transmissivity on four clear days.

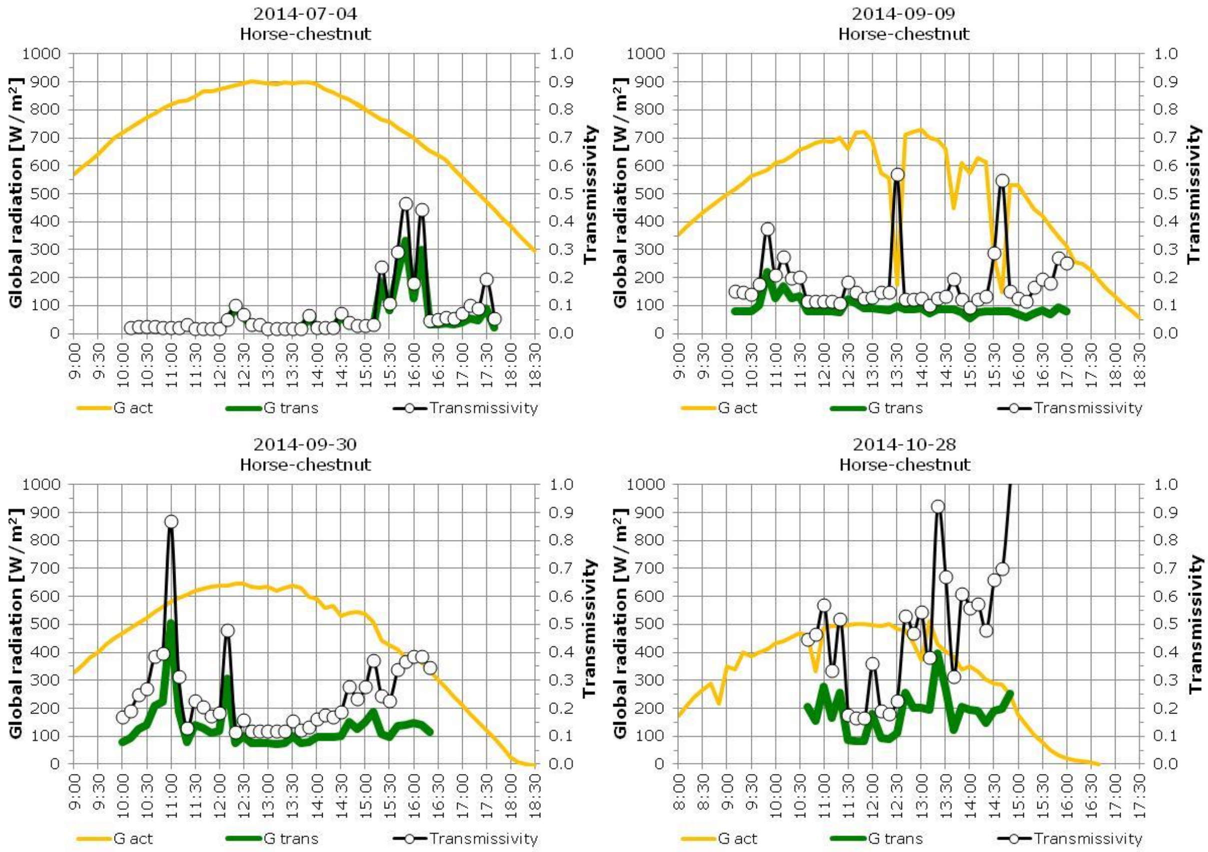
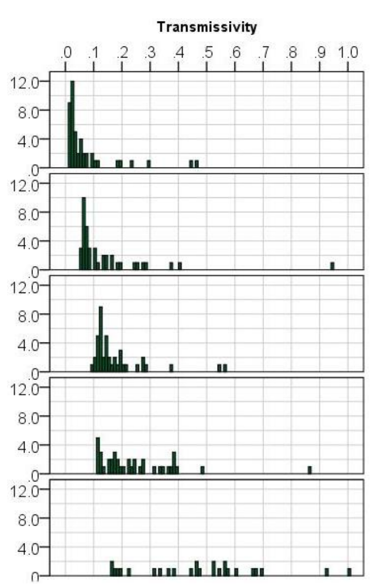


Fig. 1. Seasonal change in the solar radiation transmissivity of the horse-chestnut (time is in CET).

The daily maximum of G_{act} was around 900 W/m^2 on 4-Jul-2014, while it reached only 500 W/m^2 on the last measurement day of 28-Oct-2014 (***Fig. 2***). The autumn defoliation effect is clearly shown: although the G_{act} weakened from midsummer to late autumn, the amount of G_{trans} and, as a consequence, the transmissivity values increased continuously in the same period. G_{trans} remained under 25 W/m^2 during almost the whole measurement interval on the first day, and had only a slight peak around 12:20 (CET – Central European Time). More remarkable increase (up to 200-300 W/m^2) occurred between 15:20 and 16:10 indicating that the point where we placed the mobile station got more insolation. The transmissivity values for the fully shaded interval ranged between 0.02 (2%) and 0.1 (10%) and increased above 0.4 (40%) only in the mentioned afternoon period with the chance of more direct irradiation. On 09-Sep-2014 G_{trans} was continuously around 100 W/m^2, except the short period from 10:50 to 11:30. The most common G_{trans} values ranged between 100–200 W/m^2 on the last day of September, and the peaks were more pronounced: 500 W/m^2 and 300 W/m^2 around 11:00 and 12:00, respectively. The last day can be characterized with the highest G_{trans} values scattering around 200 W/m^2, peaking about 400 W/m^2 (***Fig. 2***).

Table 3. Frequency distribution and basic descriptive statistics of horse-chestnut's transmissivity on the different measurement days.



Date	N	SD	Mean	Median	Mode	Min.	Max.
4-Jul-2014	46	0.10	0.07	0.03	0.02	0.02	0.47
24-Jul-2014	41	0.15	0.15	0.08	0.06	0.05	0.94
9-Sep-2014	42	0.10	0.18	0.15	0.13	0.09	0.57
30-Sep-2014	39	0.14	0.25	0.21	0.11	0.12	0.87
28-Oct-2014	26	0.22	0.47	0.47	0.46	0.17	1.00

Related to the decreasing G_{act} and increasing G_{trans} values during the summer-autumn interval, the transmissivity of horse-chestnut continuously increased because of the autumn defoliation (***Table 3***). As the mean values are very sensitive to the extremes, we consider it more appropriate to characterize the frequency distribution of transmissivity with the median and mode. Half of the calculated transmissivity values were below 3% on the midsummer measurement day, while the medians were 8%, 15%, 21% and 47% on the subsequent measurement days. The corresponding mode values were almost the same, but a little lower: 2%, 6%, 13%, 11% and 46%, respectively. The mean and minimum values of transmissivity followed the same increasing order parallel with the defoliation process. The mean, median and mode values were always closer to the daily minimums than to the maximal values (***Table 3***). Worth mentioning that the seasonal comparison would be more creditable if we could keep the same chestnut tree throughout the whole measurement period, because the different dimensions of the second, healthy tree (***Table 1***) may affect the distance that solar beam have to pass through the tree crown.

Important shortcoming of the original measurement concept related to the cloudy sky conditions can be noticed on the transmissivity curve of 9-Sep-2014 (***Fig. 2***). Transmissivity increased sharply two times, exactly at 13:00 and 15:40, although the curve of G_{trans} remained plane. These apparent jumps in transmissivity did not mean real increase of solar permeability through the horse-chestnut. They can be explained with cumulus clouds that caused immediate drops in the value of global radiation – G_{act} measured more than 2 km away from the chestnut tree, above which the shadowing effect of the clouds did not prevail. If the reference G_{act} value would be measured on the top of an adjacent building, sharp decreases of G_{act} would be synchronous with a bit moderated decreases of G_{trans} curve.

3.2 Inter-species differences

As the outlined problem of 'apparent transmissivity increase' has occurred many times on measurement days with variable sky conditions, it is advisable to compare the different species based only on the clear days. Another important criteria is to have as similar weather conditions as possible, namely to investigate consecutive days when analyzing inter-species differences. From the 2014 database only the last days of September meet these demands (***Table 2***). Both days had nearly bell-shaped curves of global radiation (G_{act}) with maximal values around 650 W/m^2, but the G_{trans}-curves are obviously different indicating the differences between the tree canopies of the four species (***Fig. 3***).

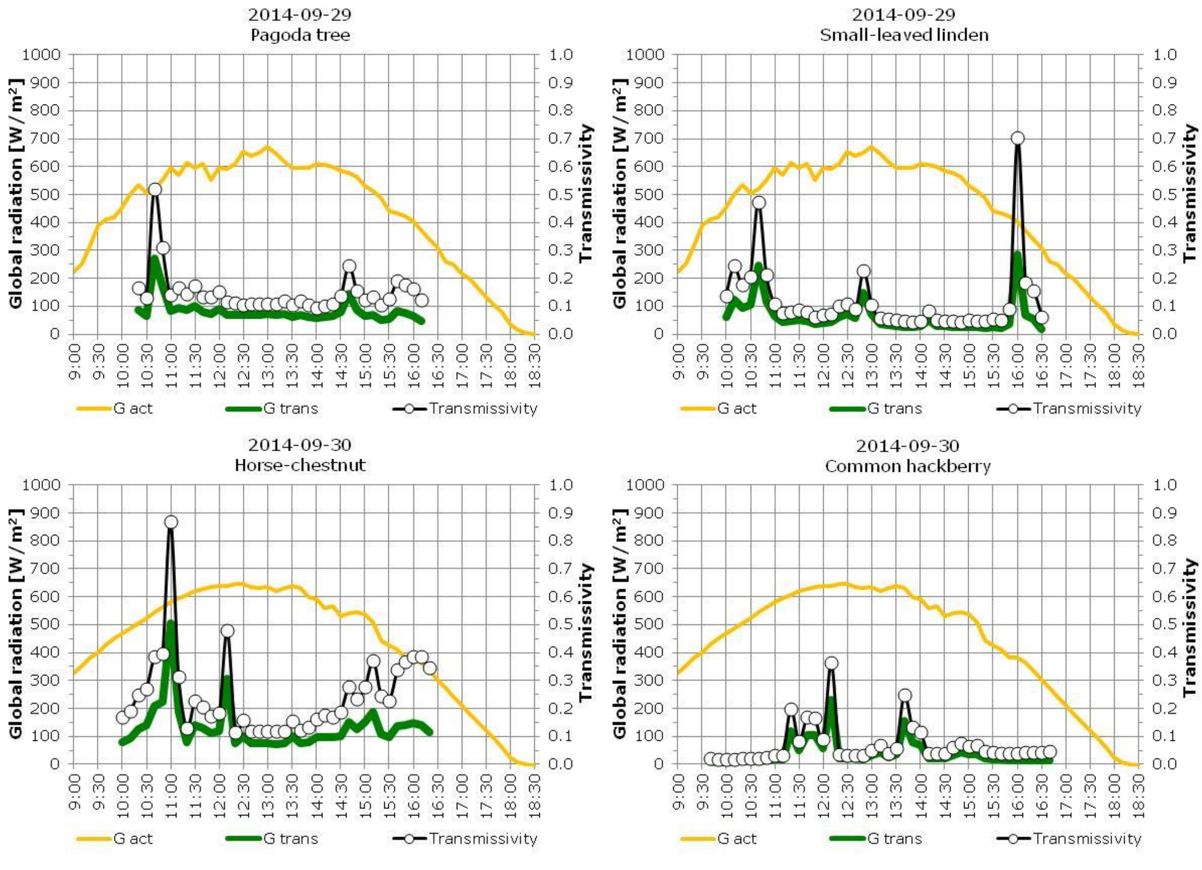
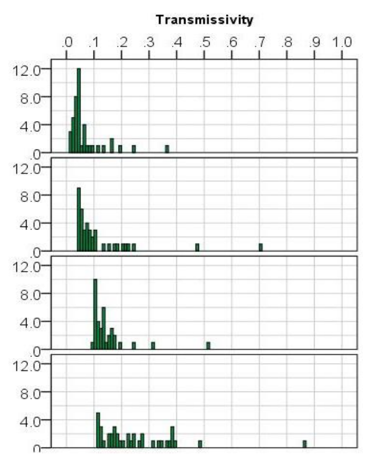


Fig. 2. Transmissivity differences between the four trees on two consecutive clear autumn days (time is in CET).

On 29-Sep-2014 the pagoda tree had clearly higher transmissivity than the small-leaved linden: median values are 13% vs. 8% and the means are about 15% vs. 12%, respectively (***Table 4***). The differences on 30-Sep-2014 between the other tree-pair are even greater. Horse-chestnuts' median transmissivity is 21% (mean: 25%), while the common hackberry can be characterized with the most effective shading: its median transmissivity is only 4% (mean: 7%). The hackberry's shading potential is 5-times stronger in the end of September than that of the chestnut tree. Not only the median, mean and mode values are higher in the case of chestnut's solar permeability, but it has also more even distribution, and the values cover wider range: 12–87%. Quite the contrary, in the case of the other species the transmissivity values cumulate around a very specific mode: this is 4% for the hackberry and the linden, and 10% for the pagoda tree (***Table 4***).

Table 4. Frequency distribution and basic descriptive statistics of the investigated species' transmissivity on the last days of September 2014.



Species	N	SD	Mean	Median	Mode	Min.	Max.
Common hackberry	43	0.07	0.07	0.04	0.04	0.02	0.36
Small-leaved Linden	40	0.13	0.12	0.08	0.04	0.04	0.70
Pagoda Tree	36	0.08	0.15	0.13	0.10	0.09	0.52
Horse-chestnut	39	0.14	0.25	0.21	0.11	0.12	0.87

4. Discussion

Human thermal comfort and the related thermal stress mitigation is one of the most intensively investigated issues of urban bioclimatology (Mayer 2008). The importance of this field is more and more obvious when we consider the predicted trends of climate change (IPCC 2014) and the increasing number of citizens (UNFPA 2011) who should live under the even warmer climatic conditions of urbanized areas. Planting trees for their shading (shortwave radiation reduction) and evaporative cooling are axiomatic and simple 'means' in the hand of urban planners to mitigate thermal stress in the climate regions with long and warm summers (Erell et al. 2011, Sashua-Bar et al. 2011). But there is still a great need for studies which offer quantitative data about the shading capacity as well as heat stress reduction potential of different types of trees. To help the work of urban planners and landscape designers, as well as to fill this research gap in Hungary, a long-term transmissivity-measurement campaign was started in the South-Hungarian city of Szeged. Small-leaved linden, pagoda tree, common hackberry and horse-chestnut were selected to investigate the yearly changes in the solar permeability, as these species occur frequently in urban parks, squares and streets in Central-European climate conditions.

The results from the end of September (***Fig. 2, Table 4***) indicated more intensive shading capacity in the case of small-leaved linden and common hackberry, while the pagoda tree's sparser canopy could be characterized with a bit higher transmissivity. Analyzes revealed clearly the less effective shading capacity in the case of horse-chestnut, which is in line with our field observations, namely, this species starts autumn defoliation the earliest. Therefore the higher solar permeability for this tree can be explained with the half-leafless condition of the canopy in the end of September. After horse-chestnut, linden and hackberry trees starts to lose their leaves (almost at the same time), while the pagoda tree is the last from this point of view. Nevertheless, compared to the hackberry and linden, the pagoda tree had higher solar permeability in the end of September, thus the transmissivity in this case may depend more on the leaf area density (LAD) than on the amount of leaves on the tree. Hackberry and linden has greater leaf surface on the one hand, and their foliage is denser than the pagoda tree's foliage on the other hand.

Worth noting however that the foliation pattern during spring follows similar order: horse-chestnut becomes leafy at first and the pagoda tree is the last one. Therefore a longer and deeper investigation-series is planned including all relevant seasons of the foliation-defoliation process. In that way it is expected to offer more detailed and reliable picture about the shading efficiency of common Hungarian park and street trees. Another good reason for a longer-time research with many investigation days in the case of the same species is that we found higher annual changes in the case of the same tree (horse-chestnut; ***Fig. 1, Table 3***) than inter-species differences on the same time of the year (end of September; ***Fig. 2, Table 4***).

5. Further research plans

Additional questions worth studying:

1. How do the solar radiation reduction capacity of trees and their temporal and inter-species differences influence the bioclimatic conditions during the different seasons?
2. What is the effect of crown-health conditions on the above-mentioned?
3. Does it worth better to plant trees with smaller but denser foliage, or has a larger and sparser tree crown more climatic benefits?

To meet the above-mentioned goals and to overcome the problem of 'apparent transmissivity increase' caused by the variable sky conditions together with the too distant reference station, new research design came into effect from the spring of 2015. The pyranometer on the top of the university (inner-city weather station) is not applied hereafter for reference global radiation (G_{act}). Instead, one of the mobile stations is placed at an open point nearby the investigated trees. This arrangement ensures that both G_{act} and G_{trans} are influenced by the very same sky conditions (sunny–cloudy periods); moreover, the temporal resolution of the data is refined for 1-minute. Further benefit of the new measurement design is the potential for complex microclimate analyzes, as short- and long-wave components of radiation budget, air temperature, humidity and wind velocity are measured not only under the tree crown but also at an open and sunny point of the same study area. Beside the micro-bioclimate regulating potential of the four tree species, seasonal status of the canopy is also observed via photos and fish-eye photos. To study the effect of foliage-health conditions on transmissivity values, from 2015 both the healthy horse-chestnut and also the leaf miner-attacked individuals are included into the investigation-series. They are monitored on consecutive days with almost the same weather conditions.

The measurement-based transmissivity values of different tree species can serve as inputs for radiation- and bioclimate modeling software to support more reliable simulations. In the near future we plan numerical simulations to investigate the effect of tree species selection (meaning transmissivity and shadowed area differences) on the resulted reduction of radiation load. SOLWEIG software is planned to become the basis tool for modeling the spatial distribution of mean radiant temperature in different urban structures (e.g. squares and streets with different orientation) planted with different types of trees. Instead of preset transmissivity values, this software allows to replace them with real, measurement based transmissivity that characterize properly the shading efficiency of Hungarian street and park trees. Because of the significant yearly change in transmissivity values (we found greater seasonal changes than inter-species differences in the same time of the year) we plan to incorporate these annual differences in the modeling procedure too.

Contribution to the knowledge about the thermal stress mitigation effect of different local tree species in urban areas will help landscape planners to design 'successful' outdoor spaces which may be perceived more comfortable by people and used more frequently by the citizens.

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