UNIVERSITY OF SZEGED

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INVESTIGATION OF SHADING EFFICIENCY OF POPULAR URBAN TREE SPECIES BASED ON EXAMPLES FROM SZEGED

NÉPSZERŰ VÁROSI FAFAJOK ÁRNYÉKOLÓKÉPESSÉGÉNEK VIZSGÁLATA SZEGEDI PÉLDÁK ALAPJÁN

PhD Thesis

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Table of contents

1. Introduction

Due to the gradually growing urbanization, more and more people are affected by the harmful effects of the urban environment (*Unger and Sümeghy* 2002). The existing urban climatology problems are further augmented by the temperature raise of the mainland and the increasing frequency of extreme weather conditions (*IPCC* 2007, 2014). The complex urban surfaces comprising mainly artificial materials, the heat excess due to the anthropogenic heat generation and, moreover, the decreased ability of ventilation of the cities significantly increase the level of heat stress on humans, which require the unearthing and elaboration of adequate adaptation methods.

The climate change and the growing number of urban population worldwide assign significant tasks to both urban ecology and empirical design. One of the main courses of the urban ecology researches aim at unearthing the exact environmental role of the vegetation and place emphasis on the quantitative evaluation of diversified ecosystem services provided by them (*Lovell and Taylor* 2013). The elaboration of adequate indicators and evaluation methods is very important for aiding the practical urban design, which is highlighted by multiple international professional documents and organizations (*Perrings et al.* 2011, *TEEB* 2011). Numerous studies are required that reflect on the temporal and spatial processes of natural environmental factors in different system. A significant proportion of papers is focused on measuring and modeling urban climate phenomena (*Mezősi et al.* 2007). Within this field, studies mainly investigate the environmental role of urban vegetation and concern urban ecology research (*Lovell and Taylor* 2013).

The comfort level of urban public places may considerably be augmented by the adequate application of tree vegetation (*Johnston and Percival* 2012). Trees are able to reduce the harmful effects of urban life such as air pollution, they sequestrate carbon dioxide and produce oxygen (*McPherson et al.* 1997, *Akbari et al.* 2009, *Nowak and Heisler* 2010). Trees affect the quantity of irradiation and raise evapotranspiration (evaporation and vaporization), hence, they provide relief for the heat-island effect (heat excess generated in cities) (*Spronken-Smith and Oke* 1999, *Sailor et al.* 2008, *Pearlmutter et al.* 2009, *Bowler et al.* 2010). They protect against winds and also reduce the risk of floods after torrential rains (*Eliasson and Upmanis* 2000, *Unger et al.* 2012, *Ronctyk et al.* 2015). They effectively filter noise and provide territory for the urban fauna (*Matzarakis* 2001, *Pelzer and Tam* 2013). Besides the listed ecosystem services, the urban vegetation indirectly contributes to the establishing and nurturing social relations of city-dwellers (*Chiesura* 2004, *Golicnik and Thompson* 2010).

The urban vegetation, more precisely, the urban tree stands may be regarded as one of the most versatile adaptation and mitigation strategies in climate-smart urban design, therefore, their protection and expansion of their territory is considered as a significant task (*Xiai et al.* 1998, *Tyrvainen et al.* 2003, *Balogun et al.* 2014, *Haase et al.* 2014, *Nowak et al.* 2014, *Berland et al.* 2017).

In general, researches mainly focus on the air temperature modifying effect of urban vegetation, and the international studies also largely investigate the climate of urban parks. These works reveal that the most significant drop in air temperature may be observed at night (*Kuttler* 1998, *Sproken-Smith and Oke* 1998). Multiple papers highlighted on the fact that the temperature can be 2-3 ºC lower in the vegetation covered areas and their close vicinity (*Taha et al.* 1989, *Saito* 1990-91).

The extent of temperature decrease depends on whether the park is only a grass covered area or trees also stand there. Regarding the composition of vegetation, it is assessed that the cooling effect of an extended area densely planted with trees is bigger than that of a sparsely planted area (*Yu and Hien* 2006, *Mathey et al.* 2010,). Due to the higher Sky View Factor (SVF) in the parks covered with grass, the warming is faster during the daytime, whereas the cooling is also more rapid. On the contrary, the SVF of the parks planted with trees is very low, which helps in the formulating of the so-called "cold island", and the nocturnal temperature drop is also lower. During the daytime, the coolest sites of the park are where tall trees with ample foliage stand or the areas with the most dense tree and bush coverage (*Potchter et al.* 2006).

Of course, the temperature reducing effect highly depends on the actual weather conditions. During sunny periods, a significant difference in temperature may be observed between the tree covered areas and urban surface with poor vegetation, whereas this difference is not that noteworthy when the sky is overcast (*Anda and Dunkel* 2000, *Kántor et al.* 2016).

Regarding the effect of tree vegetation on wind speed, if the area of tree stands is increased by 10% in a poorly developed suburban area, it may reduce wind speed by 10-20% amongst the buildings (*Hunter Block et al.* 2012). The vegetation may change the direction and speed of the wind; it usually reduces the cooling effect on the building in the winter, however, it impedes the moving of cold breeze in the summer (*Hunter Block et al.* 2012).

Besides air temperature, humidity and airflow, the mean radiant temperature also drastically affects the human thermal comfort in urban environment (*Mayer* 2008). Multiple Hungarian and international studies have proved that the extent of thermal stress during summertime essentially depends on this factor (*Gulyás et al.* 2006, *Mayer et al.* 2008, *Shashua-Bar et al.* 2011, *Lee et al.* 2013, 2016, *Kántor et al.* 2018a, 2018b). The actual value and varying of the mean radiant temperature are defined by the radiation conditions of a particular site. Firstly, for how long and to what extent a certain point is exposed to direct sunlight that depends on shading (*Thorsson et al.* 2007). Secondly, the material quality of surfaces of such point (soil surface and terrain features) that, on the one hand, define the diffuse of short wave radiation (albedo), and, on the other hand, the ability of long wave radiation emission (emissivity) (*Erell et al.* 2011).

The simplest way of reducing summer heat stress on humans is shading, hence urban tree vegetation is of high importance (*Ali-Toudert et al.* 2005, *Ali-Toudert and Mayer* 2007, *Gulyás et al.* 2006). Despite the fact that temperature reducing effect of trees is restricted, the thermal comfort is significantly raised by reducing the short wave radiation (*Oke* 1989, *Shashua-Bar et al.* 2011, *Kántor et al.* 2018a, 2018b). Due to the shade provided by the leafy crown, the short wave radiation (sunlight) is reduced, therefore, the short wave radiation reflected by the soil and surfaces of buildings and long wave radiation emitted by them are also decreased (*Shashua-Bar et al.* 2011, *Kántor et al.* 2018a, 2018b). Thus foliage considerably improves human thermal comfort, consequently, planting trees along the walkways and in places where people are exposed to direct sunlight for a longer period (bus stations, playgrounds, public places, parking areas, etc.) is highly recommended. The shading effect of course depends on the condition of the leafy crown and the angle of sunlight that constantly changes with the seasons (*Fig. 1.1)*.

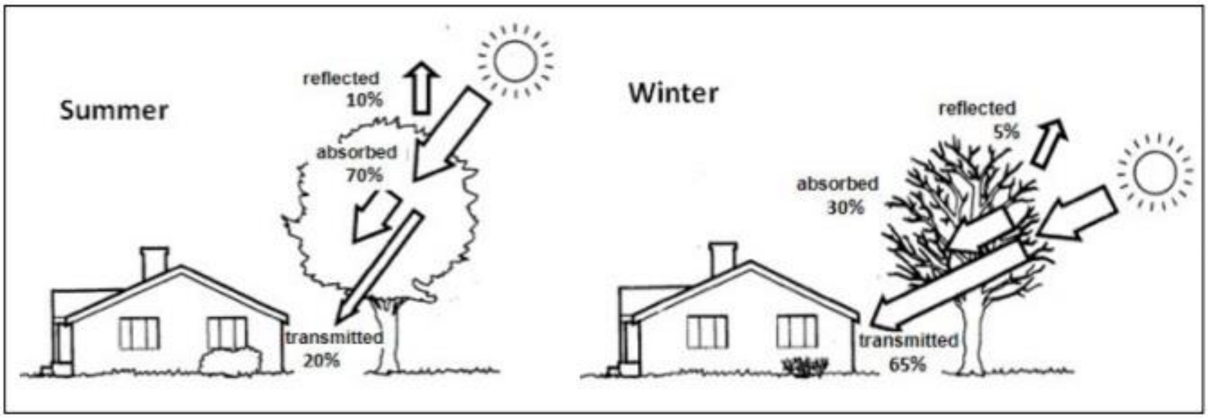

Figure 1.1: Ratio of components of sunlight absorbed within the foliage, reflected from the foliage and transmitted through the foliage during summer and winter (*Hunter Block et al.* 2012)

The density, closing, size, shape, state and structure of leaves of the foliage define the quantity of sunlight transmitted by the foliage (*Hunter Block et al.* 2012). Trees with wide and low foliage have a not very diversified shade pattern. The tall and narrow trees cast small shadow when the sun is high up, however, the shadow is large but diffused when the sun is low. Trees with wide and low foliage transmit not only the direct sunlight, but also the significant proportion of diffused radiation and the one reflected from the surrounding buildings. Depending on whether it is an evergreen or a deciduous, a tree may withhold up to 96.5% of the sunlight (*Robitu et al.* 2006). Deciduous trees lose all their leaves during the fall, at a different rate of course, hence the transmission is raised in the winter. Since leaves are transparent to a certain extent, they transmit some sunlight, however, branches and twigs are not transparent at all, consequently, full transmissivity is not expected (*Erell et al.* 2011). The structure of branches therefore significantly affects the transmissivity of foliage.

Cantón et al. (1994) investigated the transmissivity ability of four different types of trees in Argentina (*Platanus* × *acerifolia*, *Morus alba*, *Fraxinus excelsior* and *Melia azedarach*). According to this research, the average transmissivity is 9–30% in the summer and 39–71% in the winter. *Table 1.1* introduces the solar permeability of certain urban trees of North America. Based on experiments, the denser the foliage is, the less is the amount of transmitted sunlight (*Erell et al.* 2011).

Table 1.1: Transmissivity of urban trees in two seasons (*Erell et al.* 2011)

Common name	Botanical name	Transmissivity range (%)	
		Summer	Winter
Norway maple	*Acer platanoides*	5 – 14	60 – 75
Silver maple	*Acer saccharinum*	10 – 28	60 – 87
Horse-chestnut	*Aesculus hippocastanum*	8 – 27	73
European birch	*Betula pendula*	14 – 24	48 – 88
European beech	*Fagus sylvatica*	7 – 15	83
Green ash	*Fraxinus pennsylvanica*	10 – 29	70 – 71
London plane	*Platanus acerifolia*	11 – 17	46 – 64
Cottonwood	*Populus deltoides*	10 – 20	68
White oak	*Quercus alba*	13 – 38	n/a
Littleaf linden	*Tilia cordata*	7 – 22	46 – 70

Research question

Although trees play a highly important role in improving urban climate, hardly any Hungarian studies are found focusing on this subject. Moreover, the comparison of shading ability of different tree types and tree species is even more scarce.

Multiple Hungarian biometeorological studies have proved that the key element of human thermal comfort is the radiation stress that may be most effectively reduced by the shades of tress in urban environment (*Gulyás et al.* 2006, *Kántor et al.* 2016). For this reason, the transmissivity studies on frequently planted urban trees in Hungary would be of high importance.

During my researches carried out at Department of Climatology and Landscape Ecology, University of Szeged, I studied the heat stress reducing effect of tree vegetation, with special regard to the comparison of shading ability of different types of trees. Such results are scarce even at international level, and, moreover, methodological experience gained at on-site measuring is also hard to find. This is particularly true for long-term surveys carried out in multiple seasons.

<u>My research aims at unearthing the subsequent topics:</u>

- Which structural, morphological and health condition characteristics describe the tree stand in downtown Szeged? (Chapter 2)
- What is the most effective and reliable method of demonstrating the micro-climate modifying effect of tree woody vegetation, particularly their irradiation reducing capability? (Chapters 3 and 4)
- What inter species and seasonal differences can be observed regarding the transmissivity of single mature trees? (Chapters 3 and 4)
- How can we describe the complex micro-climate modification (short- and longwave radiation budget, air temperature and humidity) potential of the most popular urban tree species? (Chapter 5)

2. Investigation of tree stands of public spaces in Szeged

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Abstract

In urban areas vegetation (especially woody vegetation) is of utmost importance, since it affects the ecological conditions of the city. Urban trees play an important role in improving urban climate both at the local (city, district) and the micro-level (e.g. in public squares). Establishing and maintaining advanced and detailed information systems necessary for the management of urban tree stands is an important task of environmental and climate-conscious city management. Despite that, few of the Hungarian municipalities have a regularly updated tree database. The city of Szeged started efficient green space management in autumn 2013, when we started the creation of a detailed and up-to-date tree register for the public areas, which has been continuously expanded ever since. The survey of the present study covers the period of the growing season, from late spring to early autumn of 2013. All the trees are included in the survey and quite a number of data are recorded for each individual (e.g. species, age, size parameters, exact location, health status, etc.). The recorded data are paper-based, however they are included in a GIS-based green space inventory software, Greenformatic, where coordinates are associated to each object, while information on the state of the tree, its location and handling can be found in the attribute table. The trees included are mostly concentrated in the inner city of Szeged, but the surveys will gradually cover ever larger areas of the city. The results highlight the fact that the structural attributes of the different species' populations are formed by the integrated effect of the species' urban tolerance and planting policies of the past decades. The current database already allows highly complex analysis, which contributes to the well-being of city residents.

Keywords: urban tree, green space management, tree database, Greenformatic

2.1. Introduction

Tree stands have many positive effects on the ecological status of a city, its population's health and well-being, making the urban built environment more liveable. One of the most noticeable direct effects is changing the microclimatic conditions (*Andrade and Vieira* 2007; *Bowler et al.* 2010). During the active period of the growing season the daytime near-surface air temperature has been proved to be lower under the trees than above the free surface (*Lin and Lin* 2010). This is primarily due to the canopy reducing the amount of radiation energy from the surface, as it reflects a part of it and absorbs another part - although the extent of this effect depends on the season and the time of day (*Shashua-Bar et al.* 2011; *Konarska et al.* 2014).

This directly causes a decrease in temperature, while on the other hand it has an even more significant impact on human comfort, because it results in further physiological (heat) stress reduction, which is well detectable using different human comfort indices (*Égerházi et al.* 2013b). In areas planted with trees a much larger amount of water leaves to the air through evapotranspiration than either in grasslands or built-up areas. This increases humidity, which indirectly contributes to the development of lower temperatures under the trees and has a generally beneficial effect on human comfort, especially during heat waves (*Zhang et al.* 2013). Surface roughness increased by the presence of woody vegetation decreases the speed of near-surface air movement, which can have both positive and negative implications. In winter, it can lead to significant heating-related energy savings (*Loehrlein* 2014).

An important element of improving air quality is the absorption of air pollutants (e.g. ozone, nitrogen, sulphur-dioxide, settling dust, etc.) - the actual quantity depending on the amount of leaf surface. During photosynthesis trees use a substantial amount of CO_2 (extracting it from the air), one of the most important greenhouse gases (*Nowak et al.* 2006). Except for the latter, all those listed here have an indirect or direct impact on human health, either through human respiratory diseases or through otherwise affecting comfort.

A very important ecosystem service of urban tree stands is the massive interception of precipitation on the leaf surface, a part of which evaporates directly, while the rest is slowly conveyed towards the ground, making infiltration easier, and significantly reducing the size of flash floods following extreme precipitation events (to an extent depending on the size and state of the stand). The water trapped in this way does not burden the sewage system at the time, but seeps into the soil gradually and thus more efficiently. This in turn improves the quality of otherwise poor urban soils (*Day and Dickinson* 2008).

Creating and maintaining a green surface property cadastre is a statutory obligation for municipalities in Hungary; woody vegetation represents a substantial part of this. However, the property value in this case is much more than just the value of wood. The pollutant and carbon sequestration, the reduction in runoff, the energy savings resulting from the shading of buildings are relatively easily expressible in monetary terms. Defining the monetary value of much more abstract concepts such as the reduction of thermal comfort, the aesthetic and / or cultural value, the mental and physical regeneration effect - the further benefits of well-maintained green areas and tree stands - is much more difficult, however without doubt these also should be given some consideration. It makes monetary evaluation particularly difficult that the idea of a property gaining value over time instead of losing it is quite foreign to traditional economic thinking (*McPherson* 2003).

2.2. Study area

Szeged is situated in the south-eastern part of Hungary (46°N, 20°E; 78-85 m above sea level), in the Lower-Tisza-valley, at the confluence of the rivers Tisza and Maros. According to Péczely's climatic classification (*Péczely* 1976) the Great Hungarian Plain is characterised with a dry-warm continental climate, therefore in summer heat is typical and drought susceptibility is high in the Szeged area. The annual sunshine duration is high and air humidity is typically low. Winter snow cover is rare and the amount of snow is also low. Szeged is the biggest city of the Southern Great Plain region with an area of 281 km^2 and a population of about 170 000 (*Fig. 2.1*).

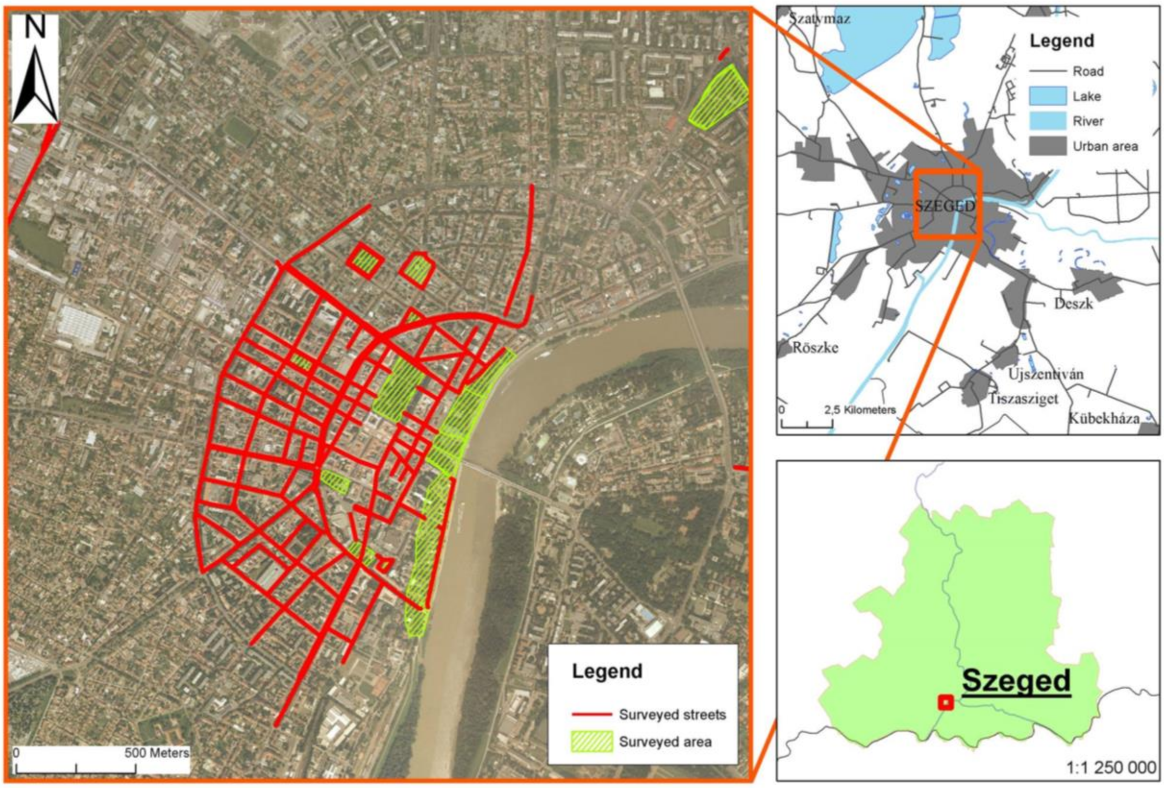


Figure 2.1: Tree alleys and squares recorded by the end of November 2013

Due to its size, the city of Szeged has easily detectable climatic effects on the local scale. The most apparent phenomenon is the formation of a so-called urban heat island as a result of artificial surfaces, which is most pronounced a few hours after sunset. In Szeged the added heat from the heat island is on average 2-3°C, but in calm, anticyclonic periods it may reach up to 6-8°C (*Balázs et al.* 2009). This (along with many other climatic effects) significantly affects the life chances of urban vegetation. It may therefore be useful if vegetation studies are supplemented with a climatological perspective, and vice versa, the climate-modifying effects of the vegetation are investigated.

2.3. Methods

In order for a city to have an efficient green space management, which is also sustainable in the long term, a detailed, up-to-date database is necessary. To this end, in 2012 the Department of Climatology and Landscape Ecology of the University of Szeged (in collaboration with the Environmental Management Office of Szeged) started to set up such a detailed tree register which helps the performance of operational tasks and maintenance while also provides an opportunity for the scientific examination of the urban ecological role of trees (e.g. complex ecosystem services evaluation). The data-recording during the field surveys was paper-based, with a high demand on time and human resources; university students were heavily involved in the work.

The ideal period for the survey is from late spring to early autumn, namely the growing season, when the foliage has fully developed and autumn defoliation has not yet started. Some parameters, such as the exact extent of the canopy or the health status of individuals can only be established with reasonable accuracy in this period. All the trees or shrubs with a dbh (diameter at breast height) over 5 cm are included in the survey and quite a number of data are recorded for each individual (e.g. species, age, size parameters, exact location, health status, etc.). Photos are also taken of each tree and added to the database.

Additional data are related to the surroundings of the tree such as the size of the planting space, the nature of a protection measure or nearby damaging factors. Health data contain information on injury and lesions detected on the root system, the trunk or the canopy, as well as other anomalies included as comments. Based on the data recorded separately for the tree parts, an assessment of the whole tree's health status is provided on a 5-point scale. The person recording the experienced damage can also make management proposals and include them in the database.

In order to get more accurate scientific analysis some extra parameters are also recorded for each individual, which so far have not featured in such registers. These include for example the proportion of dried-out crown parts, the proportion of missing or truncated parts (as a percentage) and the degree of light availability. These enable more realistic calculations of tree volume and leaf area serving as input for pollutant absorption and carbon-sequestration calculations. Thus regulatory ecosystem services can be evaluated more precisely (*Takács et al.* 2014).

In order to record and store spatial data a GIS is necessary, since visualization and spatial analysis are part of the complex requirements of users (both managers and scientific experts).

The Greenformatic - Geospatial Information Software, is a targeted GIS-based green space inventory software developed in Hungary. Coordinates are associated to each object, while information on the state of the tree, its location and handling can be found in the attribute table. This primarily serves to directly make users' everyday work easier.

The results shown in the present work were derived from the data of over 5000 tree individuals recorded until November 2013 (see the extent of the area on *Fig. 2.1*). As shown on the map in *Figure 2.1* the database assembled by that date mostly represents the densely built-up areas of the inner city, within the Great Boulevard (Nagykörút).

2.4. Results

The tree population in the register recorded by November 2013 contains 5197 objects, the tree individuals belong to 110 species and 4 categories: stumps, empty planting spaces, former planting spaces and dried-out trees. The city is quite species-rich, however approximately 60% of the individuals belong to the 10 dominant species (*Table 2.1*). There are 48 species with less than 5 individuals in the database.

Table 2.1: The most common tree species in Szeged within the surveyed areas

Tree species		**Number of individuals**	**%**
Littleleaf linden	*Tilia cordata*	634	12.2%
Pagoda tree	*Sophora japonica*	542	10.4%
Common hackberry	*Celtis occidentalis*	472	9.1%
Silver linden	*Tilia tomentosa*	458	8.8%
Large-leaved Lime	*Tilia platyphyllos*	229	4.4%
Goldenrain	*Koelreuteria paniculata*	224	4.3%
Horse-chestnut	*Aesculus hippocastanum*	168	3.2 %
Manna or flowering ash	*Fraxinus ornus*	121	2.3%
Plane	*Platanus hispanica*	121	2.3%
Norway Maple	*Acer platanoides*	117	2.3%
dominant species	3086		59.38%
other species	1655		31.85%

Almost half of the recorded individuals belong to species non-native in Hungary (*Fig. 2.2*). Of these, *Sophora japonica, Celtis occidentalis* and *Koelreuteria paniculata* are present in highest numbers (over 200 individuals each). Of native species, different species of linden trees (Tilia sp.) are most frequent (1321 individuals).

It is noteworthy that empty planting spaces, tree stumps and other miscellaneous categories make up 8.6% of the whole database, which means 490 trees were waiting to be replanted. That number continued to increase in the winter of 2013, because in addition to the winter cuts a number of individuals had to be removed during the reconstruction of Kossuth Lajos Avenue. However, some trees were also planted in the autumn of 2013 and 2014. These changes are not included in the present analysis.

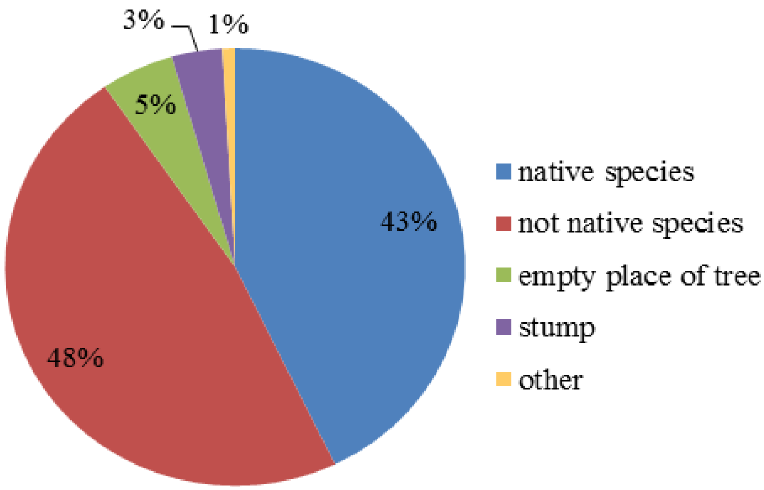


Figure 2.2: The proportion of native and non-native species (miscellaneous: e.g. dried-out tree, removed planting space, unidentified species)

This also draws attention to the vital importance of an up-to-date database, which in addition to containing the existing trees, also includes the interventions, recorded in the shortest possible time. Only thus can the database facilitate effective green space management.

In addition to allowing the approximate estimation of tree volume value, the size parameters of the individuals serve as input to a number of other analyses. Although dbh depends on a number of parameters besides age, most importantly on species, light availability and other site conditions, the current distribution of stem diameter classes may be used to refer indirectly to the age of the stands. There is little information available in the literature concerning urban trees; there are more examples of such estimations from forest stands.

Sophora japonica and *Platanus hispanica* have the largest average dbh in the Szeged database, for both species it's close to 50 cm. True, these species also have the largest standard deviation, therefore their dbh range (and probably the age as well) is higher than that of the others. Similarly, there is a large standard deviation in the case of *Celtis occidentalis*, but the average dbh is lower. *Tilia tomentosa, Koelreuteria paniculata* and *Fraxinus ornus* have the lowest average dbh. In case of the latter two species standard deviation is also the lowest therefore they show the most homogeneous age distribution of all the species in the database (*Fig. 2.3*) and are probably the youngest stands as well.

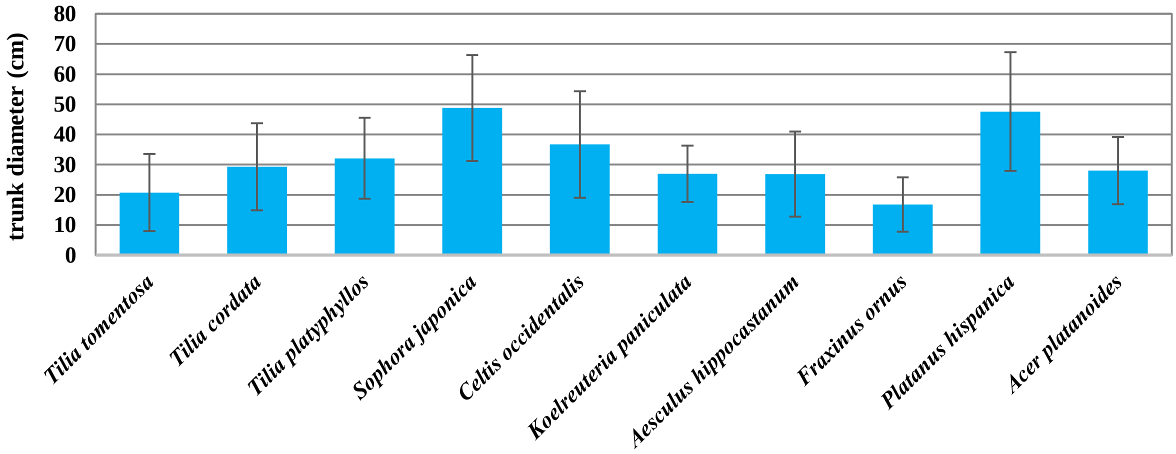


Figure 2.3: The average dbh of the 10 most common tree species along with the standard deviation

Looking at the age distribution of the total recorded tree population, the average estimated age is 36 years, while the software estimates the age of the oldest specimens as 103 years. The age group 15-45 makes up 66% of the total population (*Fig. 2.4*). The age distribution suggests that the last great tree planting campaign in this area was at the end of the 1980’s and the early 1990’s, but significant planting actions took place between the two world wars and in the 1970’s as well. (It should be noted that these results still only refer to areas of the city within Nagykörút. Since these events are intimately linked with the city's structural development, the extension of the database to the outer areas might significantly modify this picture). The number of the old trees (older than 90 years) is only 22. In the case of urban trees - with regard to the unfavourable ecological conditions and a fear of collapse damage – such high ages are very rare, especially in the light of Szeged having been destroyed by the great flood of 1879. As a result of the destruction, even the oldest trees can only be dated back to that time. Among the oldest trees are some of the planes in Széchenyi square, and a few old oak trees in Korányi Alley.

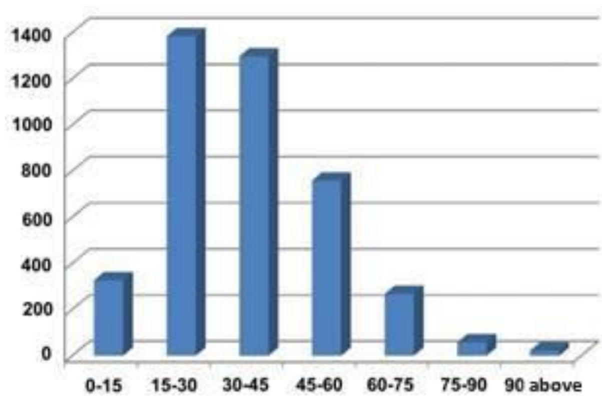


Figure 2.4: Age distribution of the whole recorded tree population

Examining in detail the age distribution of the 10 most common species, the planting practices of the last hundred years are neatly outlined. It can be seen that *Tilia plathyphyllos*, *Sophora japonica* and *Platanus hispanica* have the most diverse age structure, which suggests that these species enjoyed an almost unbroken popularity over the last hundred years; they were favoured throughout the last century in plantations (*Fig. 2.5*).

Aesculus hippocastanum was clearly a favourite of the 1970's, the vast majority of today's white-flowered population belongs to the age group 30-45. The species is in many ways an ideal park tree; it has a very significant microclimate-improving effect since it allows only a small percentage of the direct radiation through the canopy, and it is also very decorative through almost the whole year. The species was very popular until the late 1980's (until the massive invasion of horse-chestnut leaf miner - *Cameraria ohridella*) but by now the population is in a critical condition.

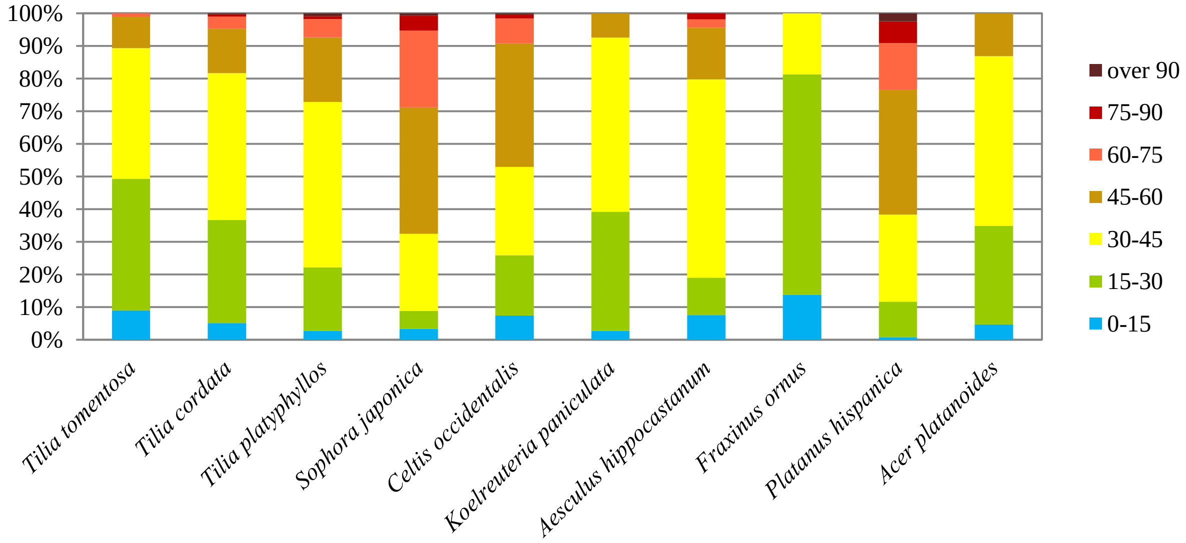


Figure 2.5: Age distribution of the 10 most common species

(1: Optimal 2: Well-cared for, 3: Deficiencies, 4: Serious deficiencies 5: Neglected)

The proportion of older individuals is the highest in the case of *Sophora japonica* and *Platanus hispanica*. However, it seems that these species have lost some of their popularity over the last 20 years, since there are very few young individuals in the database.

Celtis occidentalis (with an average age of 42) shows the most uniform age distribution in the observed population. This is due to the fact it is one of most urban-tolerant species; much more tolerant to the unfavourable urban conditions (air and soil pollution, drought) than other species, so it was commonly used in the past as well as in today's urban tree planting.

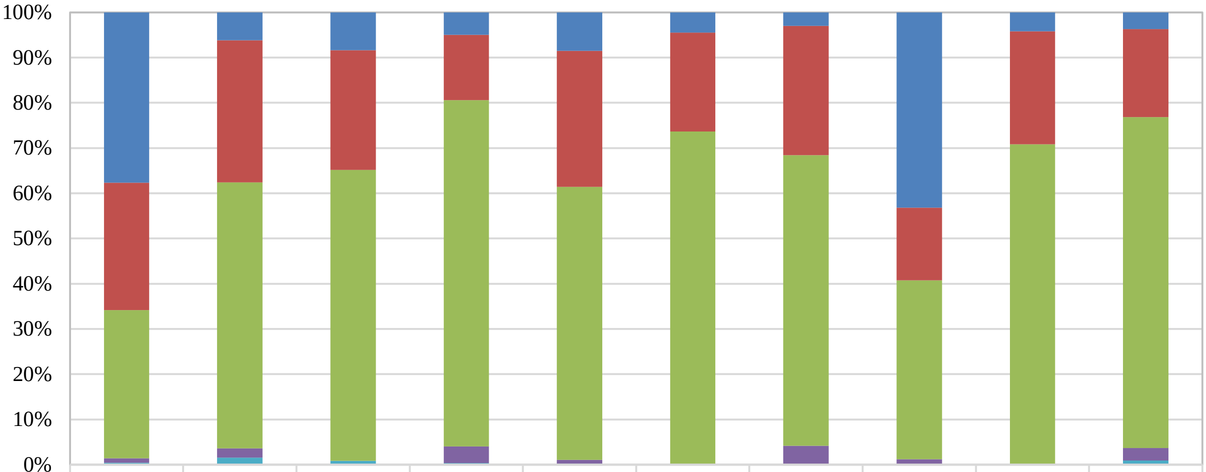
In the last 20-30 years, however, the focus has clearly shifted towards *Tilia cordata* and *tomentosa*, *Fraxinus ornus* and *Koelreuteria paniculata*. The age distribution of lindens shows that from 1965 to the present day they are the fashion trees of the city of Szeged (*Gaskó* 2008), and in recent decades a rejuvenation process can be observed. However, *Tilia tomentosa* plays a more important role among younger individuals (about 50%). This is due to the fact that in recent years many perished *Tilia platyphyllos* trees were replaced with *Tilia tomentosa* individuals, more tolerant of the harsh urban environment.

In the inner, more built-up areas of the city, it is no wonder that in the last 20 years species with relatively smaller proportions have been favoured, which would not outgrow the confined space very fast – such as *Fraxinus ornus.*

The assessment of the health status of the population was carried out according to the standards presented in the methods section. In terms of the whole observed population it is pleasing that 40% of the trees are in a relatively good state, so only minor changes of the trunk and canopy are observed. The other end of the spectrum represents individuals with severe deficiencies, i.e. where serious trunk and/or foliage damage was observed, such as deep-penetrating trunk decay, rot of the root collar or the crown - which represents an imminent risk of an accident - or withering of the treetop, which warns of major root damage. These symptoms require immediate and significant intervention, and in some cases make it impossible to save the tree. The database contains 60 such individuals, which makes up only 3% of the total observed population, but since the most densely populated inner city areas are affected, they require increased attention.

The health status data of the 10 most common species draw attention to a number of interesting facts. The highest proportion of significant deficiencies (i.e. more than slight deterioration of health status), can be observed in the case of *Sophora japonica* (77%), *Platanus hispanica* (71%), *Koelreuteria paniculata* (74%) and *Acer platanoides* (73 %) (*Fig. 2.6*). The first two species can be characterized with higher average ages, including a relatively high proportion of older trees. Of course, this may explain the health status being worse than average.

The second place of *Koelreuteria paniculata* in these rankings is an interesting phenomenon since the age distribution suggests these trees to be relatively young, so poor health is not expected. It may be a reminder of the fact that the environmental circumstances in Szeged are probably not well tolerated by this species. The same applies to the case of Acer platanoides. The "serious deficiencies" or "neglected" category contain individuals with severe crown- base or root collar rot, or a strong deep-reaching parent branch decay.



	Tilia tomentosa	*Tilia cordata*	*Tilia platyphyllos*	*Sophora japonica*	*Celtis occidentalis*	*Koelreuteria paniculata*	*Aesculus hippocastanum*	*Fraxinus ornus*	*Platanus hispanica*	*Acer platanoides*
1	*163*	*39*	*19*	*27*	*40*	*10*	*5*	*35*	*5*	*4*
2	*122*	*199*	*60*	*78*	*142*	*49*	*48*	*13*	*30*	*21*
3	*142*	*372*	*146*	*414*	*285*	*165*	*108*	*32*	*85*	*79*
4	*4*	*13*	*0*	*20*	*4*	*0*	*7*	*1*	*0*	*3*
5	*2*	*10*	*2*	*2*	*1*	*0*	*0*	*0*	*0*	*1*

Figure 2.6: Health status of the 10 most common species

(1: Optimal 2: Well-cared for, 3: Deficiencies, 4: Serious deficiencies 5: Neglected)

These two categories appear in major proportions in the case of four species, *Tilia cordata*, *Sophora japonica*, *Celtis occidentalis* and *Aesculus hippocastanum*, which seem to be the most threatened of the observed tree population of Szeged. In Hungary the horse-chestnut leaf miner (*Cameraria ohridella*) spread at a very fast rate in the early 1990's and that infection did not spare the trees in Szeged either. Even today, there are serious problems with the chestnut trees. In many cases, the individuals lose most of their foliage by the end of July, or the beginning of August and start flowering again in September – which in turn greatly weakens the tree's immune system.

Tilia tomentosa and *Fraxinus ornus* are in the best state of health among the recorded species. The proportion of individuals in the Optimal and Well-cared-for categories is way above 50%. A likely reason is that these species have the youngest stands, many of them having been planted relatively freshly.

2.5. Discussion and conclusion

Urban woody vegetation plays an important ecological role in settlements, however they are not yet always appreciated accordingly in Hungary. There are very few municipalities who have an up-to-date usable tree register. In the current budget cycle (2014-2020) of the European Union there is particular emphasis on the development of green infrastructure. It is no coincidence, since the optimally chosen vegetation can locally mitigate the extremes of global change to a large extent and it can significantly improve the unfavourable living conditions in urban areas. However that requires an up-to-date green space database, which shows health status, location of the individual trees, and is also informative of the performed and to do tasks. Progress in Hungary in this respect has first appeared in some of the bigger cities. Szeged is at the forefront in this, since the city's tree register is constantly extended and updated. Such data are essential to the effective management of green areas, but keeping the data up-to-date is also the most labour-intensive part. During the everyday work trees are continuously replaced, there are rejuvenation actions, cuttings, so changes often occur, which need to be continuously monitored.

Most of the trees are not older than 45 years; and only 10 individuals in the current database belong to the age group of more than 100 years. This can be explained by the fact that tree planting affecting today's Szeged effectively began after the catastrophe of 1879, since trees planted before that time were destroyed by the flood. Wartime cuttings should also be taken into account, when the citizens of Szeged needed to acquire fuel for heating.

The oaks of Korányi Alley are among the oldest individuals that were demonstrably planted first, right following the flood. Therefore when the reconstruction of the river protection wall was carried out this was precisely the reason for the need to exercise caution during the construction works, as these old, healthy individuals represent a huge unique value. The age distribution of the tree population raises interesting questions. The question of how long it is "worth it" to keep an old tree is important for decision-makers and managers; i.e. what is the age when maintenance would become significantly more expensive (due to an increasing need for maintenance works, risk of accident, curled concrete, etc.) than the positive effects of the individual. Such aging populations usually have higher care needs, however due to their large canopy and consequently larger leaf surface can have a very significant air quality improving role; furthermore such important aesthetic, historical, cultural values are connected to them, which are difficult to express in monetary terms.

The periods of increased tree planting are clearly visible in the age distribution data for each species, as is the fact that the constantly rejuvenated or freshly introduced species are in the best health. In some cases, however, contradictions arise, since *Koelreuteria paniculata* individuals despite the young population are in a poor state so their "profitable" maintenance is more difficult.

Concerning the health status of the Szeged tree population, in the case of certain species the proportion of the “deficiencies” category is relatively high. White-flowered *Aesculus hippocastanum* trees are especially in poor health. When the funding becomes available most probably the red-flowered variant of chestnut (*Aesculus × carnea*) will be used to replace these, which seems to be resistant to the pest destroying the other type. A noteworthy initiative to improve the health of the remaining population was the opening of the formerly asphalt-surrounded planting spaces in a substantial part of Szentháromság street. The open soil surface was covered with mulch and shrubs, which is supposed to greatly improve the state of the stand through allowing a better infiltration of rainwater. The poor health of the trees is probably related to the sometimes extremely parched urban soils. Unfortunately it is possible that the stand is already so heavily degraded that even this measure will not help.

The health status of species represented by older stands (*Tilia platyphyllos, Platanus hispanica and Sophora japonica*) is also worse than the average, the category of major deficiencies appears in their case. At present, *Tilia tomentosa* has the best health status, which may be the result of partly the young age of the stands, and partly of the fact that this sub-Mediterranean species tolerates urban conditions better than others. Therefore, it is an alternative to be considered when replacing other linden species.

Although the data presented in this study involve only a part of the total of Szeged’s street tree population, even the current database allows a highly complex analysis, of which here only species composition, age-, size- and health status distribution were examined.

The establishment of the appropriate species composition is very difficult. A lot of aspects should be taken into account by the maintainer; different public places have different needs and constraints thus different species can mean the ideal choice. In recent years *Fraxinus ornus* became fashionable; it is a popular species in fresh plantations. However planting a species with a relatively small leaf surface and high transmissivity in certain places (e.g. heavily used public squares) could contradict modern climate-conscious urban planning principles. The answers to these questions may become easier to find through in-depth data analysis and further research, which is the aim of our research group and also meets the needs of the municipality.

3. Solar permeability of different tree species in Szeged, Hungary

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Abstract

The heat stress modification capacity of urban trees is widely acknowledged and makes these natural landscape elements very important in the field of climate conscious urban planning. Many studies proved that shading, i.e. the reduction of direct solar radiation is the most effective way to moderate summer heat stress under Central European climatic conditions. The investigation aims at determining the transmissivity of four tree species that occur frequently in Hungarian cities: *Sophora japonica*, *Tilia cordata*, *Celtis occidentalis* and *Aesculus hippocastanum*. In order to accomplish that, a systematic radiation measurement campaign was carried out in the South-Hungarian city of Szeged, from early summer (foliated condition of trees) to late autumn (nearly leafless condition). Short-wave radiation from the upper hemisphere was measured with Kipp & Zonen pyranometers under carefully selected tree specimens (transmitted radiation), as well as on a roof station free from sky obstruction (actual value of global radiation). The calculated transmissivity values varied greatly with the seasonal status of the canopy (the median value of transmissivity increased from 0.03 to 0.47 in case of *A. hippocastanum*), and we found considerable inter-species differences too, evidencing that solar permeability depends on the amount of leaves, leaf density and other tree crown-related characteristics.

Keywords: shading potential, transmissivity, urban trees, Szeged, Hungary

3.1. Introduction

Urban adaptation strategies become ever more important, considering the rapid growth in urban population as well as the predicted effects of climate change (*UNFPA* 2011; *IPCC* 2014). According to the latest research results, summer heat stress will increase more in cities than in rural and natural areas (*Pochter and Ben-Shalom* 2013; *Zuvela-Aloise et al.* 2015). More severe and longer-lasting heat stress periods are expected, which means even greater challenge for city dwellers. Several earlier studies have demonstrated that many urban design-related microclimates result in significant level of bioclimatic stress in certain periods, especially in summer. Under Central-European climate conditions, extreme heat stress at the street level is usually the effect of high solar radiation and the resulting high radiation budget of pedestrians (eg. *Gulyás and Unger* 2010; *Kántor and Unger* 2011; *Égerházi et al.* 2013a; *Lee et al.* 2014). Carefully designed shading is therefore essential in the fight against heat stress and in the creation of comfortable outdoor places (*Lee et al.* 2013). The most obvious way of shadowing, which incidentally also offers the most additional services in urban ecosystems, is the usage of vegetation, especially shade trees (*Carver et al.* 2004; *Shashua-Bar et al.* 2009; *Shahidan et al.* 2010).

The heat stress mitigating nature of urban trees is widely acknowledged and makes these natural landscape elements very important in the field of climate-conscious urban planning (*Shashua-Bar and Hoffmann* 2000; *Bowler et al*. 2010; *Erell et al*. 2011; *Shashua-Bar et al.* 2011). Many studies based on micrometeorological measurements and/or model simulations have proved that shading, i.e. the reduction of direct solar radiation is the most effective way to moderate summer heat stress under Central-European climate conditions (e.g. *Mayer* 2008; *Mayer et al.* 2008; *Égerházi et al.* 2013a, 2014; *Kántor et al.* 2016). Shade trees have positive effect not only on outdoor thermal comfort, but also on thermal conditions inside buildings (*Akba*ri *et al.* 1997; *Donovan and Butry* 2009). The shadowing of exposed walls, especially west- or south-facing ones (in Central-Europe), lessens the warming of interiors. In a hot climate, trees planted around buildings (when applying the right species to the right place) positively influence the energy balance and reduce the energy requirements of cooling them through sheltering the windows, walls, and rooftops from strong direct solar radiation and from the radiation reflected from the surroundings (*Nakaohkubo and Hoyano* 2011; *Berry et al.* 2013).

The shading potential of trees is usually described by their transmissivity values (or solar permeability), i.e. by the proportion of solar radiation transmitted through their foliage (*Cantón et al*. 1994; *Konarska et al*. 2014). Despite the importance of the thermal stress reducing effect of shade trees, the number of relevant studies with practical outcomes is very small, and there is a lack of information about the species-specific shading and bioclimate-regulation capacity of trees. In order to help fill in the knowledge gap we aim to determine the transmissivity differences among common urban trees that occur frequently in Central-European climate conditions, and analyze the intra-annual changes in transmissivity as well. Our long-term objective is to provide a reliable picture of the radiation-modification effect of urban trees. In order to accomplish this, a systematic series of measurements were carried out in the city of Szeged (SE Hungary), on common urban tree species, which covered the whole vegetation period.

This study aims to present the main findings and experiences from the first year of these long-term transmissivity measurements (2014) focusing mainly on

- the temporal change in transmissivity induced by autumn defoliation,
- and the inter-species differences.

These results can be used in microclimate simulation software to enable more reliable modeling, and thus provide help for urban designers and landscape architects in selecting the appropriate shade tree species.

3.2. Methods and data

Szeged is situated in the south-eastern part of Hungary (46°N, 20°E; 82 m above sea level), with a population of about 162 000. This region of Hungary can be characterized with dry-warm continental climate, with significant drought susceptibility at summer. Based on data from the Hungarian Meteorological Service, the total annual sunshine is 2023 hours; the mean annual temperature is 10.5°C, while the annual sum of precipitation is only 495 mm (*WMO* 1996). The street network of the city forms a circuit-avenue system, and there are several different land-use types from the densely built-up inner city to the detached housing suburban region. The study areas for this investigation are recreational places (at the Búvár lake, Kodály sq., Mátyás sq., and Rákóczi sq.) in the urbanized region of Szeged (*Fig. 3.1*).

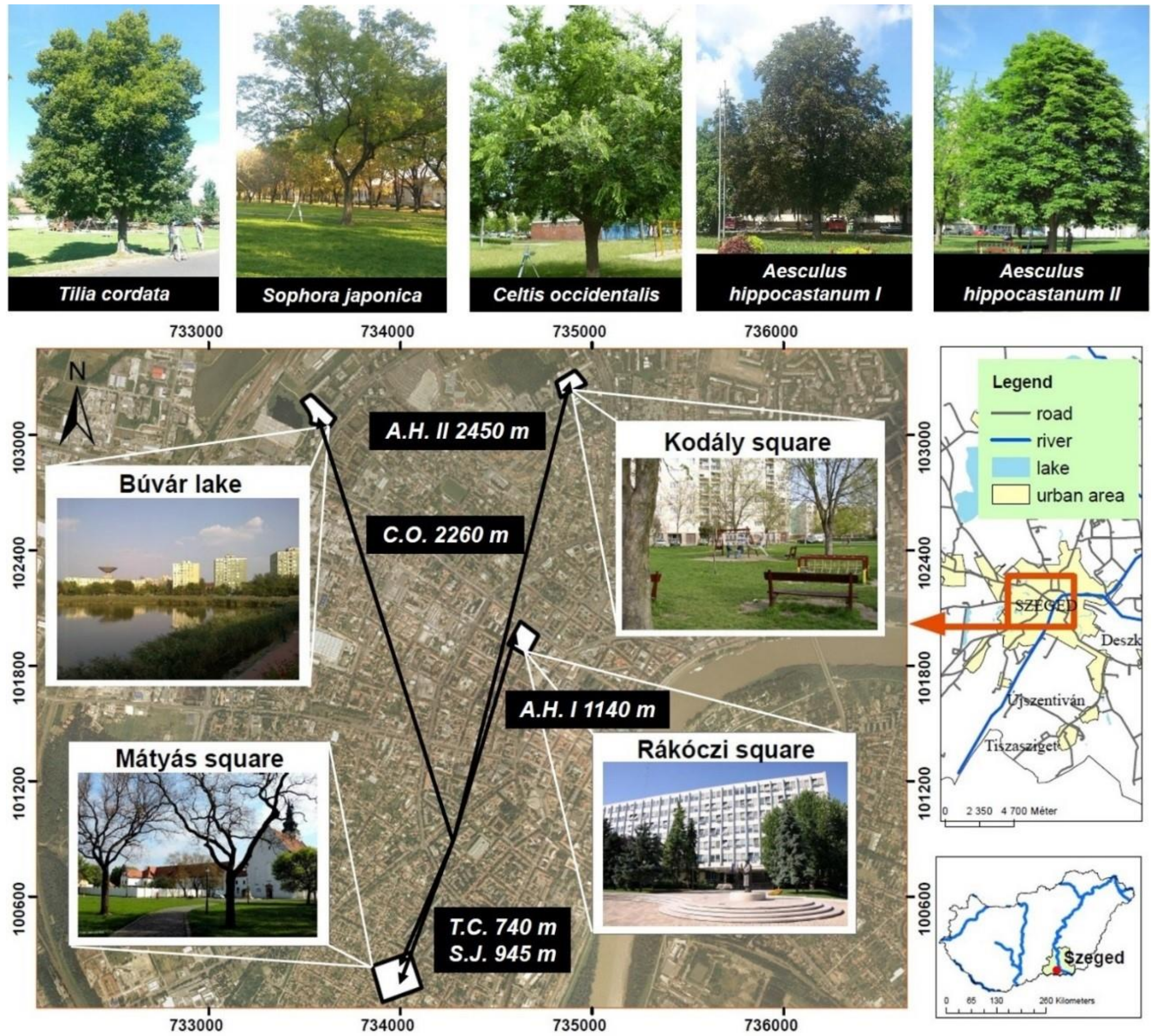

Figure 3.1: The examined tree specimens and study areas in Szeged, Southeast Hungary

A systematic measurement series was organized in order to analyze the intra-annual changes of transmissivity of four tree species frequently planted in Hungarian towns as street trees or park trees. The species are:

- *Tilia cordata* (small-leaved linden)
- *Sophora japonica* (pagoda tree)
- *Celtis occidentalis* (common hackberry)
- *Aesculus hippocastanum* (horse-chestnut).

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 then calculated 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 radiation 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 the recorded parameters significantly during the measurement period (typically from 10 am to 4 pm). Suitable *T. cordata* and *S. japonica* individuals were found in Mátyás square within 1 km distance from the reference station (*Table 3.1*). The selected *C. occidentalis* tree stands by the Búvár-lake at a distance of over 2 km, while the *A. hippocastanum* specimen is in Rákóczi square within almost 1.1 km. However, during the first summer period this specific tree was attacked by *Cameraria ohridella* (horse-chestnut leaf miner), resulting in earlier defoliation. In order to ensure continuous measurements a new, healthy *A. hippocastanum* individual was selected in Kodály square at a distance of almost 2.5 km (*Table 3.1*).

Two 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 did not exceed 25 W/m^2 in absolute value in more than 80% of the cases. The sensors were placed at a distance of 2 m on the northern side of the tree trunks, with special care concerning the right orientation, height and leveling. Pyranometers were situated at 1.1 m above ground level which corresponds to the gravity center of an adult European man, the usually applied standard subject in outdoor thermal comfort investigations (*Mayer* 2008; *Mayer et al.* 2008).

Table 3.1: Main dimensional attributes of the investigated urban trees

Species	***Tilia cordata***	***Sophora japonica***	***Celtis occidentalis***	***Aesculus hippocastanum I***	***Aesculus hippocastanum 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

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

In 2014 the field campaign lasted from June (foliated condition of trees) to November (nearly leafless condition) to determine not only the interspecies differences, but also the intra-annual changes of transmissivity induced by the autumn defoliation (*Table 3.2*).

Table 3.2: Measurement days and intervals in 2014 (colored days were selected for the analyses)

Date	**Sky conditions**	***Tilia cordata***	***Sophora japonica***	***Celtis occidentalis***	***Aesculus hippocastanum***
27 / Jun / 2014	cloudy		10:10 – 17:20		
1 / Jul / 2014	overcast	10:10 – 17:30			
2 / Jul / 2014	cloudy			9:50 – 18:10	
4 / Jul / 2014	clear				10:10 – 17:40
24 / Jul / 2014	cloudy			9:40 – 18:10	10:10 – 16:50
25 / Jul / 2014	cloudy	9:40 – 17:50	10:00 – 17:40		
28 / Aug / 2014	cloudy	10:00 – 16:50	10:20 – 16:30		
9 / Sep / 2014	mostly clear			9:50 – 17:20	10:10 – 17:00
18 / Sep / 2014	mostly clear	10:00 – 16:30	10:20 – 16:10		
29 / Sep / 2014	clear	10:00 – 16:30	10:20 – 16:10		
30 / Sep / 2014	clear			9:40 – 16:40	10:00 – 16:20
28 / Oct / 2014	clear			10:10 – 15:00	10:40 – 14:50
4 / Nov / 2014	clear	10:00 – 14:50	10:20 – 14:30		

After the first four days, parallel measurements under the canopies of two different tree species were carried out at the same time allowing the comparison of their solar permeability under completely identical meteorological background conditions.

3.3. Results

3.3.1. Seasonal change of the foliage

As clear sky conditions occurred most frequently in the case of *A. hippocastanum*, the effect of foliation status on solar permeability is presented on the example of this species. *Fig. 3.2* illustrates the daily curves of global radiation, transmitted radiation as well as the calculated values of transmissivity on four clear days.

The daily maximum of G_{act} was approx. 900 W/m^2 on 4 / Jul / 2014, while it reached only 500 W/m^2 on the last measurement day (28 / Oct / 2014) (*Fig. 3.2*). The autumn defoliation effect is clearly shown: although G_{act} decreased from midsummer to late autumn, G_{trans} and consequently the transmissivity values as well 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 increases (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 and 0.1 and increased above 0.4 only in the mentioned afternoon period with the chance of more direct irradiation. On 9 / 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 at about 400 W/m^2 (*Fig. 3.2*).

In conjunction with the decreasing G_{act} and increasing G_{trans} values during the summer-autumn interval, the transmissivity of *A. hippocastanum* continuously increased because of the autumn defoliation (*Table 3.3, Fig. 3.3*). Since the arithmetic 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 0.03 on the midsummer measurement day, while the medians were 0.08, 0.15, 0.21 and 0.47 on the subsequent measurement days. The corresponding mode values were almost the same, but a little lower: 0.02, 0.06, 0.13, 0.11 and 0.46, 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 maximum values (*Table 3.3, Fig. 3.3*).

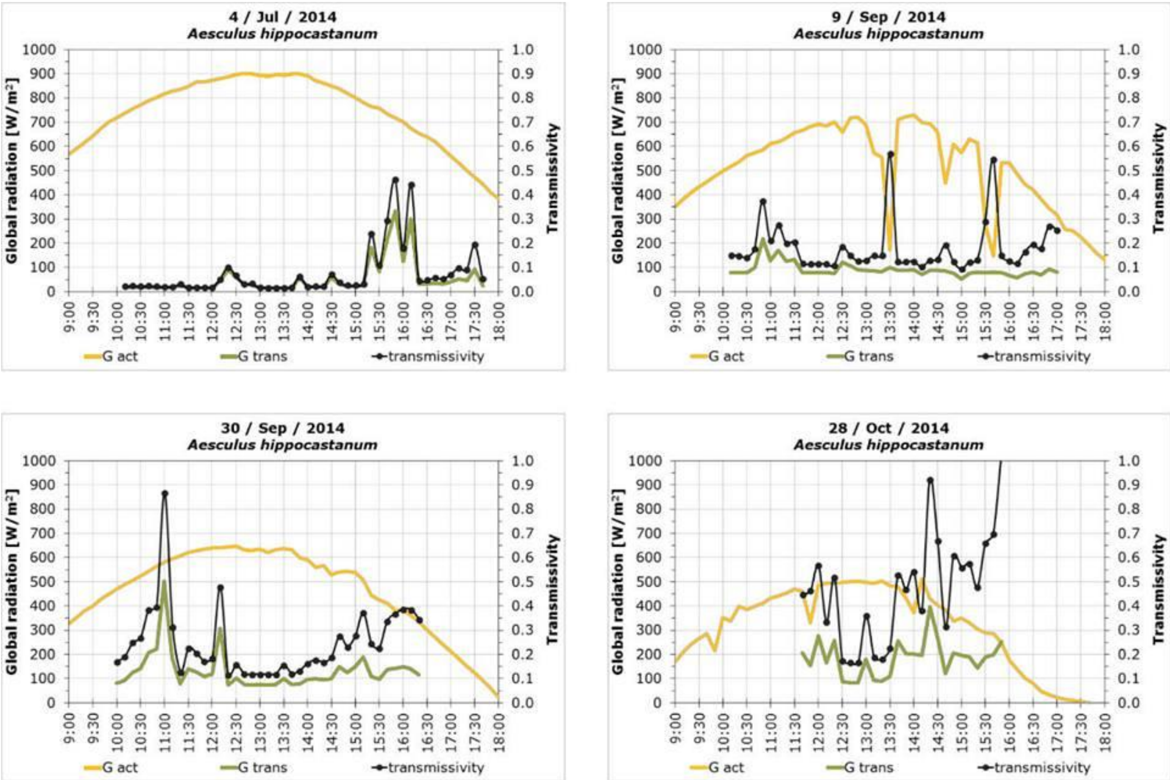

Figure 3.2: Seasonal change of solar permeability through the foliage of *A. hippocastanum* (time is in CET, G_{act} – actual value of global radiation, G_{trans} – transmitted radiation)

Table 3.3: Basic descriptive statistics of *Aesculus hippocastanum*'s transmissivity on different days

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

An important shortcoming of the original measurement concept related to cloudy sky conditions can be noticed on the transmissivity curve of 9 / Sep / 2014 (*Fig. 3.2*). Transmissivity increased sharply twice during the day, at 13:00 and 15:40, while the curve of G_{trans} remained consistent. These apparent jumps in transmissivity did not mean a real increase in the solar permeability of *A. hippocastanum*. They can be explained with cumulus clouds above the reference station that caused immediate drops in the value of global radiation – however G_{act} was measured more than 2 km away from the tree, which was thus unaffected by the clouds' shadow. If the reference G_{act} value was measured on the top of an adjacent building, such sharp decreases of G_{act} would be synchronous with the moderated decreases of G_{trans} curve.

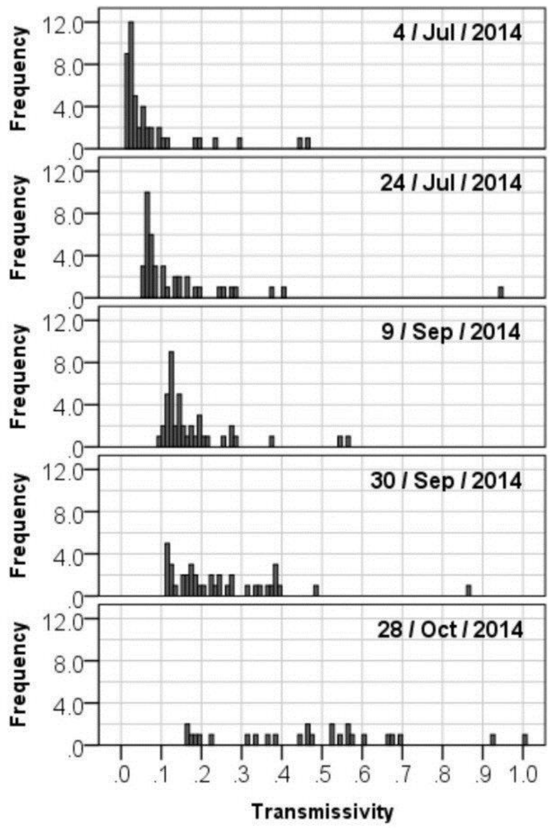

Figure 3.3: Transmissivity values of the *Aesculus hippocastanum* on different measurement days

3.3.2. Interspecies 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 on the data of clear days only. 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 3.2*). Both days had nearly bell-shaped curves of global radiation (G_{act}) with maximum 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. 3.4*).

On 29 / Sep / 2014 *S. japonica* had clearly higher transmissivity than *T. cordata*: median values are 0.13 vs. 0.08 and the means are about 0.15 vs. 0.12, respectively (*Table 3.4, Fig. 3.5*).

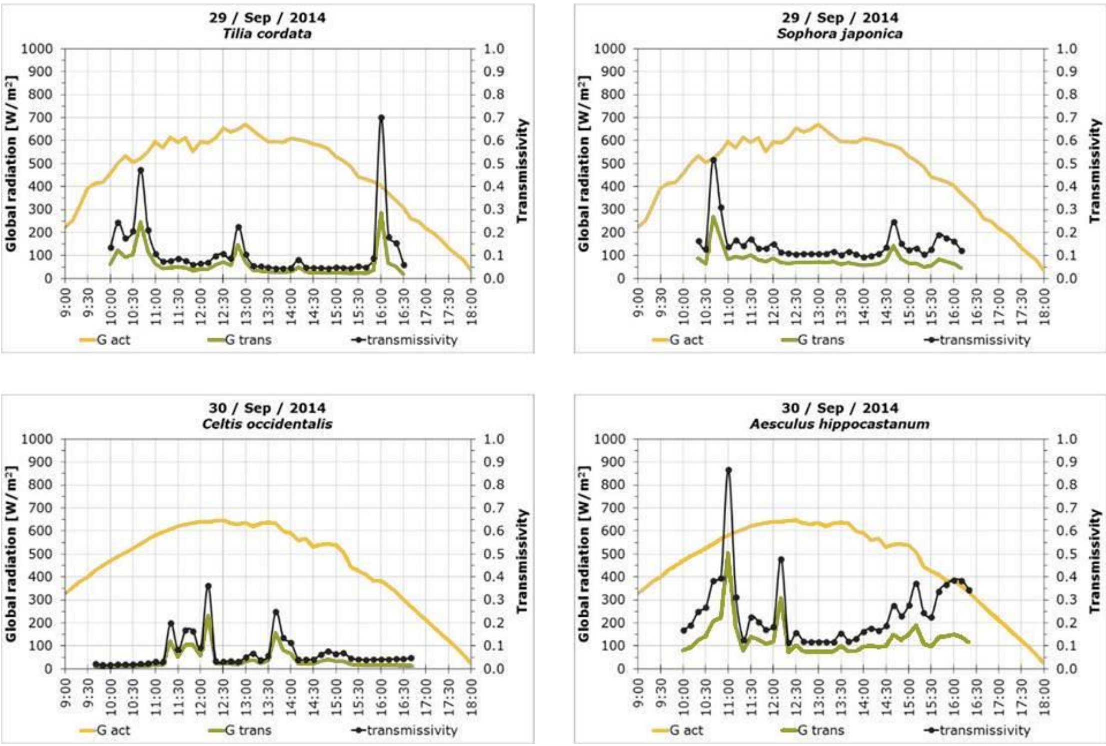

Figure 3.4: Transmissivity differences between the four trees on two consecutive clear days (time is in CET, Gact – actual value of global radiation, Gtrans – transmitted radiation).

The differences on 30 / Sep / 2014 between the other tree-pair are even greater. *A. hippocastanum's* median transmissivity is 0.21 (mean: 0.25), while *C. occidentalis* can be characterized with the most effective shading: its median transmissivity is only 0.04 (mean: 0.07). The latter's shading potential is 5-times stronger in the end of September than that of *A. hippocastanum*. Not only the median, mean and mode values are higher in the case of *A. hippocastanum*'s solar permeability, but it also has a more even distribution, and the values cover a wider range: 0.12–0.87. On the contrary, in the case of the other species the transmissivity values are clustered around a very specific mode: this is 0.04 for *C. occidentalis* and *T. cordata*, and 0.1 for *S. japonica* (*Table 3.4, Fig. 3.5*).

Table 3.4: Basic descriptive statistics of the investigated species' transmissivity on the last two days of September 2014

Species	N	Mean	SD	Mode	Median	Min.	Max.
Celtis occidentalis	43	0.07	0.07	0.04	0.04	0.02	0.36
Tilia cordata	40	0.12	0.13	0.04	0.08	0.04	0.70
Sophora japonica	36	0.15	0.08	0.10	0.13	0.09	0.52
Aesculus hippocastanum	39	0.25	0.14	0.12	0.21	0.12	0.87

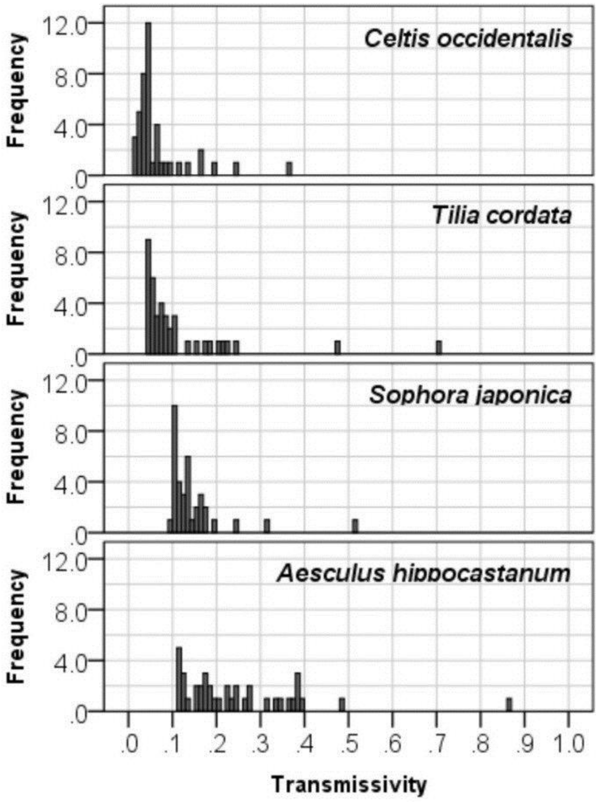

Figure 3.5: Transmissivity values of the different species on the last two days of September 2014

3.4. Discussion

3.4.1. Discussion of the results

The results from the end of September (*Figs. 3.4–3.5*, *Table 3.4*) indicated higher shading capacity in the case of *T. cordata* and *C. occidentalis*, while *S. japonica*'s sparser canopy could be characterized with higher transmissivity. The analysis clearly revealed a lower shading capacity in the case of *A. hippocastanum*, which is in line with our field observations, as this species starts autumn defoliation the earliest. Therefore the higher solar permeability of this tree can be explained with the half-leafless condition of the canopy at the end of September. *T. cordata* and *C. occidentalis* start to lose their leaves almost at the same time, after *A. hippocastanum* and before *S. japonica*. Nevertheless, compared only to *T. cordata* and *C. occidentalis*, *S. japonica* still 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. *T. cordata* and *C. occidentalis* have greater leaf surface and their foliage is denser than that of *S. japonica*'s.

However it is worth noting that the foliation pattern during the spring follows a similar order: *A. hippocastanum* is the first to come into leaf and *S. japonica* the last. Therefore a longer and more thorough measurement campaign is planned including all relevant seasons of the foliation-defoliation process. In that way the results are expected to offer more detailed and reliable picture about the shading efficiency of common Hungarian park and street trees. Another good reason for prolonged research with many investigation days is that we found higher intra-annual changes in the case of the same tree (*A. hippocastanum*; *Figs. 3.2–3.3, Table 3.3*) than the inter-species differences at the same time of the year (end of September; *Figs. 3.4–3.5, Table 3.4*).

Seasonal comparison would be more creditable if the same *A. hippocastanum* specimen could be kept throughout the whole measurement period, because the dimensions of the studied trees (*Table 3.1*) may affect the G_{trans} values. The greater tree crown volume in the first *A. hippocastanum* individual means a longer distance through the tree crown that the solar beam has to pass, enhancing the foliage absorption therefore lowering G_{trans}. On the other hand, the greater trunk height in the second *A. hippocastanum* specimen means that larger amount of diffuse radiation may reach the sensor placed under the tree from lateral directions. Theoretically, both of these size-related differences allow measuring greater G_{trans} under the second *A. hippocastanum* at the same time of the year, provided that both individuals are healthy.

Understanding the importance of the mentioned dimensional attributes and many other factors requires longer and deeper investigation. Namely, the microclimate regulation potential of trees depends not only on dimensional characteristics and age but other factors including leaf area, shape and structure of canopy, etc. Moreover, these factors vary if the trees' state of health deteriorates (*Nowak et al.* 2008). The decline in health is more pronounced if the tree specimen does not tolerate harsh urban growing conditions or does not demonstrate resilience to other local conditions (*Jim* 2012). Climate-conscious planning, preliminary site assessment and prudent selection of species (or cultivars) positively influence the health of the planted trees, and ensure that they can offer the full scale of their ecosystem services that the urban population expects from them. This study may be considered as the basic step offering direct data about the shading capacity, i.e. the micro-climate regulation services of different urban trees.

3.4.2. Application of the results

In order to facilitate urban landscape planning it would be important to use specific transmissivity values in numerical models that characterize appropriately the tree species planted frequently as street and park trees in a given geographical region. The outcomes of this study, as well as the results presented by earlier research (e.g. *Shashua-Bar et al.* 2010; *Konarska et al*. 2014), evince that canopy transmission shows huge differences reaching 4-30% in summer and 40-80% (deciduous trees) in winter. Although solar permeability 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 a single default value to this attribute for all tree species. However, by the use of the SOLWEIG model (*Lindberg et al.* 2008; *Lindberg and Grimmond* 2011) it would be possible to alter this parameter (*Konarska et al.* 2014).

The empirical transmissivity values of typical Hungarian tree species are planned to be integrated into radiation and micro-bioclimate modeling. In that way we can support the work of Hungarian landscape designers to simulate the bioclimatic effect of differently vegetated (planted with different species or cultivars in different extent) recreation areas, moreover to simulate the micro-bioclimatic effect of vegetation in the different seasons according to the foliation-defoliation process.

3.5. Conclusion

3.5.1. Summary

Human thermal comfort and the related thermal stress mitigation is one of the most intensively investigated issues of urban bioclimatology. The importance of this field is obvious when we consider the predicted trends of climate change and the increasing number of city-dwellers who would 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. 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. In order 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. *Tilia cordata, Sophora japonica, Celtis occidentalis* and *Aesculus hippocastanum* were selected to investigate the interspecies differences and temporal changes in solar permeability, as these species occur frequently in urban parks, squares and streets in Central-European climate conditions.

The calculated transmissivity values varied greatly with the seasonal status of the canopy, and we found considerable inter-species differences too, evidencing that solar permeability depends on the amount of leaves, leaf density and other tree crown-related characteristics. Nevertheless, most microclimate simulation software set this attribute as default in the case of all trees. Our results therefore underline the importance of the usage of variable transmissivity values in numerical models in order to provide more reliable simulations. Such assessments can contribute to finding the most suitable tree species in urban landscape planning. Besides the micro-scale results, they can also contribute to the methodological development of local scale heat stress mapping, moreover to the indicator development for mapping climate regulation ecosystem services of urban green spaces.

3.5.2. Future research plans

Additional questions worth studying:

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

To meet the above-mentioned goals and to overcome the problem of 'apparent transmissivity increase' caused by the variable sky conditions and the too distant reference station, a new research design was introduced from the spring of 2015. Reference global radiation (G_{act}) data are no more recorded using the pyranometer on the top of the university building (inner-city weather station). 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 to 1-minute. A further benefit of the new measurement design is the potential for complex microclimate analyses, as short- and long-wave components of the 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. Besides the micro-bioclimate regulating potential of the four tree species, the seasonal status of the canopy is also recorded via photos and fish-eye photos. To study the effect of foliage-health conditions on transmissivity values, from 2015 both the healthy *A. hippocastanum* and 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 input 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 resulting reduction of radiation load. SOLWEIG software is planned to become the basic 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 replacing them with real, measurement based transmissivity that characterizes properly the shading efficiency of Hungarian street and park trees. Because of the significant annual change in transmissivity values (we found greater seasonal changes than inter-species differences at 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.

4. Study on the transmissivity characteristics of urban trees in Szeged, Hungary

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Abstract

This study aims to determine the solar permeability characteristics of some common urban tree species in Hungary and to analyze their shading efficiency in different sky conditions. The results are based on a measurement-series implemented during the whole vegetation period in 2015. This paper compares different tree species regarding their transmissivity, and looks for differences between different sized tree individuals belonging to the same species. The following order was found among the investigated species regarding their shading-capacity: *T. cordata*, *A. hippocastanum* and *S. japonica*. Additionally, higher transmitted radiation and consequently higher transmisivity values were detected in the case of the smaller investigated *A. hippocastanum*.

Keywords: solar permeability, transmissivity, tree species, Hungary

4.1. Introduction

The global climate change has a considerable impact on the urban population, which consists of more than half of the Earth's population and which is predicted to be two-thirds of the ten billion inhabitants by 2050 (*UN* 2014). Projections of the regional climate models indicate that the frequency of the heat waves is likely to be higher in the Carpathian Basin in the forthcoming decades. Indeed, by last decades of this century a significant increase in the length of 'heat wave periods' can be expected (*Pongrácz et al*. 2013).

In urban areas significant excess heat is generated by modified surface coverage, complex morphology and anthropogenic heat emission. Compared to the neighboring rural areas increased air temperature and modified radiation circumstances can be observed in cities; both at micro- and local level (*Lelovics et al*. 2014; *Thorsson et al*. 2014). Several investigations demonstrated the impact of these modifications on human thermal comfort and usage of public places (e.g. *Kántor and Unger* 2010; *Égerházi et al*. 2013b). Thermal comfort conditions can be improved by carefully selected construction materials (*Yang et al.* 2013; *Erell et al.* 2014), shading by appropriate building height (*Bajsanski et al.* 2015), ensured ventilation (*Gál and Unger* 2009; *Ng* 2009), established water surfaces (*Sun and Chen* 2012) as well as by planting effective vegetation (*Dimoudi and Nikolopoulou* 2003; *Bowler et al.* 2010).

Urban forests provide a wide range of ecosystem services (from the environmental through the economic to the social benefits) to the city residents (*Haase et al.* 2014; *Mullaney et al*. 2015). One of the most important services from the viewpoint of the altering climatic background is their climate modification effect. Under Central European climate conditions extreme heat stress at the street level is usually the effect of high solar radiation and the resulting high radiation budget of pedestrians (e.g. *Kántor and Unger* 2011; *Lee et al.* 2014). On the one hand, urban tree stands have many positive impacts on the climatic characteristics and air quality in cities at local scale, for example by the sequestration of carbon dioxide and the removal of various air pollutants, and by reducing stormwater runoff (*Jim and Chen* 2008; *Kirnbauer et al.* 2013; *Nowak et al.* 2013).

On the other hand, vegetation decreases the level of heat stress at micro-scale directly through evapotranspiration and shading (reduction of direct solar radiation). Canopy-shading reduces slightly the near-surface air temperature under the trees (*Abreu-Harbich et al.* 2015; *Coutts et al.* 2016). Compared to air temperature the reduction of the radiation energy income is more important, which entails significant decrease of physiological thermal stress (*Gulyás et al.* 2006; *Kántor et al.* 2016). Shading potential of trees depends on species-related characterisctics (e.g. crown density, leaf area parameters), age and health status of the tree stands. Large differences can be shown in shading efficiency during the vegetion period, depending on the sesonal foliation-defoliation processes (*Takács et al.* 2016a). Even more important differences may exist among various species (*Konarska et al.* 2014; *Takács et al.* 2015c). There is still a lack of information about the species-specific shading capacity of trees. However, broadening the knowledge about these features would help in designing more effective urban green areas.

In line with this general goal, the aim of our study is to determine the solar permeability characteristics of some of the most common urban tree species in Hungary during the whole vegetation period.

We set the specific targets of this study as follows:

- comparison of different tree species regarding their transmissivity, and
- looking for differences between different sized tree individuals belonging to the same species.

These results can be directly integrated into microclimate modeling and small-scale outdoor thermal stress projection. Thus, our investigations provide indirect help for urban designers and landscape architects in the planning of climate-conscious green infrastructure.

4.2. Methods and data

4.2.1. The city of Szeged

In order to achieve the above mentioned objectives, a long-term radiation measurement-series was implemented in Szeged. The city is situated in the southeastern part of Hungary (46°N, 20°E), and can be characterized with a population of about 162,000 and an urbanized area of about 50 km^2. 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 (*Andrade and Vieira* 2007).

The region has a warm temperate climate with uniform annual distribution of precipitation. According to the multi-year (1971–2000) measurement series of the Hungarian Meteorological Service in Szeged the mean annual temperature is 10.6ºC. The daily mean temperature is normally above 10ºC from April to October; these months correspond to the woody vegetation period, and usually this period of the year is regarded to be the most suitable for outdoor activities. The annual amount of precipitation is 489 mm, while sunshine duration approaches 2000 hours per year (*HMS* 2015).

4.2.2. Preparations for the radiation measurements

In Szeged, the first measurement-series on the short-wave radiation-modification effect of urban trees was conducted in 2014. These field surveys lasted from June to November and involved 13 measurement days. Based on the experiences of this 'pilot campaign' (e.g. *Takács et al.* 2015c, 2015b, 2016a), a second measurement-series was implemented in 2015 with more measurement days. In the course of the second measurement campaign we conducted simultaneous measurements with two human-biometeorological stations. One of them was placed under carefully selected urban trees, and the other was placed to an open point of the same study area. That is, the first station stood in the shade while the second instrument was fully exposed to direct solar radiation during the measurement period.

Before the micrometeorological measurement campaign, thorough field surveys were conducted in Szeged aiming to select the appropriate study locations and trees. We sought to represent those species that are frequently planted in Hungarian towns as street or park trees. The main criteria were to find healthy, adult, single shade tree specimens without the disturbing effect of other landscape elements (*Shahidan et al.* 2010; *Konarska et al.* 2014; *Abreu-Harbich et al.* 2015), in order to ensure that other trees or buildings do not influence the recorded parameters. We selected trees that stood in a park or a square with considerable amount of open sunny locations in order to facilitate the nearby ’sunlit’ measurements.

Finally, five specimens that met the above criteria were selected for the purpose of our investigations:

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

The study areas comprised four recreational places in Szeged (Mátyás sq., Búvár lake, Rákóczi sq. and Kodály sq.) (*Fig. 4.1*).

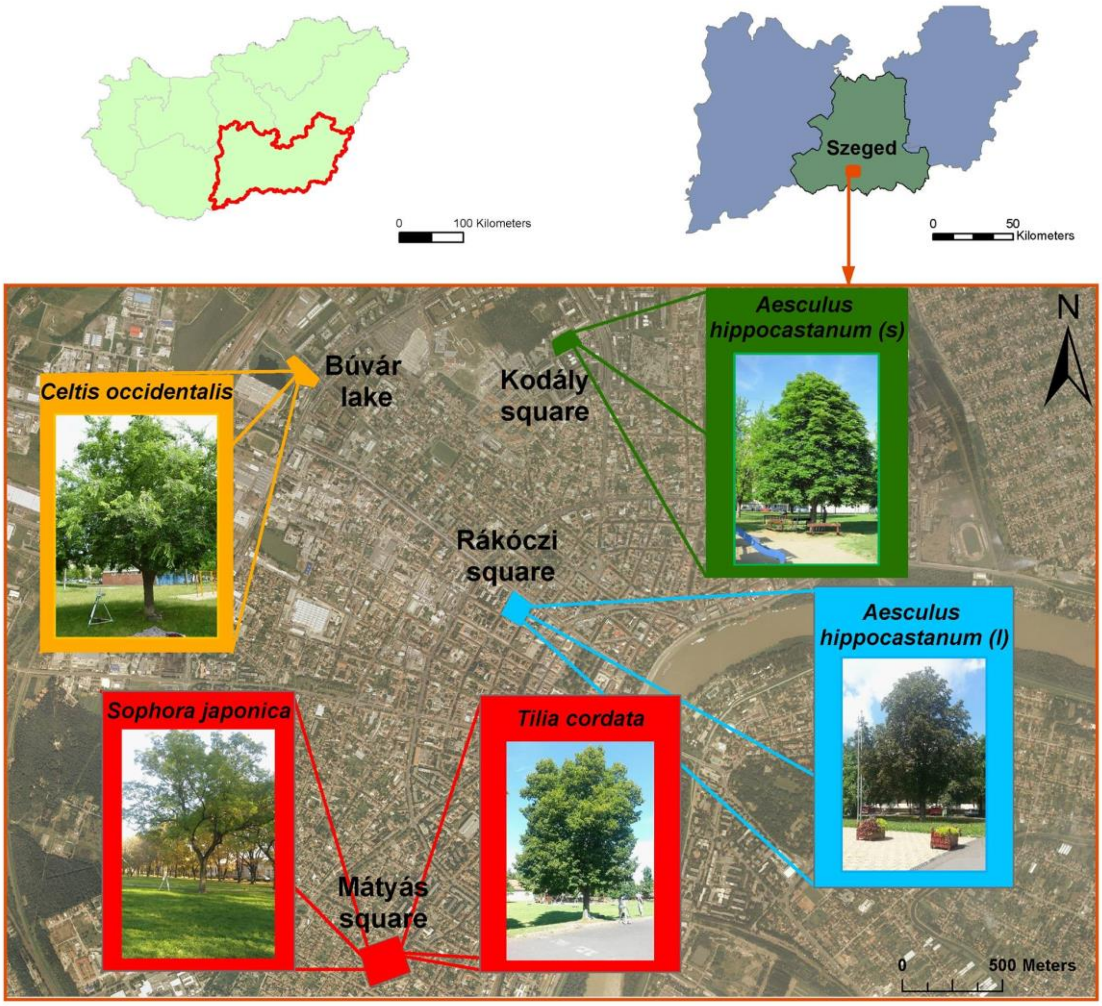

Figure 4.1: Investigated trees and their location in the city of Szeged, Hungary

It should be highlighted that the two *A. hippocastanums* have different dimensional characteristics. One of them has larger full height and canopy diameter while slightly lower trunk height. (This specimen is called hereinafter as ’larger’ and abbreviated as ’l’, while the other specimen is denominated as ’smaller’ or ’s’.) Regarding full height, trunk height and canopy diameter, the *T. cordata* has comparable dimensions with the two *A. hippocastanums*. However, the selected *S. japonica* and *C. occidentalis* have smaller full height but larger canopy diameter than the other species (*Table 4.1*).

Table 4.1: Main dimensional attributes of the investigated urban trees

Species	*Aesculus hippocastanum (l)*	*Aesculus hippocastanum (s)*	*Tilia cordata*	*Sophora japonica*	*Celtis occidentalis*
Full height [m]	15.0	13.5	15.5	12.0	9.0
Trunk height [m]	2.0	2.5	2.5	3.0	1.8
Canopy diameter [m]	10.0	9.0	9.0	12.0	14.0
Trunk diameter [cm]	78.0	57.0	70.5	75.0	70.0

4.2.3. Details of the radiation measurements in 2015

The data collection was carried out with two special human-biometeorological stations, both of them equipped with sensors measuring the same meteorological variables in one-minute resolution. Each day, the instruments were installed 10–20 min prior to the dedicated measurement period in order to allow sensors to stabilize. The stations allow us to record all meteorological parameters that influence the human energy budget (*Takács et al.* 2016d). However, since this study is focusing on the shading capacity of trees, we analyze the changes of one parameter only. This parameter is the global radiation (*G*), which involves the short-wave radiation flux densities from the upper hemisphere and includes both direct and diffuse parts of the soral radiation.

- G_{trans} [W/m^2] is the transmitted solar radiation measured under the selected urban trees, at a distance of two meters on the northern side of the tree trunk,
- G_{act} [W/m^2] is the actual value of global radiation measured at the nearby open site.

Transmissivity – a dimensionless value ranging from 0 to 1 – was calculated as the ratio of the measured *G* values:

$$\text{Transmissivity} = \frac{\text{G trans}}{\text{G act}}$$

G data were recorded by Kipp & Zonen radiometers, i.e. by the upper pyranometers of a CNR 1-type net radiometer in the case of the shaded station and of a CNR 4-type in the case of the sunlit instrument. 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 (*Mayer et al.* 2008; *Lee et al.* 2013, 2014). Following the instructions of the manual of the net radiometers, we took special care about the horizontal levelling and their orientation to South.

The comparability of the two pyranometers was tested on a cloudy and a totally clear summer day. In the frame of the test, both equipment were placed to the sun. The average differences between the measured global radiation values were only 10.14 and 3.8 W/m^2 on the two days, respectively. All data considered, the differences ranged from –35 to 50 W/m^2 and did not exceed 25 W/m^2 in absolute value in more than 80% of the cases.

The radiation measurements lasted from April to October in 2015 and consisted of 36 measurement days, i.e. the campaign covered the whole vegetation period (*Table 4.2*).

Table 4.2: Measurement days in 2015 under the selected tree specimens*

Aesculus hippocastanum (l)	***Aesculus hippocastanum (s)***	***Tilia cordata***	***Sophora japonica***	***Celtis occidentalis***
-	23-Apr-2015	16-Apr-2015	-	-
12-May-2015	18-May-2015	11-May-2015	07-May-2015	06-May-2015
01-Jun-2015	02-Jun-2015	30-May-2015	29-May-2015	28-May-2015 03-Jun-2015
02-Jul-2015	01-Jul-2015	03-Jul-2015	06-Jul-2015	05-Jul-2015
21-Jul-2015	22-Jul-2015	01-Aug-2015	06-Aug-2015	23-Jul-2015
27-Aug-2015	28-Aug-2015	31-Aug-2015	01-Sep-2015	29-Aug-2015
01-Oct-2015	02-Oct-2015	-	-	03-Oct-2015
28-Oct-2015	29-Oct-2015	26-Oct-2015	27-Oct-2015	30-Oct-2015

*Coloured days were selected for the analyses.

4.2.4. Data analysis

This study focuses on the differences regarding the shading-capacity of the investigated trees. For studying the inter-species differences we selected the *T. cordata*, the *S. japonica* and the smaller *A. hippocastanum*. Then we compared the two *A. hippocastanums* in order to examine the impact of mere dimensional inequalities. For these two analyses 20 days were selected from the total 36 measurement days (*Table 4.2*) based on the following aspects.

Inter-species differences were examined only in the hottest period of the year (summer). This comparison was based on the data of days when similar global radiation background was found. (Days close to each other were selected to improve the accuracy of comparison.) One of the main criteria was to select such day-combinations that can be characterized with the least disturbing effect of clouds.

In the case of the larger and smaller *A. hippocastanum*, the comparison period covered almost the whole measurement period (*Table 4.2*). Only three days were excluded: the sole day in April, as well as two days in late autumn due to the disturbing effect of other trees and buildings caused by the low sun elevation. The two *A. hippocastanum* specimens were monitored on consecutive days in almost every case in order to ensure as similar conditions regarding the potential global radiation background as possible. Data analyses were performed within the statistical software SPSS.

4.3. Results

4.3.1. Inter-species differences

One of the specific goal of the study was to explore differences in the solar permeability of different shade tree species during the hottest period of the year. The selected trees include the smaller *A. hippocastanum*, the *T. cordata* and the S. *japonica*; each of them represented with four measurement days in summer (*Table 4.2*). The smaller individual was selected from the two *A. hippocastanums* for the purpose of this comparison since it was monitored more frequently under favorable sky conditions.

Fig. 4.2 illustrates the daily curves of G_{act}, G_{trans} and transmissivity, while *Table 4.3* shows the corresponding descriptive statisctics of daily transmissivity values. It is important to note that the table statistics are based on the data of 'sunny minutes' only, aiming to get rid of the disturbing effect of clouds, which caused sometimes sharp 'apparent transmissivity increases': see for example the cases of July 1 (around 12 am and 1 pm) as well as July 6 (around 1.40, 2.10 and 3.20 pm) when sharp decreases of G_{act} coinciding with moderate decreases of G_{trans} caused smaller or greater jumps in the transmissivity curve (*Fig. 4.2*). Clear sky conditions however can be characterized with smooth, bell-shaped G_{act} curves, and in these circumstances the sharp increases in G_{trans} result in real jumps of transmissivity.

A slight temporal tendency can be observed within the summer period for all species, i.e. the lowest transmissivities were calculated for early or late July, while the highest ones were obtained at the end of August (*Fig. 4.2, Table 4.3*). *S. japonica* had the highest transmissivity in all measurement periods, generally exceeding 0.1, except for early July. According to the obtained transmissivity values, *T. cordata* can be considered to be the most effective shade tree species in the investigation period. In early August, its transmissivity values scattered around 0.04 and for most of the day its G_{trans} values were below 50 W/m^2 (*Fig. 4.2*). Even at the end of August when the compared trees showed the highest solar permeability within summer we measured still fairly low transmissivities, being lower than 0.1 (median: 0.073, mean: 0.088) (*Fig. 4.2, Table 4.3*). Thus, we can set a shading-capacity sequence among the investigated species as follows: *T. cordata*, *A. hippocastanum (s)* and *S. japonica*.

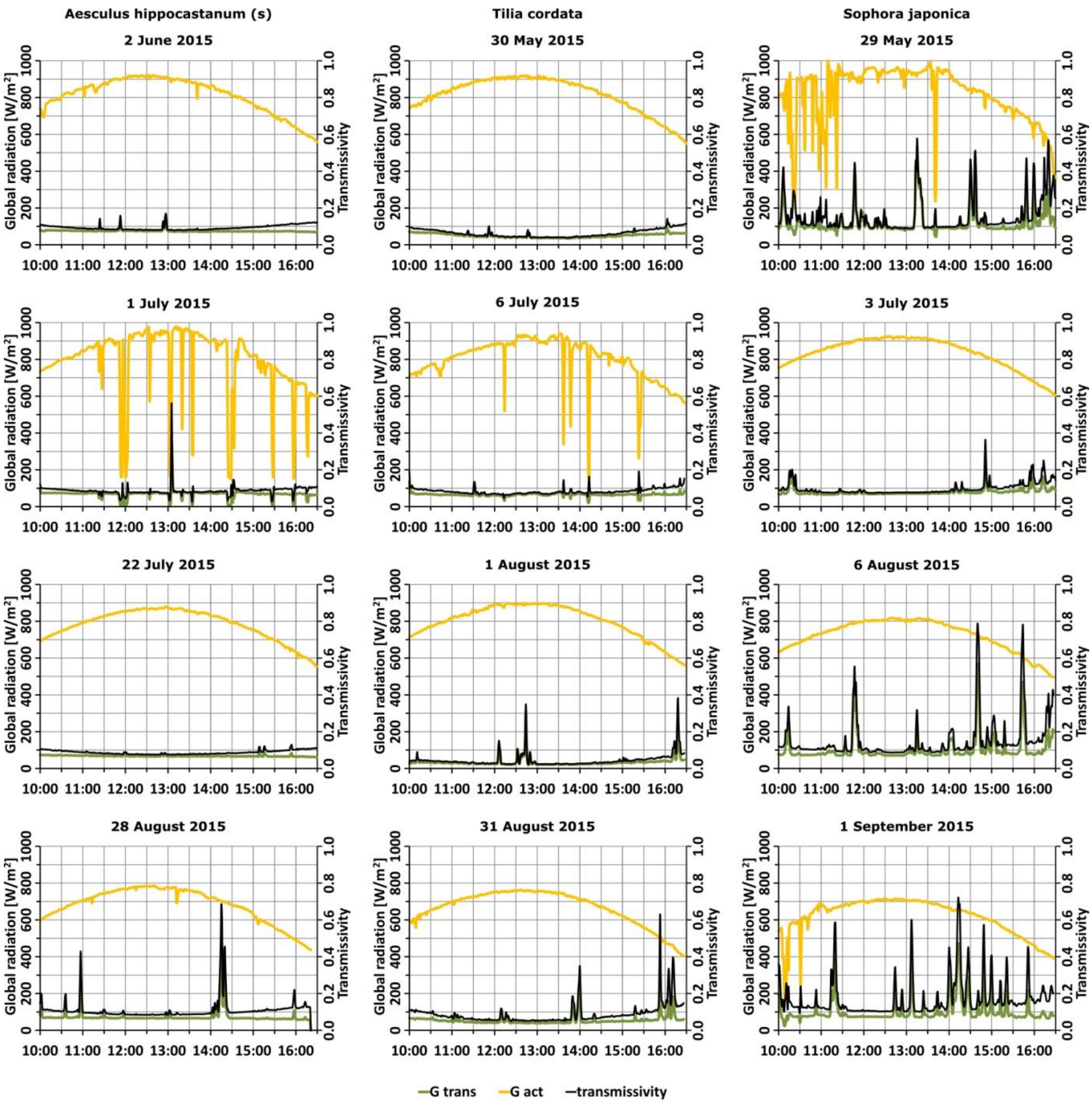

Figure 4.2: Differences in solar permeability in summer through the foliage of three different species: (s) *Aesculus hippocastanum II (s)*, *Tilia cordata* and *Sophora japonica* (time is in CET, G_{act} – actual value of global radiation, G_{trans} – transmitted radiation)

Standard deviation of transmissivity of *S. japonica* approached or exceeded 0.1 in three-quarters of the cases (0.097, 0.107 and 0.104 in May, August and September, respectively), while *A. hippocastanum*'s transmissivity values had the lowest standard deviation (they were between 0.011–0.014 in three days) (*Table 4.3*).

There is an additional feature regarding the transmissivity of lonely shade trees that can be noticed on the charts of *Fig. 4.2*, especially in the cases of *T. cordata*: see that the transmissivity values tend to be the lowest when the global radiation reaches its daily maximum. On the other hand, during the earliest and latest hours of the measurement period, when the bell-shaped G_{act} curve reaches its lowest values, the transmissivity shows a slight but monotonic increase. That is, the rate of decline in global radiation is not followed by the decrase in transmitted radiation. In fact, G_{trans} keeps its level or may be even greater at lower sun elevations because more diffuse radiation may reach the 'shaded pyranometer' from lateral directions at these situations.

Table 4.3: Basic descriptive statistics regarding the transmissivity values of the smaller *Aesculus hippocastanum* (A. h. (s)), *Sophora japonica* (S. j.) and *Tilia cordata* (T. c.) on their investigation days*

Tree	Date	N	Stan. Dev.	Min.	Median	Mean	Max.
S. j.	29-May-2015	345	0.097	0.086	0.113	0.154	0.578
T. c.	30-May-2015	389	0.021	0.038	0.057	0.063	0.141
A. h. (s)	02-Jun-2015	389	0.013	0.079	0.090	0.094	0.169
A. h. (s)	01-Jul-2015	350	0.014	0.057	0.085	0.087	0.269
S. j.	03-Jul-2015	388	0.034	0.074	0.086	0.099	0.364
T. c.	06-Jul-2015	373	0.016	0.047	0.079	0.083	0.191
A. h. (s)	22-Jul-2015	390	0.011	0.075	0.084	0.088	0.128
T. c.	01-Aug-2015	388	0.036	0.022	0.035	0.044	0.386
S. j.	06-Aug-2015	388	0.107	0.086	0.113	0.149	0.785
A. h. (s)	28-Aug-2015	381	0.059	0.083	0.099	0.111	0.686
T. c.	31-Aug-2015	387	0.056	0.051	0.073	0.088	0.634
S. j.	01-Sep-2015	376	0.104	0.101	0.133	0.172	0.722

*The statistics are based on the data of sunny minutes (N) only.

4.3.2. Dimensional differences

Now we are looking for the effectiveness of solar radiation reduction in the light of pure size differences. For this purpose we consider the two *A. hippocastanum* specimens with different dimensional attributes. The daily courses of actual global radiation, transmitted radiation as well as the transmissivity values are depicted on *Fig 4.3*. Besides, *Table 4.4* contains the main descripitive statistics regarding the daily transmissivity values. It should be highlighted again that only those minutes were considered for these statistics that were free from the effects of clouds (see the different case numbers – N – in the table).

The daily curves of actual global radiation reflect the normal seasonal differences occurring in our region: G_{act} approached 1000 W/m^2 in July while it remained below 700 W/m^2 during the autumn days (*Fig. 4.3*).

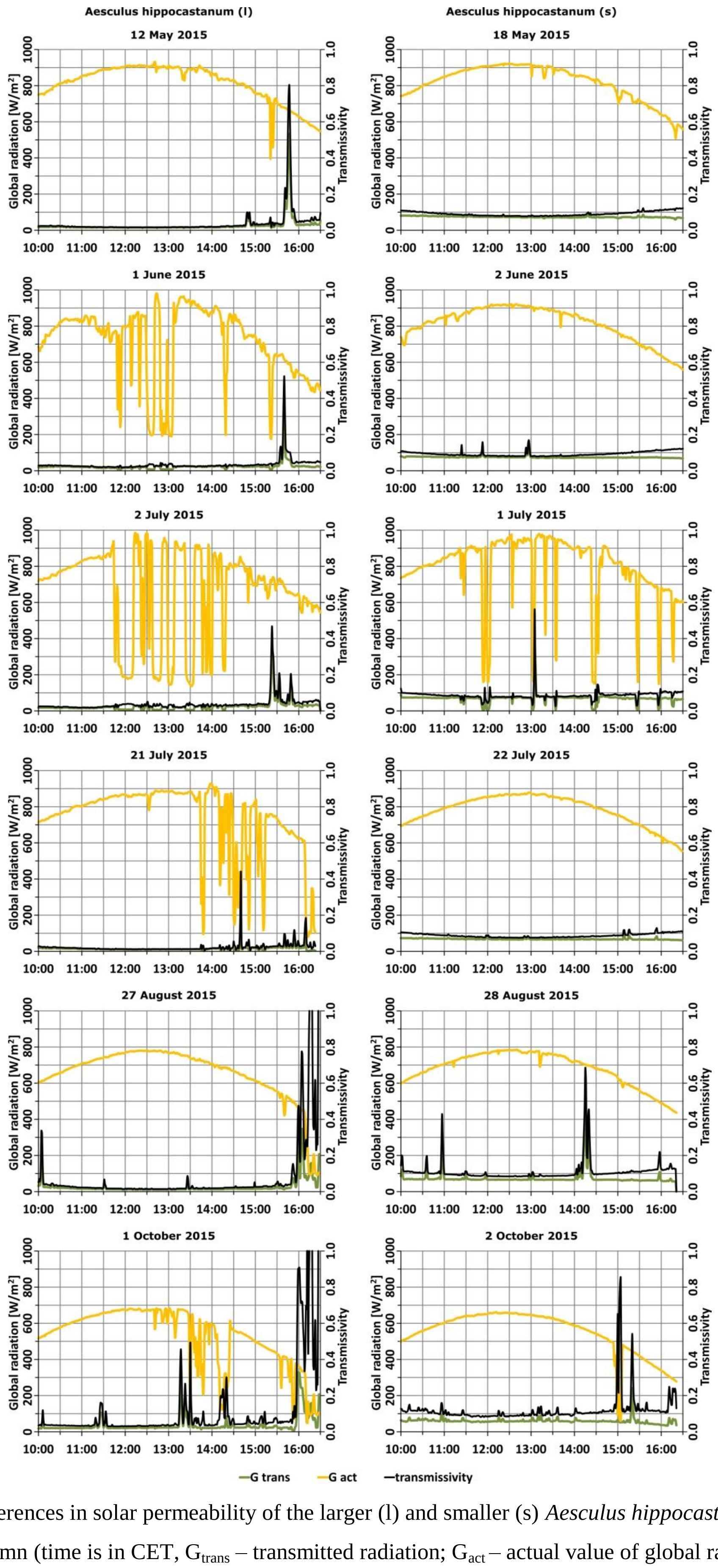

Figure 4.3: Differences in solar permeability of the larger (l) and smaller (s) *Aesculus hippocastanum* from spring to autumn (time is in CET, G_{trans} – transmitted radiation; G_{act} – actual value of global radiation)

Different dimensional characteristics of the investigated specimens affected obviously the solar permeability of the tree crown in the case of each day-pair. Namely, higher transmitted radiation and consequently higher transmisivity values were detected in the case of the smaller *A. hippocastanum* (*Fig. 4.3*). The descriptive statistics in *Table 4.4* confirm this statement: all median and mean transmissivity values were higher under the smaller individual.

The solar permeability showed a decreasing order along the spring and summer months in the case of both trees. In the case of the larger specimen the transmissivity values fell in the range of 0.02–0.04 in spring and they were below 0.02 in mid-summer, while they declined from 0.09 to 0.085 concerning the smaller tree. After that, the transmissivity values started to increase and they peaked in October when the values of the smaller individual often exceeded 0.1 (*Fig. 4.3, Table 4.4*). This phenomenon can be explained obviously by the sesonal foliation status of the trees.

The decline in G_{act} values on cloudy days implies relatively smaller increase in tranmissivity values in summer when transmissivity values are already the lowest. We found comparably high transmissivity values in the case of the larger *A. hippocastanum* at the end of the daily measurement period on the late summer day and the autumn measurement day (*Fig. 4.3*). Accordingly, we got remarkably different median and mean values on these days (median of 0.022 and mean of 0.039 on 27 August, and median of 0.037 and mean of 0.074 on 1 October; *Table 4.4*). Comparing the transmissivity of the two tree individuals based on their daily medians, we found considerably higher values in the case of the smaller specimen (*Table 4.4*), that is, even in the case of adult trees, the dimensional characteristics have a great impact on the shading capacity.

Table 4.4: Basic descriptive statistics regarding the transmissivity of the larger (l) and smaller (s) *Aesculus hippocastanum* (A. h.) trees*

Tree	Date	N	Stan. Dev.	Min.	Median	Mean	Max.
A.h. (l)	12-May-2015	371	0.075	0.014	0.020	0.037	0.801
A.h. (s)	18-May-2015	360	0.012	0.077	0.087	0.091	0.122
A.h. (l)	01-Jun-2015	316	0.042	0.018	0.028	0.037	0.523
A.h. (s)	02-Jun-2015	389	0.013	0.079	0.090	0.094	0.169
A.h. (s)	01-Jul-2015	350	0.014	0.057	0.085	0.087	0.269
A.h. (l)	02-Jul-2015	301	0.045	0.017	0.029	0.040	0.468
A.h. (l)	21-Jul-2015	321	0.013	0.007	0.016	0.019	0.118
A.h. (s)	22-Jul-2015	390	0.011	0.075	0.084	0.088	0.128
A.h. (l)	27-Aug-2015	369	0.081	0.014	0.022	0.039	0.775
A.h. (s)	28-Aug-2015	381	0.059	0.083	0.099	0.111	0.686
A.h. (l)	01-Oct-2015	342	0.130	0.030	0.037	0.074	0.908
A.h. (s)	02-Oct-2015	372	0.039	0.082	0.104	0.111	0.542

*The statistics are based on the dats of sunny minutes (N) only.

Concerning the differences in standard deviation (*SD*) of the two specimens, almost the same *SD* values were observed in late July (0.013 and 0.011; *Table 4.4*). At this time of the year the foliage is expected to be fully developed and most dense. In other days however, the larger individual had considerably higher *SD*. The reason for this can be attributed to the 'regular jump' of the larger tree's transmissivity in the afternoon, which was caused by canopy-structural characteristics (a greater broken off branch).

4.4. Discussion and outlook

Planting and maintaining urban tree stands is one of the most obvious ways to fight against heat stress and to create comfortable outdoor places in urban areas. Vegeation mitigates the level of thermal stress most effectively via shading, i.e. by reduction of incoming short-wave radiation (*Konarska et al.* 2014; *Kántor et al.* 2016; *Takác*s *et al.* 2016a, 2016d). We presented the results of a long-term field measurement series, which covered the whole vegetation period. In line with the primary goal of the sudy, the analyses focused on the shading capacity of single, mature trees belonging to those species that are frequently planted in Hungarian towns as street or park trees. As a measure dimensionless transmissivity values were calculated. We were looking for inter-species differences, and examined the effect of dimensional differences on the shading capacity of mature trees. The resulted graphs (*Figs. 4.2 and 4.3*) revealed that transmissivity is sensitive to the background sky conditions, especially to the rapid changes of sunny and cloudy periods. Therefore, we performed the main descriptive analyses on the basis of clear sky condition values only (*Table 4.3 and 4.4*).

Shading efficiency of urban trees and its variation among different species and seasons can provide useful information with regards to climate sensitive planning and modelling of outdoor thermal comfort in cities (*Konarska et al.* 2014). However, there is still a lack of information in experimental transmissivity data. As an international comparison, *Fig. 4.4* summarizes the outcomes of the available transmissivity studies that have been carried out in different geographical areas. The displayed mean transmissivity values were based on clear (or mostly clear) measurement days in summer – or at least on those days when the investigated trees were fully foliated. (The mean values of the present study were based on the days in *Table 4.3*.) *Fig. 4.4* illustrates great inter-species differences, and evinces the effective shading of *Tilia* and *Aesculus* species.

Besides, similarily to previous investigations (e.g. *Cantón et al.* 1994; *Konarska et al.* 2014; *Takács et al.* 2015c), this study revealed significant annual differences in transmissivity

(*Fig. 4.3*), which depend on the species-specific foliation-defoliation cycle. Due to these findings, application of monthly, or at least seasonally transmissivity values would be required in radiation and bioclimate modelling.

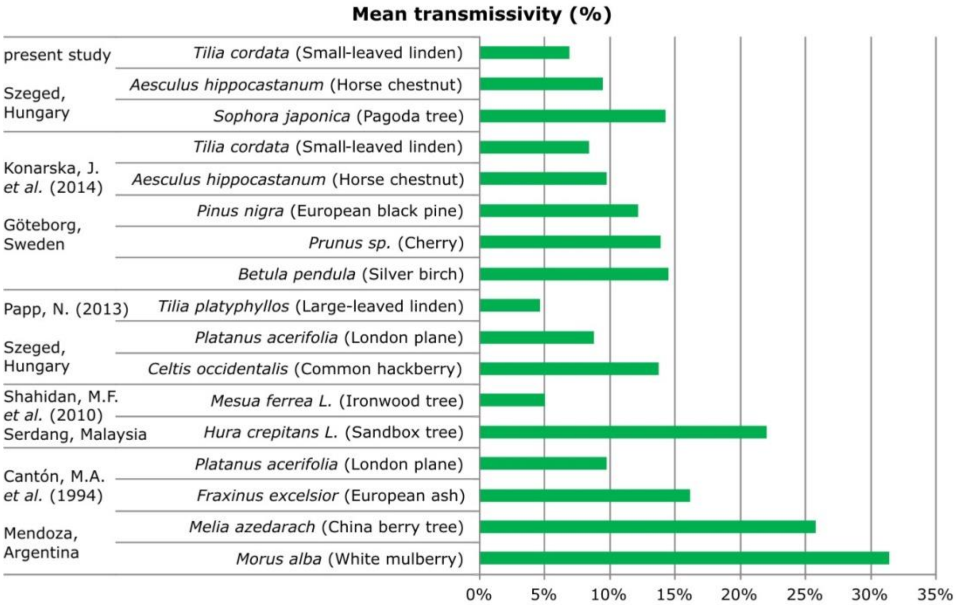

Figure 4.4: Comparison of mean transmissivity values found in different experimental studies

Fig. 4.5 offers a graphical summary about the main findings of this study, including the disturbing impact of clouds on the calculated transmissivity values, the dimension-related effects and the inter-species differences. The chart-montage shows the daily graphs of *S. japonica*, *T. cordata* and the two *A. hippocastanum*s based on the data of four nearby summer days.

The effect of clouds is clearly reflected in the higher and most variable transmitted radiation and thus transmissivity values during the afternoon hours of 21 July (*Fig. 4.5a*). One reason for that may be that the ratio of diffuse radiation (as part of the global radiation) increases at the expense of direct radiation during cloudy conditions. The foliage however is more effective regarding the interception of direct radiation than diffuse radiation (*Cantón et al.* 1994; *Konarska et al.* 2014). In cloudy conditions, the actual value of G may drop because of the decrease of direct radiation, however the diffuse part that is less effectively shielded by tree crown is almost the same. This may result in much greater decrease in G_{act} than in G_{trans}, thus an increase in transmissivity.

The frequency of temporary transmittance of direct radiation through the foliage is a species-related attribute depending on canopy-structural characteristics (*Shahidan et al.* 2010). Of course, if we put species-specific characteristics in the focus of the investigations, it is suggested to analyze a dataset free from the disturbing effect of clouds. Our results confirmed that transmissivity values are more balanced on sunny days, which underpins the necessity of clear days for the more detailed transmissivity investigations focusing on inter-species and canopy-dimensional differences.

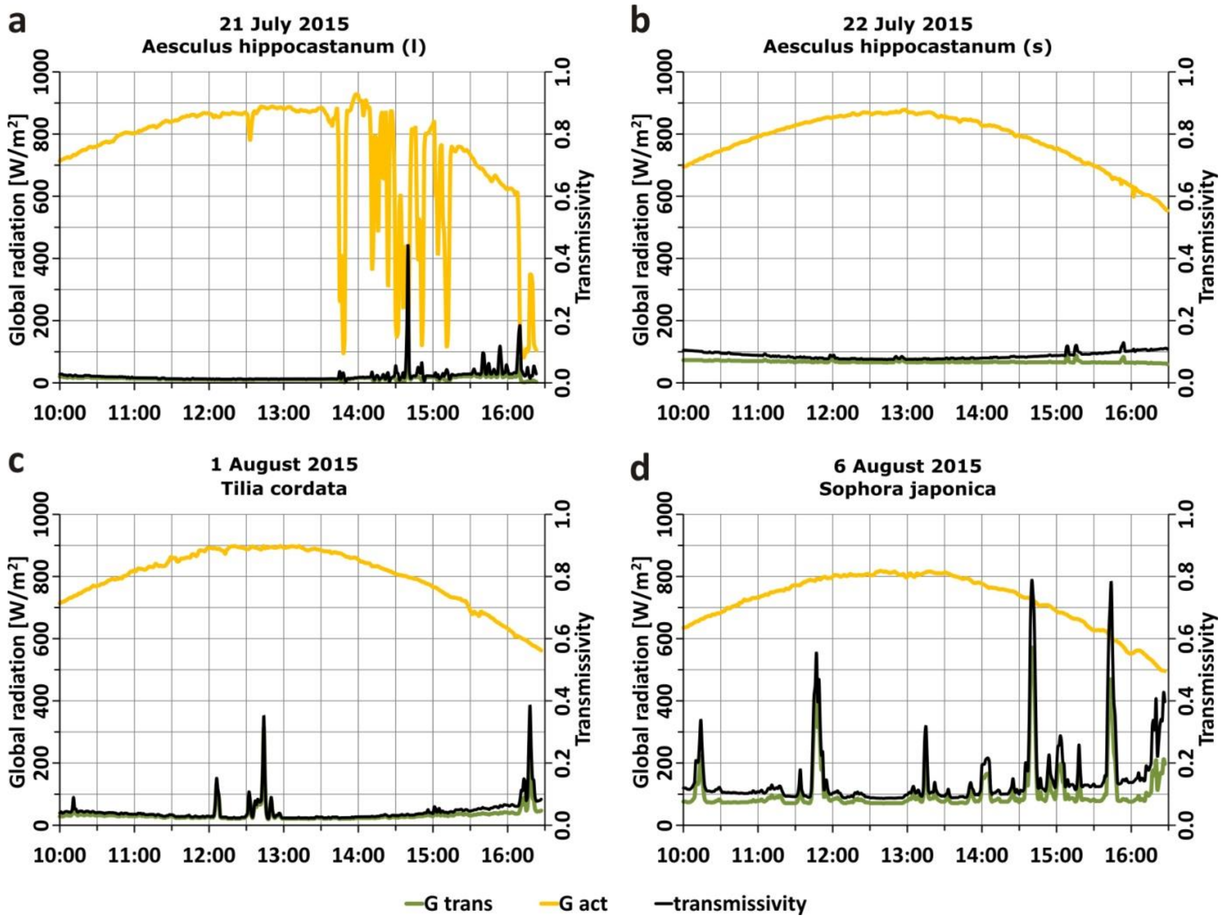

Figure 4.5: Transmissivity and the short-wave radiation from the upper hemisphere measured under different shade-trees as well as in a nearby open point (time is in CET, G_{trans} – transmitted radiation; G_{act} – actual value of global radiation)

The comparison of the results of two *A. hippocastanum* trees provided information on the effect of dimensional differences (*Fig. 4.3, Fig. 4.5a-b*). In the case of the larger individual the lower transmitted radiation values were associated with reduced transmissivity. One reason for this could be the greater crown volume in the large *A. hippocastanum* individual (*Table 4.1*), which implies a longer distance through the canopy that the direct solar beam has to pass, enhancing the foliage absorption therefore lowering G_{trans}. On the other hand, the greater trunk height of the smaller *A. hippocastanum* specimen (*Table 4.1*) connotes that larger amount of diffuse radiation may reach the sensor placed under the tree from lateral directions. Thus, both of these dimensional-related differences allow measuring greater G_{trans} under the smaller *A. hippocastanum* at the same time of the year, provided that both individuals are healthy (*Fig. 4.3, Fig. 4.5a-b*). Increased transmissivity values were found in the case of the larger *A. hippocastanum* at the end of the daily measurment period on the investigation days in late summer and autumn (*Fig. 4.3*). This may be the result of lower sun elevation, cloudy conditions or structural defficiences at certain parts of the tree crown that increased the value of G_{trans} (*Fig. 4.3*).

The remarkable difference between the median and mean values characterizing the transmissivity of the larger *A. hippocastanum* is the consequence of the fact that the arithmetical mean is very sensitive to extremes (*Table 4.4*; *Andrade and Vieira* 2007; *Takács et al.* 2015c). Since tranmissivity may change rapidly and may show some outlier values depending on the slight movements of leaves because of wind as well as the monotonous change in sun elevation and azimuth, we consider it more appropriate to characterize the distribution of transmissivity with the median value.

The obtained inter-species differences (*Fig. 4.2, Fig. 4.4, Fig. 4.5*) in transmissivity may be explained with the characteristics of canopy structure and leaf density (see also *Shahidan et al.* 2010). Due to the dense foliage, there is relatively small and consistent transmitted radiation in the case of *T. cordata,* which results in small transmissivity values. The good shading potential of *Tilia* species was also shown by *Papp* (2013) in Szeged and *Konarska et al.* (2014) in Göteborg, Sweden. On the contrary, we found always higher transmissivity values in the case of *S. japonica* due to its sparse canopy allowing direct radiation to reach the instrument more frequently. This attribute is clearly reflected in the fluctuating G_{trans} and transmissitivity values concerning *S. japonica* (*Fig. 4.2, Fig. 4.5d*).

We consider that the presented measurement method is suitable for gaining generic information about the shading capacity of trees. According to the resulted transmissivity values, the species can be ranked based on their shading capability, and these information are directly usable in the course of green space planning and in selection of appropriate trees.

The obtained results can be used as input data in microclimate simulations to enable more reliable modeling. For example, from the group of tools designed for the assessment of human thermal comfort conditions, SOLWEIG model allows the users to add or change the transmissivity value of the modelled trees. This means that in the course of outdoor space design the effect of altered transmissivity can be evaluated on a territorial basis.

5. 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.

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

5.1. Introduction

In the light of the excessive level of urbanization as well as the predicted effects of climate change (*IPCC* 2014) 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 (*Meehl and Tebaldi* 2004; *Koffi and Koffi* 2008) that will likely lead to increased mortality (*Páldy and Bobvos* 2014; *Rosenthal et al.* 2014), especially among heat-sensitive population groups like infants and elderly people (*D'Ippoliti et al.* 2010; *Xu et al.* 2012). Recent studies report that summertime heat stress may increase much more in cities than in rural and natural areas (*Potchter and Ben-Shalom* 2013; *Zuvela-Aloise et al.* 2015). 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 (*Mayer et al.* 2008; *Erell et al.* 2011). Such strategies, as well as the related local (governmental) decision making, have a significant role in settlement management all over the world (*Birkmann et al.* 2010). The specific steps of their implementation can influence either only the built environment, e.g. through ensuring adequate ventilation (*Ng* 2009), adopting high-albedo materials (*Erell et al.* 2009; 2011), or also the establishment of water bodies (*Sun and Chen* 2012) and the green surfaces through planting and maintaining urban trees and other types of vegetation (*Erell et al.* 2011).

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 (*Erell et al.* 2011). Ecosystem services provided by green areas include, among others, carbon sequestration, energy saving and the recreational value of urban parks as well (*Gómez-Baggethun and Barton* 2013). 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 (*Jim and Chen* 2006; *Buchel and Frantzeskaki* 2015). 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 (*Golicnik and Thompson* 2010; *Kántor and Unger* 2010).

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 (*2013), 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 (*Kandziora et al.* 2013). 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 (*van Oudenhoven et* *al.* 2012). Development of several indicators has been in progress all over the world relating to the investigation of urban ecosystems (*Dobbs et al.* 2011). There are detailed reviews about the usage of indicators developed according to service-categories (*La Rosa et al.* 2016). Other studies assessed several types of services with different indicators (*Breuste et al.* 2013). 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 (*Kohsaka et al.* 2013; *Alam et al.* 2016).

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 (*Schwarz et al.* 2011). Intra-urban differences may be evaluated through Urban Morphology Types (*Cavan et al.* 2014), while Vegetation Structure Types may be useful for small-scale spatial planning (*Lehmann et al.* 2014). Earlier investigations focused primarily on the air temperature reduction capacity of vegetation (see for example the detailed review work by *Bowler et al.* 2010, as well as the works of *Bastian et al.* 2012, and *McPhearson et al.* 2013). 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 (*WHO* 2004; *Mayer* 2008). Earlier studies have demonstrated that the sensitivity of people regarding the different components of outdoor thermal environment is different (*Stathopoulos et al.* 2004; *Kántor et al.* 2012a; 2012b).

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 (*Erell et al.* 2011). It is widely known that vegetation enhances the intensity of evaporation (*Andrade and Vieira* 2007). This intensity can be assessed via remote sensing (*Nouri et al.* 2013) and the evaporative cooling can be calculated through different models (*Vidrih and Medved* 2013). 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 (*Andrade and Vieira* 2007; *Konarska et al.* 2014; *Abreu-Harbich et al.* 2015). It is important to note that the reduced amount of direct radiation under the tree canopy means mitigated thermo-physiological strain (*Streiling and Matzarakis* 2003; *Lee et al.* 2013; 2014).

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 (*Mayer* 2008, *Erell et al.* 2011). 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.

5.2. 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 5.1*). According to *Fábián and Matyasovszky* (2010) 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.

Table 5.1: 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*

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 *Fábián and Matyasovszky* 2010; *Krüzselyi et al.* 2011 and by *Pongrácz et al.* 2013). 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 (*Andrade and Vieira* 2007).

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 5.2*). As basic factors, air temperature – Ta [°C] and relative humidity – RH [%] were recorded under mature urban trees as well as in nearby sunlit sites (*Fig. 5.1*). 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 5.2: Investigated parameters and their relation to thermal discomfort in summertime conditions (based on *WHO*, 2004)

Notation	*Parameter*	*Influence on the thermal budget of the human body, and thus on thermal discomfort*
Ta [°C]	air temperature	High Ta means greater convective heat gain for the human body. The possibility of heat stress and discomfort increases with rising Ta above the surface temperature of the human body (with a typical value of 33°C).
RH [%]	relative humidity	The effect of humidity depends on Ta; in the case of high Ta, 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 Ta 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	

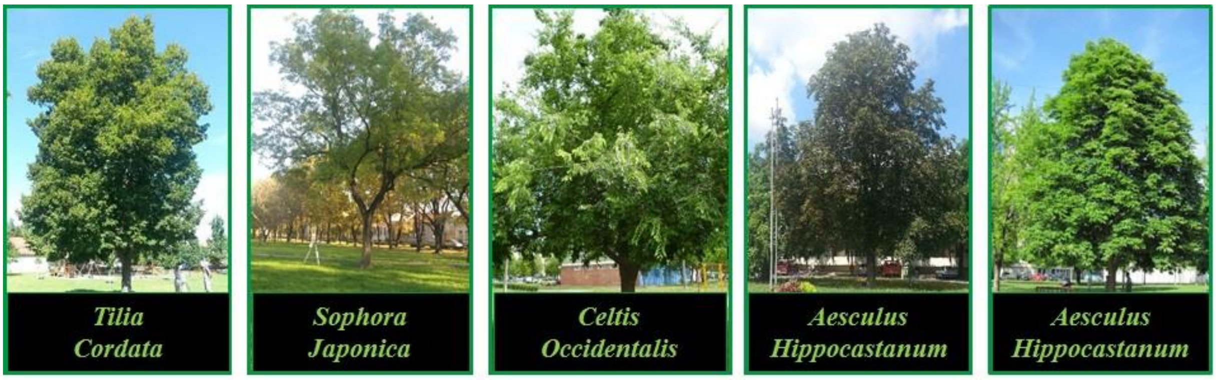

Figure 5.1. Photos about the investigated trees

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 Ta-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.

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 5.2-5.3*). 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 (*Mayer et al.* 2008, *Lee et al.* 2013, 2014). 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 (*Shahidan et al.* 2010; *Konarska et al.* 2014, *Abreu-Harbich et al.* 2015), 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. 5.1, Table 5.3*):

- 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 5.3: 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

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 5.4*).

Table 5.4: 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

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 *Andrade and Vieira* (2007), 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.

5.3. 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 5.5*). However, the strength of the regulation effect differs among the investigated microclimate elements (*Fig. 5.2*).

Fig. 5.2.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. 5.2.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. 5.2.c-f*).

Table 5.5: 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
Ta [°C]	-73.854	0.000	based on positive ranks when 'Ta under tree' > 'Ta 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'

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. 5.2.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. 5.2.d*). However, the absolute value of this modification, i.e. the reduction in reflected radiation is rather small compared to K_u.

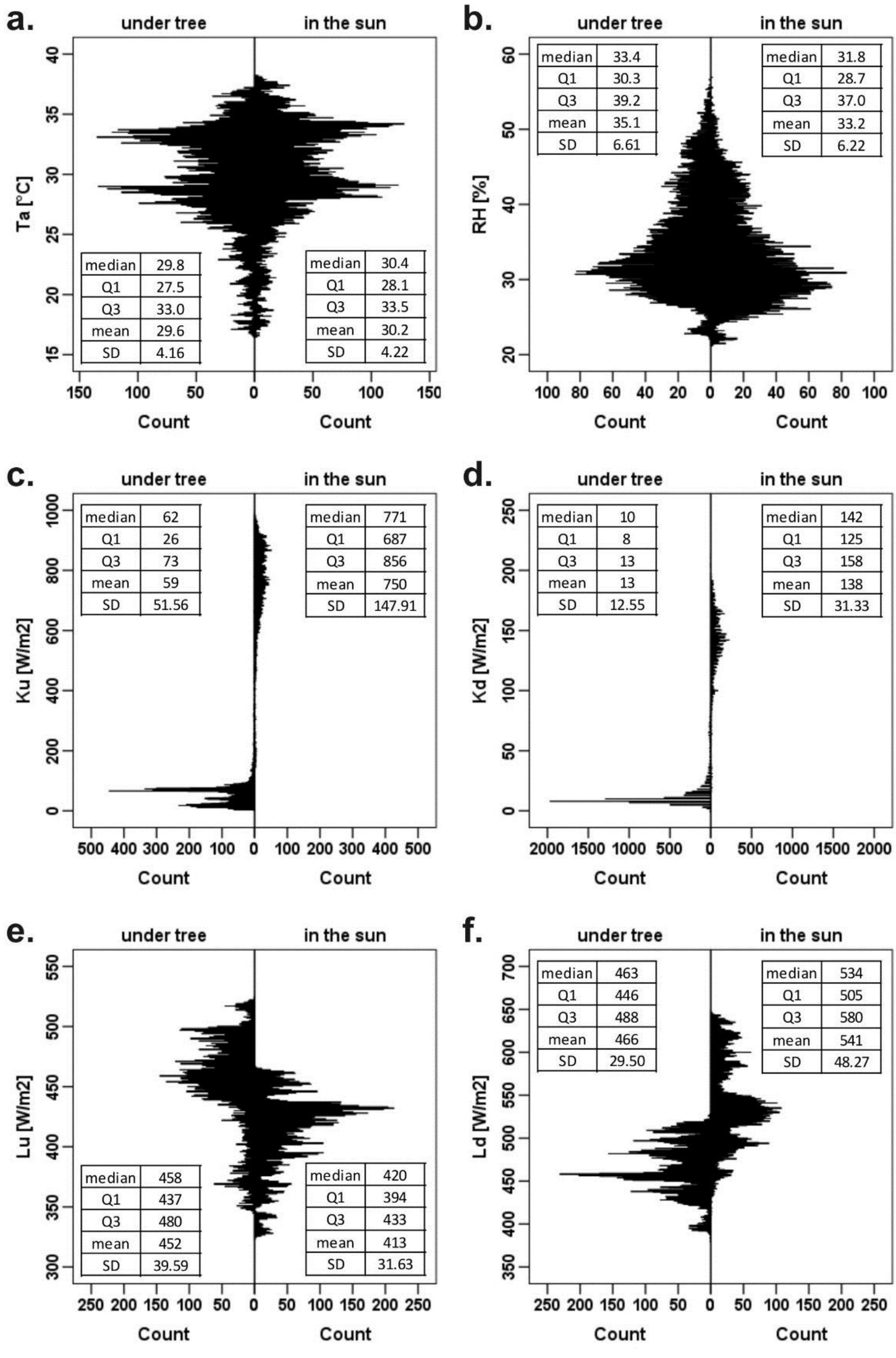

Figure 5.2: Bean plots and the main distributional statistics of the measured parameters under tree and in the sun (Q1: first quartile, Q3: third quartile, SD: standard deviation)

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. 5.2.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. 5.2.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. 5.2.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. 5.3-5.4*). 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. 5.3*). 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 5.3*). 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. 5.3*). 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).

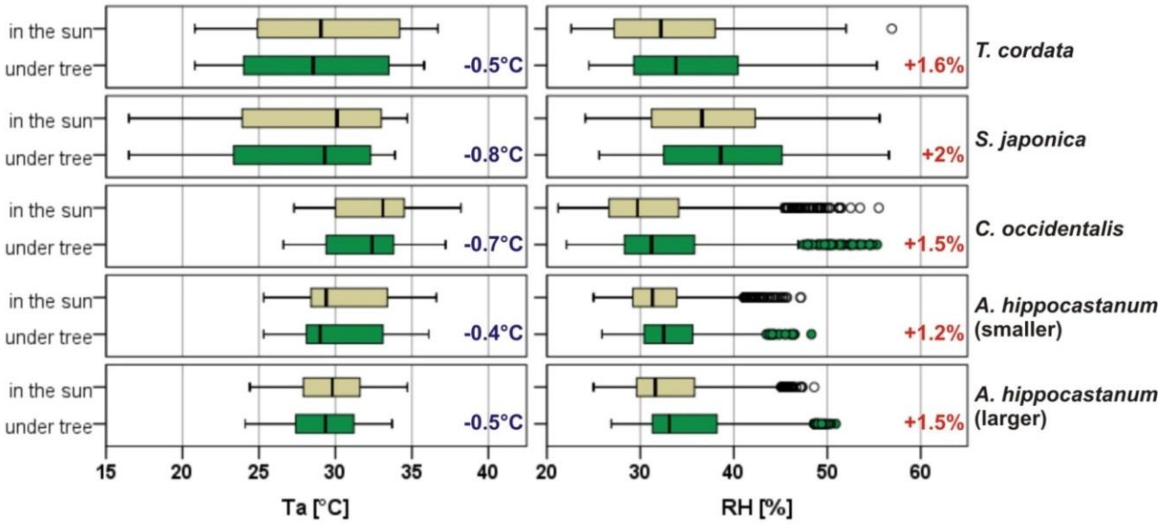

Figure 5.3: Box-plot diagrams of 'under tree' and 'in the sun' air temperature and relative humidity, split by the investigated tree specimens (Blue and red values in the left bottom corner indicate the change of the median values)

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. 5.4.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 5.6*). The IQR range was quite narrow under the trees, indicated by the green boxes on *Fig. 5.4.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. 5.4.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 5.6*).

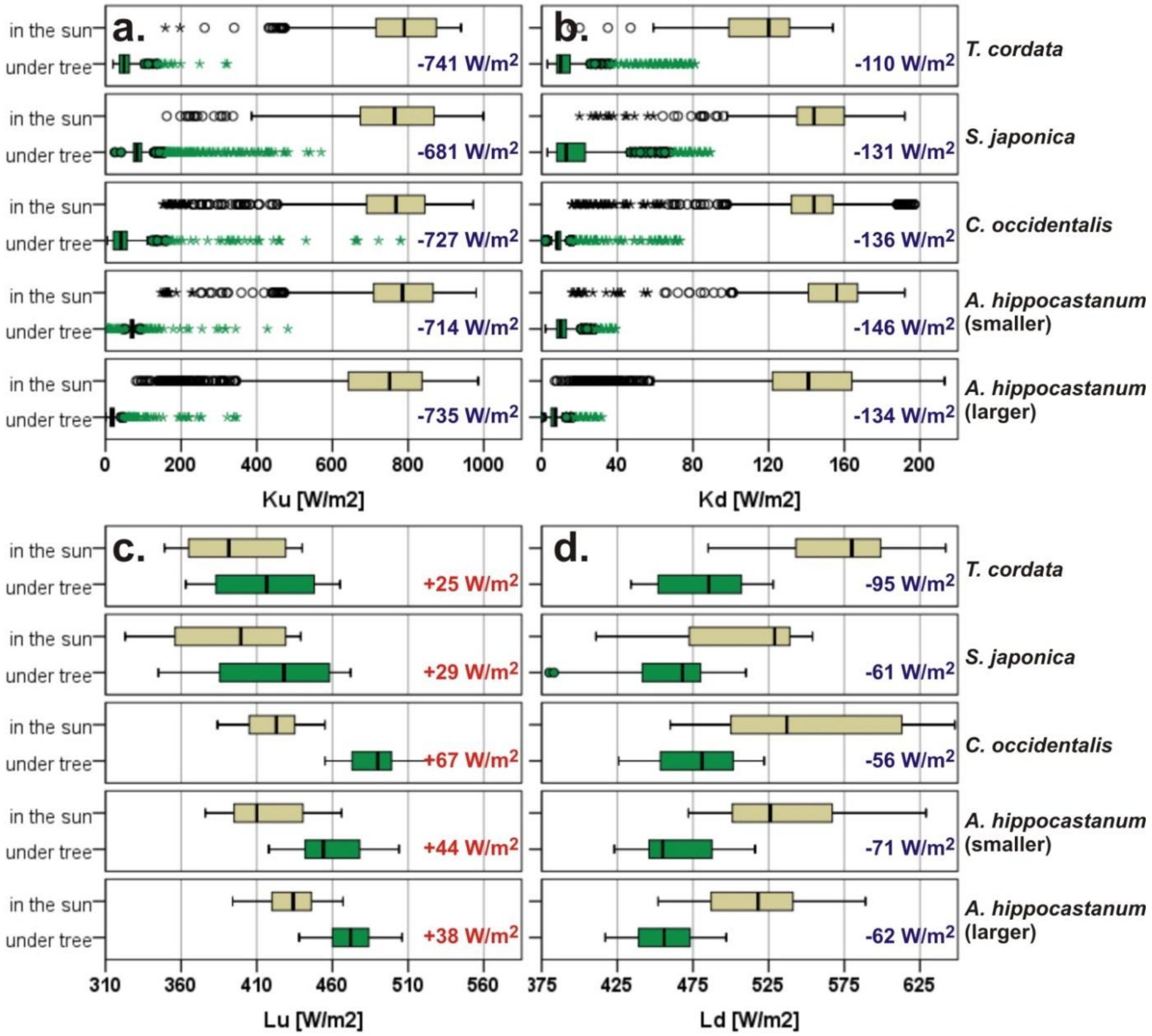

Figure 5.4: Box-plot diagrams of short- and long-wave radiation flux densities from the upper and lower hemisphere under tree and in the sun, split by the investigated tree specimens (Blue and red values in the left bottom corner indicate the change of the median values)

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. 5.4.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 5.3*). 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 5.6, Fig. 5.4.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 5.6, Fig. 5.5.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 5.6, Fig. 5.5.c*).

Table 5.6: 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%

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 5.3*). 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 5.6* 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. 5.5*), and these components were changed by trees only slightly (green markers on *Fig. 5.5*), the relative modification of the radiation Sum is less than 50% (*Table 5.6*).

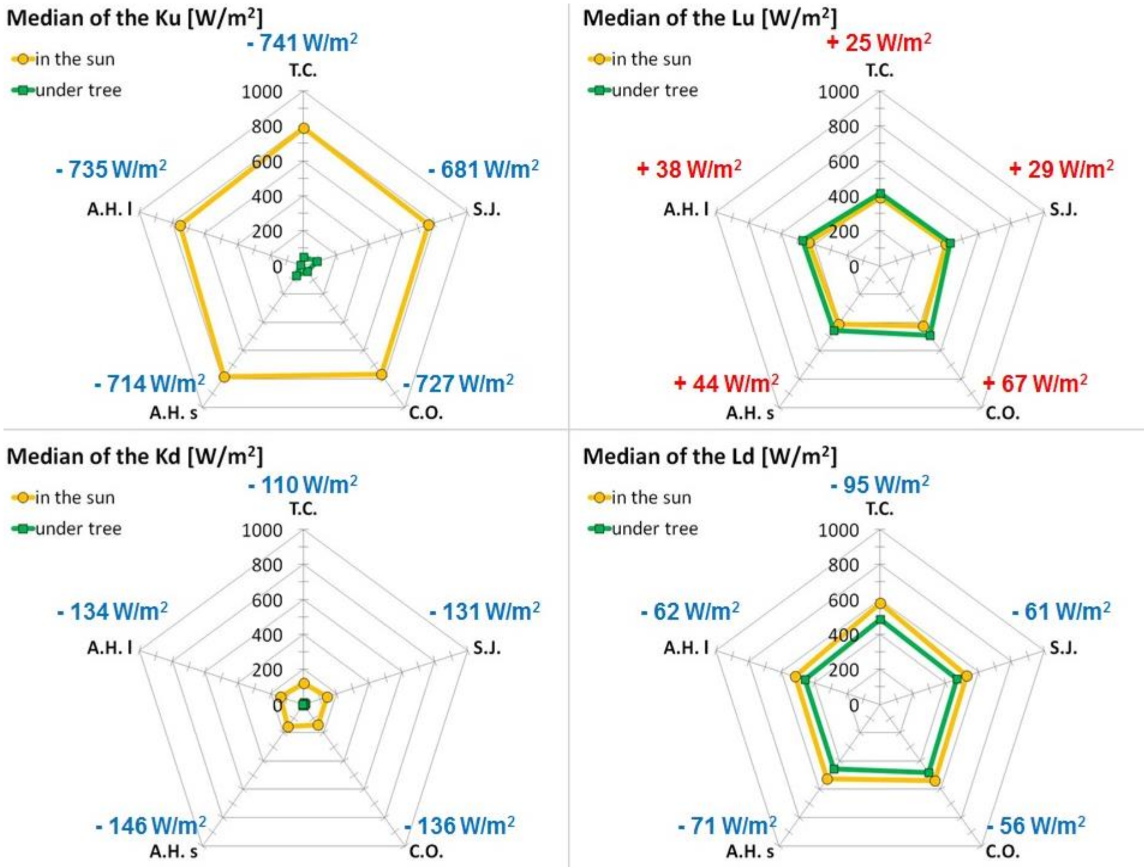

Figure 5.5: Summary about the modification of radiation components by *T. cordata* (T.C.), *S. japonica* (S.J.), *C. occidentalis* (C.O.), and the smaller and larger *A. hippocastanum* (A.H.s, A.H.l)

5.4. 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 Ta-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. *Gulyás and Unger* 2010; *Égerházi et al.* 2013a). 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. *Mayer et al.* 2008; *Lee et al.* 2013, 2014). 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 (*Kántor and Unger* 2011). 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 (*Abreu-Harbich et al.* 2014). *Lindberg and Grimmond* (2011) 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 (*Takács et al.* 2014). 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. *CNT* 2010, *Depietri et al.* 2012), which could be generically used in different climate zones.

6. Summary

The most important results and conclusions are summarized below.

I. Establishment and structural analysis of the tree cadastre of Szeged (*Gulyás et al.* 2015, *Takács et al.* 2015a)**.**

With my participation and coordination, the field surveys carried out between 2013 and 2016 lead to the establishment of tree cadastre of Szeged containing 9870 trees. My dissertation, however, concerns only those 5197 tree specimens which are located in the downtown.

- The surveyed tree stand is very rich in species (110 different species). However, almost 60% of the trees belong to 10 dominant species, and there are 48 species in the database that have less than 5 specimens.
- The native species constitute 43% of the entire stand, mainly from the linden genus (1321 trees). Regarding non-native trees, pagoda tree, common hackberry and golden rain tree (*Koelreuteria paniculata*) are dominant.
- In the surveyed stand, pagoda trees and maple-leaved plane trees (*Platanus x acerifolia*) have the widest trunk diameter almost reaching 50 cm; however, the highest standard deviation was experienced also among them. This is the case regarding common hackberry as well, notwithstanding with a thinner trunk diameter. Silver linden (*Tilia tomentosa*), golden rain tree and flowering ash (*Fraxinus ornus* 'Mecsek') have the thinnest trunk diameter, and standard deviation is the lowest concerning the two latter species.
- The trunk diameter helps to assess the age of the tree, the average age of the stand examined so far is 36 years, and age group of 15-45 years constitutes 66% of the entire stand. Characteristics observed in the trunk of maple-leaved plane tree and pagoda tree allude that the age distribution of the two species is much diversified. This wide diversity characterizes common hackberry, however, the systematic planting of such specie started far later than the above-mentioned two. Only 0.5% of the trees are above age 90, that is to say, the overwhelming majority of the trees of Szeged were planted subsequent to the great flood of 1879.
- The database also reveals that the horse-chestnut trees are in very bad health condition as they were attacked by horse-chestnut leaf miner. Similarly, bad health condition characterizes stands with older age distribution (large-leaf linden (*Tilia*

platyphyllos), maple-leaved plane, pagoda tree), in many cases, the categories regarding the worst health status may be observed. At present, the silver linden stand is the healthiest group that may be due to the young age distribution.

The up-to-date tree cadastre is a significant step towards the tree registry of Hungarian cities required for the effective green area management that is, at the same time, a starting point of further scientific works.

II. A critical review of micrometeorological measurements regarding urban vegetation and improvement of the transmissivity measurement methodology (*Takács et al.* 2015b, 2015c, 2016a, 2016b, 2016c, 2016d)**.**

- Subsequent to analyzing the international studies, it can be assessed that the examinations carried out so far are very heterogenic as far as methodology is concerned. A systematic comparison of international results was hindered by the application of pyranometers with different accuracy and the different measuring design (at single point, at multi point, moving the sensors etc.) or the heterogeneity of reference data (data received from different altitudes). Moreover, there was a study whose methodology could not be reproduced at all. In many cases (9 of the total 14), the international examinations didn't include continuous datasets, hence they were not adequate for characterizing the entire vegetation period. Therefore I have followed my own, preliminarily defined measuring protocol and carried out examinations on multiple days of the vegetation period, mainly on days with clear sky conditions (13 field examination days in 2014 and 36 in 2015).
- Based on the experiences of the 2014 measurements a modification of the transmissivity survey design was necessary in the next year. During the analysis of the 2014 dataset I realized that the global radiation values gained from longer distances (1-2 km) may not be used as reference values for the partly cloudy periods. Namely, in partly cloudy conditions I have detected several times higher radiation values under the trees than the 1-2 km far rooftop reference station. The altered measuring design of 2015 — that is, using both well-equipped mobile stations at the survey area (shaded point and sunny point measurements) — along with more reliable transmissivity values, enabled a multifacedet analysis of the micrometeorological modification effects of single trees as well.

III. Comparison of transmissivity values of common urban tree species and their ranking by shading ability (*Takács et al.* 2015b, 2015c, 2016a, 2016b)**.**

- The apparent increase in transmissivity during the 2014 session due to the frequently cloudy sky conditions and the of rooftop reference pyranometer significantly reduced the number of days with reliable transmissivity values. For the comparison of all four investigated species I necessitated close days with clear sky conditions. I came across such measuring days in 2014 only at the end of September. Common hackberry had the most effective shading with 0.04 median value, followed by the small-leaved linden (0.08), then the pagoda tree (0.13) and finally by the horse-chestnut (0.21). This latter starts fall defoliation the earliest among the investigated species that accords with shading ranking (that is to say, it explains the high transmissivity value). Horse-chestnut is followed by the small-leaved linden and the common hackberry, then finally by the pagoda tree. The high transmissivity value of this latter specie is not related with early defoliation (with the quantity of leaves on the tree), but rather with loose canopy (scarce foliage density).

IV. Significance of seasonal change of foliage regarding transmissivity (*Takács et al.* 2016a, 2016b, 2016c)**.**

As opposed to the tendency of the international studies — transmissivity values for summer or occasionally also for winter were determined for a certain specie generally based on only one specimen and only one measurement day) — my surveys enabled the continuous monitoring of transmissivity during the entire vegetation period.

- Because during the 2014 survey period I had only a few clear-sky measurement day I was able to demonstrate the seasonal effect only in the case of horse-chestnut. Median value of transmissivity with full foliage of the horse-chestnut (July 4, 2014) was 0.033, while this figure was 0.475 on the last measuring day (October 28, 2014) with almost total defoliation.

- The measuring series of 2015 with considerably more clear sky days enabled the continuous monitoring of foliation-defoliation cycle and the corresponding transmissivity changes during the vegetation period in the case of three species: small-leaved linden, pagoda tree and horse-chestnut. In accordance with the totally developed foliage the lowest transmissivity values are measured in the summer, hence shading is the most effective during this period (small-leaved linden: 0.035, horse-chestnut: 0.084 and pagoda tree: 0.113). The spring values of small-leaved linden (0.057) and horse-chestnut (0.090) are a little bit higher than that of the summer, whereas the spring and summer values of the pagoda tree are the same (0.113). Higher transmissivity values are observed in early fall regarding all three species (small-leaved linden: 0.073, horse-chestnut: 0.099 and pagoda tree: 0.133) than in the springtime. The most significant changes were detected concerning small-leaved linden (after foliation: 0.057; summer: 0.035; early fall: 0.073), however, the difference is only a few hundredths.

V. Transmissivity differences of dissimilar specimens (size and age) of the same specie during the vegetation period (*Takács et al.* 2016c)**.**

- Based on the 2015 database, I proved that there are significant differences in transmissivity even among dissimilar entities of the same specie (horse-chestnut). During the vegetation period, the older (larger) tree had lower transmissivity value than the younger (smaller) one. The larger horse-chestnut had a transmissivity of 0.020 in the spring, 0.016 in the summer and 0.037 in late fall, whereas these values were 0.087, 0.084 and 0.104 concerning the younger tree.
- The extent of intraspecies transmissivity difference (due to dimensional dissimilarities) may be compared with the extent of interspecies transmissivity difference (see values in Section IV). Consequently, if transmissivity is attained by measuring under only one tree entity, it may significantly bias the outcome. Hence I highly recommend that future examination shall be based on the measuring under more specimens of the same species, and, as far as it is possible, under entities with "typical size and typical shape". Moreover, my experience also highlights the fact that sometimes the health and development status of a certain tree is more important than its specie.

VI. Highlighting the complex climate-modification effect of urban trees (*Takács et al.* 2016d)**.**

Based on the survey period of 2015, I analyzed the modifying effect of five alone-standing entities (belonging to four species) on air temperature, air humidity and the components of the radiation budget. Survey data included in the analysis were measured under very similar global radiation conditions: in the hottest hours of summer days with clear sky (between 10:00 and 16:00).

- Regarding the temperature modifying effect, the pagoda tree and common hackberry had the best cooling effect (mean temperature was reduced by 0.8 °C and 0.7 °C). This is due to the fact that these trees have the foliage with the widest diameter. Lower cooling potential was observed regarding the small-leaved linden (0.5 °C), the older horse-chestnut (0.5 °C) and the younger horse-chestnut (0.4 °C) that have smaller and narrower crown.
- Regarding air humidity, opposing trends may be detected, and the value of relative humidity slightly rises, systematically, under all five trees. This may be due to the increased evapotranspiration. According to my measuring outcomes, the trees more significantly affect the radiation flux densities (especially global radiation) than the above-mentioned microclimatic parameters. The significant radiation modifying effect may be observed in the transmissivity differences defined in the above section, however, it is more overt by the individual analysis of the radiation components.
- The short wave radiation from upwards (K_u) was significantly lower under the trees regarding all examined species. Based on the results, K_u was reduced by 681 W/m^2 concerning pagoda tree having the highest transmissivity values. The highest reduction was measured in the case of small-leaved linden (741 W/m^2) closely followed by the older horse-chestnut (735 W/m^2), the common hackberry (727 W/m^2) and finally by the younger horse-chestnut (714 W/m^2). The K_u reduction potential of the pagoda tree is certainly a characteristic feature of the specie, namely, the loose foliage and smaller leaves which let sun beams penetrate more than in the case of other species.
- Because of K_u reduction, the short wave radiation from downwards (K_d), that is, the reflected radiation reduced considerably as well. Due to the different surface cover (asphalt), the value is lower (110 W/m^2) regarding the small-leaved linden than the other species situated on green surfaces. The relative K_d modification of shading trees seems to be more effective (decrease by 91–95%) when compared to the values measured under the sun, however, it is only 110–146 W/m^2 in absolute value.
- I observed a noticeably smaller modifying extent regarding long wave radiation components (L_u, L_d). The values of long wave radiation from downward (L_d) was decreased by 95 W/m^2 by the small-leaved linden and 56 W/m^2 by the common hackberry, corresponding to a 16% and a 10% relative reduction, respectively.

- A slight modification (increase) was detected also regarding long wave radiation form upward (L_u). The common hackberry increased L_u by 67 W/m^2, which is due to the wider foliage, more dense foliage structure and the shorter stem height. The pagoda tree has a similar foliage concerning diameter, in turn, it leafy crown is not that dense and it has smaller leaves, hence the increase of long wave radiation form upward was only 29 W/m^2.
- The modifying effect of the foliage on the radiation components is more pronounced (at least 90%) in the short wave radiation spectrum (K_u) than in the long wave spectrum (16% at maximum). This is of high significance as K_u component is to be held the most important regarding the human heat stress in summer.

The outcomes of my research facilitate the better understanding of the complex microclimate modifying effect of woody vegetation in urban environment. They may contribute to the more effective indicator development for analyzing the climate regulation ecosystem services of (single) trees, and may offer help for the climatically more aware public area design and building energetic developments. At present, these data serve as basic data for a building energetic software development that will aid designers to consider the energetic aspects of tree vegetation surrounding the facility in a more sophisticated way.

7. Összefoglalás

Doktori értekezésem zárásaként összegzem munkám fontosabb eredményeit és következtetéseit az 1. fejezetben kitűzött általános célok alapján.

I. Szegedi fakataszter-adatbázis létrehozása és strukturális elemzése (*Gulyás et al.* 2015, *Takács et al.* 2015a).

Részvételemmel, illetve koordinálásommal a 2013-tól 2016-ig terjedő terepi fafelmérések révén a szegedi fakataszter 9870 faegyed adatait tartalmazó adatbázissá bővült. A tudományos értekezésem faállományadatbázis-elemzése azonban csak a belvárosi állományra vonatkozik (5197 faegyedet tartalmaz).

- A felmért faállomány fajösszetétele igen gazdag (110 különböző faj), de az egyedek mintegy 60%-a 10 domináns fajhoz tartozik. Emellett 48 olyan faj van az adatbázisban, amely esetében 5-nél kisebb az egyedszám.
- A feltérképezett egyedeknél az őshonos fajok az egész állomány 43%-át teszik ki, melyek közül a legnagyobb számban a hárs nemzetségből származó egyedek találhatók (1321 példánnyal). A nem őshonos fajok közül a legnagyobb számban a japánakác, a nyugati ostorfa, a bugás csörgőfa (*Koelreuteria paniculata*) egyedei vannak jelen.
- A felmért állományban a legnagyobb törzsátmérővel a japánakác és a juharlevelű platán (*Platanus x acerifolia*) rendelkezik, megközelítik az 50 cm-t, ugyanakkor ezeknél a fajoknál tapasztaltam a legnagyobb szórást is. A nyugati ostorfánál is nagy szórás mutatkozik, kisebb átlagos törzsátmérő mellett. A legkisebb törzsátmérővel az ezüsthárs (*Tilia tomentosa*), a bugás csörgőfa és a gömb kőris (*Fraxinus ornus* 'Mecsek') rendelkezik, a két utóbbi faj esetén a legalacsonyabb a szórás.
- A törzsátmérőből (szakirodalmi adatok alapján) következtetni lehet a fa korára, így ezen adatok alapján koreloszlás-vizsgálatot végeztem. A koreloszlást vizsgálva megállapítható, hogy az eddig felmért állomány átlagéletkora 36 év, a 15–45 éves korosztály teszi ki a teljes állomány 66%-át. A juharlevelű platán és a japánakác törzsátmérőben tapasztalt jellegzetességei arra utalnak, hogy a két faj egyedeinek koreloszlása nagyon diverz. Ugyanez a széles diverzitás jellemzi a nyugati ostorfát is, azzal a különbséggel, hogy a faj szisztematikus telepítése a városban később kezdődött. A jelenlegi adatbázisban az egyedek mindössze 0,5%-a tartozik a 90 év feletti korosztályba, ami arra is utal, hogy város faállománya jórészt az 1879-es árvizet követő újjáépítés után eredeztethető.

- Az adatbázis alapján megállapítható, hogy az egészségi állapot tekintetében különösen rossz egészségi állapotban vannak a vadgesztenyék a nagyarányú vadgesztenyelevél-aknázómoly fertőzöttség miatt. Az idősebb koreloszlású állományoknál (pl. nagylevelű hárs (*Tilia platyphyllos*), juharlevelű platán és japánakác) általában rosszabb az egészségi állapot, több esetben megjelennek a legrosszabb egészségi állapotra vonatkozó kategóriák. Jelenleg a legjobb egészségi állapotú az ezüst hárs állomány, ami részben a fiatal koreloszlásból adódhat.

A naprakész fakataszter nagyon fontos előrelépés a magyarországi nagyvárosok faállomány-nyilvántartásában, mely előfeltétele a hatékony zöldfelületi menedzsmentnek, ugyanakkor fontos kiindulópontja minden további tudományos elemzésnek is.

II. A városi vegetációra vonatkozó mikrometeorológiai mérési módszertan kritikai áttanulmányozása, illetve a városi fafajok transzmisszivitás vizsgálati módszertanának fejlesztése (*Takács et al.* 2015b, 2015c, 2016a, 2016b, 2016c, 2016d)**.**

- A nemzetközi szakirodalmi elemzés alapján megállapítható, hogy a témában eddig végzett mérések módszertanilag igen heterogének. Hátráltatta a szisztematikus összehasonlíthatóságot és elemzést például a különböző pontosságú piranométerek alkalmazása, az eltérő mérési metodikák (egy ponton, több ponton, a műszer mozgatásával stb.) vagy a referenciaadatok heterogenitása (több különböző magasságból származó adat), de előfordult olyan tanulmány is, melynél nem is volt reprodukálható a módszertan. A nemzetközi vizsgálatok sok esetben nem rendelkeznek folyamatos adatsorral (a tanulmányozott nemzetközi példák esetén 14-ből 9), ezért nem alkalmasak a vegetációs periódus teljes időszakának jellemzésére. A reprezentativitás érdekében saját vizsgálataimat ezért a vegetációs időszak több – lehetőleg derült égboltviszonyokkal jellemezhető – napján végeztem el (2014 során 13, 2015 során 36 terepi vizsgálati nap), előre meghatározott mérési protokollt követve.
- Tapasztalataim alapján szükség volt a transzmisszivitás számításához szükséges sugárzási mérési módszertan megváltoztatására. Az első mérési sorozat elemzése közben ugyanis arra a következtetésekre jutottam, hogy a nagyobb távolságból (1-2 km) származó globálsugárzás- értékek nem megfelelően használhatók referenciaértékként, különösen változóan felhős időszakok során. Több esetben

fordult elő ugyanis, hogy a fák alatt magasabb besugárzásértéket detektáltunk, mint az égboltkorlátozástól mentes tetőn. A 2015-ös év megváltoztatott mérési koncepciója – a hitelesebb transzmisszivitás értékek mellett – többrétű analízist tett lehetővé, köszönhetően a helyszínen felállított két mobil állomás azonos és gazdag felszereltségének.

III. Gyakran alkalmazott városi fafajok transzmisszivitás értékeinek összevetése, árnyékolóképesség szempontú sorrend felállítása (*Takács et al.* 2015b, 2015c, 2016a, 2016b).

- A 2014-es vizsgálati periódusban – a gyakori felhősödésből, illetve a tetőn lévő referencia piranométer alkalmazásából adódó – látszólagos transzmisszivitás növekedés jelentősen beszűkítette a hiteles transzmisszivitás értékek kiszámítását lehetővé tevő napok számát. A négy fafaj összevetéséhez megfelelően közel eső, teljesen derült mérési napokra 2014. szeptember végén volt lehetőségem. A legeffektívebb árnyékhatással a nyugati ostorfa rendelkezik, 0,04-es medián értékkel, ezt a fajt követi a kislevelű hárs (0,08), majd a japánakác (0,13), és végül a vadgesztenye (0,21). Az őszi lombhullási sorrendet a vadgesztenye kezdi, mely összecseng az árnyékolási sorrenddel (vagyis megmagyarázza a magas transzmisszivitási értéket), majd a kislevelű hárs és a nyugati ostorfa követi, s végül a japánakác zárja a sort. Ez utóbbi faj nagyobb áteresztőképessége szeptember végén tehát nem a korai lombvesztéssel (vagyis a fán lévő levélmennyiséggel), hanem a levélsűrűséggel van összefüggésben.

IV. A lombkorona évszakos változásának jelentősége a transzmisszivitás tekintetében (*Takács et al.* 2016a, 2016b, 2016c).

A nemzetközi szakirodalomban általában megfigyelhető tendenciával (egy faj – egy egyed – egy napos mérésből származó átlagos transzmisszivitás érték a nyári és esetleg a téli évszakra) szemben mérési eredményeim lehetővé tették a transzmisszivitás folyamatos nyomon követését a teljes vegetációs periódus során.

- A 2014-es méréssorozatban kevesebb mérési napon uralkodtak végig teljesen derült égboltviszonyok, így ekkor csupán a vadgesztenye példáján tudtam szemléltetni a jelenséget. Míg a vadgesztenye lombkoronájának teljesen ép állapotában (2014. július 4-én) a transzmisszivitás értékek mediánja 0,033-nek, addig az utolsó mérési napon (2014. október 28-án), szinte teljes lombhullás esetén 0,475-nek adódott.

- A jóval több derült mérési napot felölelő 2015-ös méréssorozat lehetővé tette a vegetációs perióduson belüli változások folyamatos nyomon követését a kislevelű hárs, a japánakác és a vadgesztenye esetében is. A lombkorona teljes kifejlettségével összhangban, adott faj esetén mindig nyáron mérhetőek a legalacsonyabb transzmisszivitás értékek, vagyis ekkor a leghatékonyabb az árnyékolás (kislevelű hárs: 0,035; vadgesztenye: 0,084; japánakác: 0,113). A tavaszi érték a kislevelű hárs (0,057) és a vadgesztenye (0,090) esetén némiképp nagyobb a nyárinál, míg a japánakác esetén a nyárival azonos (0,113). Ez – tekintetbe véve a tavaszi mérések igen közeli dátumát – a japánakác korábbi lombfakadását bizonyítja. Mind a három faj esetén magasabb transzmisszivitás értékeket figyelhetünk meg kora ősszel (hárs: 0,073; vadgesztenye: 0,099; japánakác: 0,133), mint tavasszal. A három faj közül a legmarkánsabb éves változásokat a kislevelű hárs esetén kaptam (lombfakadás után: 0,057; nyáron: 0,035; kora ősszel: 0,073), de még ez esetben is csupán pár századnyi különbségről beszélhetünk.

V. Egy adott faj eltérő (különböző méretű és korú) egyedei közötti transzmisszivitás különbségek a vegetációs időszak alatt (*Takács et al.* 2016c)**.**

- A 2015-ös mérési adatbázis alapján bebizonyítottam, hogy ugyanazon faj (vadgesztenye) eltérő egyedei között is jelentős transzmisszivitásbeli különbségek mutathatók ki. Az idősebb egyednél a teljes vegetációs időszakban sokkal kisebb transzmisszivitás értékek voltak jellemzők, mint a fiatalabb egyednél. Tavasszal 0,020 értéket mutatott az idősebb egyed, nyáron 0,016 értéket mértem, késő ősszel pedig 0,037-et. A fiatalabb egyednél tavasszal 0,087-es értéket mértem, nyáron 0,084-et, ősszel pedig 0,104-et.
- A fajon belüli (egyedi eltérésekből adódó) transzmisszivitás különbség mértéke összemérhető a különböző fajok közti transzmisszivitás különbség mértékével (lásd IV. tézispontban szereplő értékeket). Ebből kifolyólag, ha a szakirodalomban csak egy faegyed mérési adatainak átlagolásával kapják meg a közölt transzmisszivitás értékeket egy-egy fajra, akkor az nagyban torzíthatja az eredményt. Éppen ezért fontosnak tartom a jövőbeli vizsgálatoknál, hogy minden vizsgált fafaj esetén több „tipikus méretű és tipikus alakú" faegyed alatti mérésre alapuljanak a közölt transzmisszivitás eredmények. Kutatási tapasztalataim emellett arra is rámutatnak, hogy az árnyékot szolgáltató fa fajánál olykor nagyobb jelentőségű az, hogy az illető faegyed egészséges, és kifejlett példány-e.

VI. A városi fák komplex mikroklíma-módosító hatásának kimutatása (*Takács et al.* 2016d)**.**

A 2015-ös felmérési periódus nyári adatbázisa alapján részletesen elemeztem a vizsgált, öt db (négy külön fajba tartozó), magányosan álló faegyed módosító hatását a léghőmérsékletre, légnedvességre, valamint a sugárzási mérleg összetevőire. Az elemzésbe bevont mérések mindegyik fa esetében hasonló globálsugárzási viszonyok között történtek: derült nyári napokon a nap legmelegebb óráiban (10:00 és 16:00 között).

- A hőmérséklet-módosító hatás tekintetében megfigyelhető, hogy a japánakácnak és a nyugati ostorfának a legjobb a hűtőhatása (előbbi esetében a hőmérséklet mediánja 0,8 °C-kal, utóbbi esetében 0,7 °C-kal csökkent). Ennek oka, hogy ezek a fák rendelkeznek a legnagyobb átmérőjű lombkoronával. Kisebb mértékű hűtési potenciált mutatott a kislevelű hárs (0,5 °C), az idősebb vadgesztenye (0,5 °C) és a fiatalabb vadgesztenye (0,4 °C), melyek keskenyebb és kisebb lombkoronával rendelkeznek.
- A légnedvesség esetében a tendenciák épp ellenkezőek, a relatív páratartalom értéke enyhe szisztematikus emelkedést mutat mind az öt vizsgált fa alatt. Ennek oka, a megnövekedett evapotranspiráció lehet.
- Mérési eredményeim bizonyították, hogy a fák az előbbi mikroklíma-paramétereknél jóval nagyobb hatást gyakorolnak a sugárzási fluxusokra (különösen a globálsugárzás értékére). A jelentős sugárzásmódosító hatás az előző tézispontokban megfogalmazott transzmisszivitásbeli különbségekben is jól kirajzolódik, de még szemléletesebb a sugárzási komponensek egyenkénti elemzése esetén.
- A felülről érkező rövidhullámú sugárzás (K_u) minden vizsgált faj esetében szignifikánsan alacsonyabb volt a fák alatt. Az eredmények alapján a legmagasabb transzmisszivitás értékkel jellemezhető japánakác esetében a K_u 681 W/m^2-rel csökkent. Abszolút értékben a legnagyobb csökkenést a kislevelű hárs esetében mértem (741 W/m^2), melyet szorosan követ az idősebb vadgesztenye (735 W/m^2), majd azt követi a nyugati ostorfa (727 W/m^2) és végül a fiatalabb vadgesztenye (714 W/m^2). A japánakác kisebb mértékű K_u- t csökkentő potenciálja minden bizonnyal a fajra jellemző, ritkább lombkorona szerkezettel és a kisebb méretű levelekkel magyarázható.

- A K_u csökkenése következtében az alulról érkező rövidhullámú sugárzás (K_d) mennyisége is csökkent. A kislevelű hárs esetében, az eltérő felszíni borítás miatt (aszfalt) alacsonyabbak az értékek (110 W/m^2), mint a többi vizsgált egyed esetében, melyek a zöldfelülethez köthetőek. Az árnyékoló fák relatív K_d módosítása hatékonynak tűnik (91–95%-os csökkenés) a napon mért értékekhez hasonlítva, azonban abszolút értékben ez csak 110–146 W/m^2 volt.
- A hosszúhullámú sugárzási komponensek esetében (L_u, L_d) jóval kisebb mértékű módosulást tudtam kimutatni. Az alulról érkező hosszúhullámú sugárzás (L_d) értékét a kislevelű hárs 95 W/m^2-rel csökkentette, a nyugati ostorfa pedig 56 W/m^2-rel, ami 16%-os, illetve 10%-os csökkenést jelent.
- A felülről érkező hosszúhullámú sugárzásnál (L_u) valamivel nagyobb mértékű módosítást figyeltem meg. A nyugati ostorfa 67 W/m^2 értékkel növelte L_u értékét, ami a szélesebb fakoronának, a sűrűbb lombkorona-struktúrának, valamint a rövidebb törzsmagasságnak tulajdonítható. A japánakác esetében is hasonló a lombkorona átmérője, viszont a lombozata kevésbé sűrű és sokkal kisebb levelekből áll, így ennél a felülről érkező hosszúhullámú sugárzás növekedése mindössze 29 W/m^2.
- A fa koronájának a sugárzási komponensekre gyakorolt hatása a rövidhullámú tartományban (K_u) nagyobb (legalább 90%), mint a hosszúhullámú tartományban (legfeljebb 16%). Ez azért kiemelten fontos, mert az emberi hőháztartás esetleges felborulásáért is K_u komponens tehető a leginkább felelőssé.

Kutatásaim eredményei lehetőséget teremtenek arra, hogy az eddiginél sokkal pontosabb módon fejezzük ki a városi környezetben a fás vegetáció mikroklíma-módosító hatását. Hozzájárulnak a fák által nyújtott klímaregulációs ökoszisztéma-szolgáltatás elemzésében a hatékonyabb indikátorfejlesztéshez, valamint a gyakorlati tervezés számára nyújtanak hathatós segítséget a klímatudatosabb köztér- és épületenergetikai fejlesztésekhez. Jelenleg például egy olyan épületenergetikai szoftverfejlesztéshez nyújtanak alapadatokat, amely által a tervező árnyaltabb módon veheti figyelembe az épületet körülvevő fás vegetáció energetikai hatását.

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References

Abreu-Harbich LV, Labaki LC, Matzarakis A (2014): Thermal bioclimate as a factor in urban and architectural planning in tropical climate – The case of Campinas, Brazil. *Urban Ecosystems 17*, 489–500.

Abreu-Harbich LV, Labaki LC, Matzarakis A (2015): Effect of tree planting design and tree species on human thermal comfort in the tropics. *Landscape and Urban Planning 138*, 99–109.

Akbari H, Bretz S, Kurn D, Hanford J (1997): Peak power and cooling energy savings of high-albedo roofs. *Energy and Buildings 25*, 117–126.

Akbari H, Menon S, Rosenfeld A (2009): Global cooling: increasing world-wide urban albedos to offset CO_2. *Climatic Change 94*, 275–286.

Alam M, Dupras J, Messier C (2016): A framework towards a composite indicator for urban ecosystem services. *Ecological Indicators 60*, 38–44.

Ali-Toudert F, Djenane M, Bensalem R, Mayer H (2005): Outdoor thermal comfort in the old desert city of Beni-Isguen, Algeria. *Climate Research 28*, 243–256.

Ali-Toudert F, Mayer H (2007): Thermal comfort in an east–west oriented street canyon in Freiburg (Germany) under hot summer conditions. *Theoretical and Applied Climatology 87*, 223–237.

Anda A, Dunkel Z (2000): Agrometeorológia. Egyetemi jegyzet, VE-GMK, Keszthely, 127 p.

Andrade H, Vieira R (2007): A climatic study of an urban green space: The Gulbenkian park in Lisbon (Portugal). *Finisterra 42*, 27–46.

Bajsanski IV, Milosevic DD, Savic SM (2015): Evaluation and improvement of outdoor thermal comfort in urban areas on extreme temperature days: Applications of automatic algorithms. *Building and Environment 94*, 632–643.

Balázs B, Unger J, Gál T, Sümeghy Z, Geiger J, Szegedi S (2009): Simulation of the mean urban heat island using 2D surface parameters: empirical modeling, verification and extension. *Meteorological Applications 16*, 275–287.

Balogun AA, Morakinyo TE, Adegun OB (2014): Effect of tree-shading on energy demand of two similar buildings. *Energy and Buildings 81*, 305–315.

Bastian O, Haase D, Grunewald K (2012): Ecosystem properties, potentials and services – The EPPS conceptual framework and an urban application example. *Ecological Indicators 21*, 7–16.

Berland A, Shiflett SA, Shuster WD, Garmestani AS, Goddard HC, Herrmann DL, Hoptonc ME (2017): The role of trees in urban stormwater management. *Landscape and Urban Planning 162*, 167–177.

Berry R, Livesley SJ, Ayeb L (2013): Tree canopy shade impacts on solar irradiance received by building walls and their surface temperature. *Building and Environment 69*, 91–100.

Birkmann J, Garschagen M, Kraas F, Quang N (2010): Adaptive urban governance: new challenges for the second generation of urban adaptation strategies to climate change. *Sustainability Science 5*, 185–206.

Bowler DE, Buyung-Ali L, Knight TM, Pullin AS (2010): Urban greening to cool towns and cities: a systematic review of the empirical evidence. *Landscape and Urban Planning 97*, 147–155.

Breuste J, Schnellinger J, Qureshi S, Faggi A (2013): Urban ecosystem services on the local level: urban green spaces as providers. *Ekológia (Bratislava) 32*, 290–304.

Buchel S, Frantzeskaki N (2015): Citizens' voice: A case study about perceived ecosystem services by urban park users in Rotterdam, the Netherlands. *Ecosystem Services 12*, 169–177.

Cantón MA, Cortegoso JL, de Rosa C (1994): Solar permeability of urban trees in cities of western Argentina. *Enery and Buildings 20*, 219–230.
Carver AD, Unger DR, Parks CL (2004): Modeling energy savings from urban shade trees: An assessment of the CITYgreen energy conservation module. *Environmental Managment 34*, 650–655.
Cavan G, Lindley S, Jalayer F, Yeshitela K, Pauleit S, Renner F, Gill S, Capuano P, Nebebe A, Woldegerima T, Kibassa D, Shemdoe R (2014): Urban morphological determinants of temperature regulating ecosystem services in two African cities. *Ecological Indicators 42*, 43–57.
Chiesura A (2004): The role of urban parks for the sustainable city. *Landscape and Urban Planning 68*, 129–138.
CNT (2010): Center for neighborhood technology, The value of green infrastructure – A guide to recognizing its economic, environmental and social benefits. http://www.americanrivers.org/wp-content/uploads/2013/09/Value-of-Green-Infrastructure.pdf?506914 (downloaded: 10.09.2015).
Coutts AM, White EC, Tapper NJ, Beringer J, Livesley SJ (2016): Temperature and human thermal comfort effects of street trees across three contrasting street canyon environments. *Theoretical and Applied Climatology 124*, 55–68.
Day SD, Dickinson SB (2008): Managing stormwater for urban sustainability using trees and structural soils. Virginia Polytechnic Institute and State University, Blacksburg, VA, 63 p.
Depietri Y, Renaud FG, Kallis G (2012): Heat waves and floods in urban areas: a policy-oriented review of ecosystem services. *Sustainability Science 7*, 95–107.
Dimoudi A, Nikolopoulou M (2003): Vegetation in the urban environment: microclimatic analysis and benefits. *Energy and Buildings 35*, 69–76.
D'Ippoliti D, Michelozzi P, Marino C, de'Donato F, Menne B, Katsouyanni K, Kirchmayer U, Analitis A, Medina-Ramón M, Paldy A, Atkinson R, Kovats S, Bisanti L, Schneider A, Lefranc A, Iñiguez C, Perucci CA (2010): The impact of heat waves on mortality in 9 European cities: results from the EuroHEAT project. *Environmental Health 9*, 37.
Dobbs C, Escobedo FJ, Zipperer WC (2011): A framework for developing urban forest ecosystem services and goods indicators. *Landscape and Urban Planning 99*, 196–206.
Donovan GH, Butry DT (2009): The value of shade: Estimating the effect of urban trees on summertime electricity use. *Energy and Buildings 41*, 662–668.
Eliasson I, Upmanis H (2000): Nocturnal airflow from urban parks − implications for city ventilation. *Theoretical and Applied Climatology 66*, 95−107.
Erell E, Eliasson E, Grimmond S, Offerle B, Williamson T (2009): Incorporating spatial and temporal variations of advected moisture in the canyon air temperature (CAT) model. Proceedings of ICUC7 - The 7th International Conference on Urban Climate, Yokohama, Japan.
Erell E, Pearlmutter D, Williamson TJ (2011): Urban microclimate: Designing the spaces between buildings. Earthscan, London, 266 p.
Erell E, Pearlmutter D, Boneh D, Kutiel PB (2014): Effect of high-albedo materials on pedestrian heat stress in urban street canyons. *Urban Climate 10*, 367–386.
Égerházi LA, Kántor N, Gál T (2013a): Evaluation and modelling the micro-bioclimatological conditions of a popular playground in Szeged, Hungary. *International Review of Applied Sciennces and Engineering 4*, 57–61.
Égerházi LA, Kovács A, Unger J (2013b): Application of microclimate modelling and onsite survey in planning practice related to an urban micro environment. *Advances in Meteorology*, Article ID: 251586.

Égerházi LA, Kovács A, Takács Á, Égerházi L (2014): Comparison of the results of two micrometeorological models and measurements. *Acta Climatologica Chorologica 47−48*, 33–42.
European Commission (2013): Green Infrastructure – Enhancing Europe's Natural Capital (Communication from the Commission to te European Parliament, the Council, the European Economic and Social Committee nad the Committee of the Regions). European Commission, Brussels.
Fábián ÁP, Matyasovszky I (2010): Analysis of climate change in Hungary according to an extended Köppen classification system, 1971–2060. *Időjárás 114*, 251–261.
Gaskó B (2008): Természettudományi Tanulmányok. Studia naturalia 4. A Móra Ferenc Múzeum évkönyve. Csongrád Megyei Múzeumok Igazgatósága, Szeged.
Gál T, Unger J (2009): Detection of ventilation paths using high-resolution roughness parameter mapping in a large urban area. *Building and Environment 44*, 198–206.
Golicnik B, Thompson CW (2010): Emerging relationships between design and use of urban park spaces. *Landscape and Urban Planning 94*, 38–53.
Gomez-Baggethun E, Barton DN (2013): Classifying and valuing ecosystem services for urban planning. *Ecological Economics 86*, 235–245.
Gulyás Á, Unger J, Matzarakis A (2006): Assessment of the microclimatic and human comfort conditions in a complex urban environment: modelling and measurements. *Building and Environment 41*, 1713–1722.
Gulyás Á, Unger J (2010): Analysis of bioclimatic loads inside and outside the city in a long-term and an extremely hot short-term period (Szeged, Hungary). *Urban Climate News 37*, 11–14.
Gulyás Á, Kiss M, Takács Á, Varga L (2015): Szeged közterületi faállományának vizsgálata. In: *Rakonczai János, Blanka Viktória, Ladányi Zsuzsanna* (szerk.) Tovább egy zöldebb úton: A Szegedi Tudományegyetem Földrajzi és Földtani Tanszékcsoport részvétele a ZENFE programban (2013-2015), Szeged, 67-79.
Haase D, Larondelle N, Andersson E, Artmann M, Borgström S, Breuste J, Gomez-Baggethun E, Gren A, Hamstead Z, Hansen R, Kabisch N, Kremer P, Langemeyer J, Rall EL, McPhearson T, Pauleit S, Qureshi S, Schwarz N, Voigt A, Wurster D, Elmqvist T (2014): A quantitative review of urban ecosystem service assessments: concepts, models and implementation. *Ambio 43*, 413–433.
HMS (2015): Climate characteristics of Szeged. http://www.met.hu/eghajlat/magyarorszag_eghajlat a/varosok_jellemzoi/Szeged/
Hunter Block A, Livesley SJ, Williams NSG (2012): Responding to the urban heat island: A review of the potential of green infrastructure. Victorian Centre for Climate Change Adaptation Research, Melbourne, 62 p.
IPCC (2007): Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 841 p.
IPCC (2014): Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K., Meyer, L.A. (eds.)]. IPCC, Geneva, 151 p. *https://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_SPM.pdf*
Jim CY, Chen WY (2006): Perception and attitude of residents toward urban green spaces in Guangzhou (China). *Environmental Management 38*, 338–349.
Jim CY, Chen WY (2008): Assessing the ecosystem service of air pollutant removal by urban trees in Guangzhou (China). *Journal of Environmental Management 88*, 665–676.

Jim CY (2012): Roadside trees in urban Hong Kong: Part IV: Tree growth and environmental condition. *Arboricultural Journal 21*, 89–99.

Johnston M, Percival G (2012): Trees, people and the built environment. Proceedings of the Urban Trees Research Conference. Forestry Commission Research Report. Forestry Commission, Edinburgh, 268 p.

Kandziora M, Burkhard B, Müller F (2013): Interactions of ecosystem properties, ecosystem integrity and ecosystem service indicators – A theoretical matrix exercise. *Ecological Indicators 28*, 54–78.

Kántor N, Unger J (2010): Benefits and opportunities of adopting GIS in thermal comfort studies in resting places: An urban park as an example. *Landscape and Urban Planning 98*, 36–46.

Kántor N, Unger J (2011): The most problematic variable in the course of human-biometeorological comfort assessment – The mean radiant temperature. *Central European Journal Geosciences 3*, 90–100.

Kántor N, Égerházi L, Unger J (2012a): Subjective estimation of thermal environment in recreational urban spaces – Part 1: investigations in Szeged, Hungary. *International Journal of Biometeorology 56*, 1075–1088.

Kántor N, Unger J, Gulyás Á (2012b): Subjective estimations of thermal environment in recreational urban spaces – Part 2: international comparison. *International Journal of Biometeorology 56*, 1089–1101.

Kántor N, Kovács A, Takács Á (2016): Small-scale human-biometeorological impacts of shading by a large tree. *Open Geosciences 8*, 231–245.

Kántor N, Chen L, Gál CV (2018a): Human-biometeorological significance of shading in urban public spaces – Summertime measurements in Pécs, Hungary. *Landscape and Urban Planning 170*, 241–255.

Kántor N, Gál CV, Gulyás Á, Unger J (2018b): The impact of façade orientation and woody vegetation on summertime heat stress patterns in a Central-European square – comparison of radiation measurements and simulations. *Advances in Meteorology, Article* ID: 2650642.

Kirnbauer MC, Baetz BW, Kenney WA (2013): Estimating the stormwater attenuation benefits derived from planting four monoculture species of deciduous trees on vacant and underutilized urban land parcels. *Urban Forestry & Urban Greening 12*, 401–407.

Koffi B, Koffi E (2008): Heat waves across Europe by the end of the 21st century: multiregional climate simulations. *Climate Research 36*, 153–168.

Kohsaka R, Pereira HM, Elmqvist T, Chan L, Moreno-Peñaranda R, Morimoto Y, Inoue T, Iwata M, Nishi M, Mathias M da Luz, Souto Cruz C, Cabral M, Brunfeldt M, Parkkinen A, Niemelä J, Kulkarni-Kawli Y, Pearsall G (2013): Indicators for management of urban biodiversity and ecosystem services: city biodiversity index. In: Urbanization, biodiversity and ecosystem services: challenges and opportunities. Heidelberg: Springer Netherlands, 699–718.

Konarska J, Lindberg F, Larsson A, Thorsson S, Holmer B (2014): Transmissivity of solar radiation through crowns of single urban trees – application for outdoor thermal comfort modelling. *Theoretical and Applied Climatology 117*, 363–376.

Krüzselyi I, Bartholy J, Horányi A, Pieczka I, Pongrácz R, Szabó P, Szépszó G, Torma Cs (2011): The future climate characteristics of the Carpathian Basin based on a regional climate model mini-ensemble. *Advences in Science and Research 6*, 69–73.

Kuttler W (1998): Stadtklima. In: *Sukopp H, Wittig R (szerk.)* Stadtökologie: Ein Fachbuch für Studium und Praxis. Fischer, Stuttgart.

La Rosa D, Spyra M, Inostroza L (2016): Indicators of cultural ecosystem services for urban planning: A review. *Ecological Indicators 61*, 74–89.

Lee H, Holst J, Mayer H (2013): Modification of human-biometeorologically significant radiant flux densities by shading as local method to mitigate heat stress in summer within urban street canyons. *Advances in Meteorology 38*, 1–13.

Lee H, Mayer H, Schindler D (2014): Importance of 3-D radiant flux densities for outdoor human thermal comfort on clear-sky summer days in Freiburg, Southwest Germany. *Meteorologische Zeitschrift 23*, 315–330.

Lehmann I, Mathey J, Rößler S, Bräuer A, Goldberg V (2014): Urban vegetation structure types as a methodological approach for identifying ecosystem services – Application to the analysis of micro-climatic effects. *Ecological Indicators 42*, 58–72.

Lelovics E, Unger J, Gál T, Gál CV (2014): Design of an urban monitoring network based on Local Climate Zone mapping and temperature pattern modeling. *Climate Reserarch 60*, 51–62.

Lin BS, Lin YJ (2010): Cooling effect of shade trees with different characteristics in a subtropical urban park. *HortScience 45*, 83–86.

Lindberg F, Holmer B, Thorsson S (2008): SOLWEIG 1.0 – Modelling spatial variations of 3D radiant fluxes and mean radiant temperature in complex urban settings. *International Journal of Biometeorology 52*, 697–713.

Lindberg F, Grimmond CSB (2011): The influence of vegetation and building morphology on shadow patterns and mean radiant temperatures in urban areas: model development and evaluation. *Theoretical and Applied Climatology 105*, 311–323.

Loehrlein M (2014): Sustanable Landscaping. Principles and Practicles. Taylor & Francis Group 978-1-4665-9321-3 (e-Book).

Lovell ST, Taylor JR (2013): Supplying urban ecosystem services through multifunctional green infrastructure in the United States. *Landscape Ecology 28*, 1447–1463.

Mathey J, Rößler S, Wende W (2010): Role of urban green spaces for cities under climate change aspects of planning and implementation, UNECE, Prague, 17 p.

Matzarakis A (2001): Die thermische komponente des Stadtklimas. Berichte des Meteorologischeen Institutes der Univerität Freiburg 6, Freiburg, 287 p.

Mayer H (2008): KLIMES – a joint research project on human thermal comfort in cities. *Berichte des Meteorologischen Instituts der Albert-Ludwigs Universität Freiburg 17*, 101–117.

Mayer H, Holst J, Dostal P, Imbery F, Schindler D (2008): Human thermal comfort in summer within an urban street canyon in Central Europe. *Meteorologische Zeitschrift 17*, 241–250.

McPherson E, Nowak D, Heisler G, Grimmond S, Souch C, Grant R, Rowntree R (1997): Quantifying urban forest structure, function, and value: the Chicago Urban Forest Climate Project. *Urban Ecosystems 1*, 49–61.

McPherson EG (2003): A benefit-cost analysis of ten street tree species in Modesto, California, U.S. *Journal of Arboriculture 29*, 1–8.

McPhearson T, Kremer P, Hamstead ZA (2013): Mapping ecosystem services in New York City: Applying a social-ecological approach in urban vacant land. *Ecosystem Services 5*, 11–26.

Meehl GA, Tebaldi C (2004): More intense, more frequent, and longer lasting heat waves in the 21st century. *Science 305*, 994–997.

Mezősi G, Mucsi L, Rakonczai J, Géczi R (2007): A városökológia fogalma, néhány elméleti kérdése. *In: Mezősi G.* (szerk.): Városökológia. Földrajzi Tanulmányok I., JATEPress, Szeged, 9–17.

Mullaney J, Lucke T, Trueman SJ (2015): A review of benefits and challenges in growing street trees in paved urban environment. *Landscape and Urban Planning 134*, 157–166.

Nakaohkubo K, Hoyano A (2011): Development of passive designe tool using 3D-Cad compatible thermal simulation – prediction of indoor radiation environment considering solar shaving by surrounding trees and buildings. In: *Proceedings of Building Simulation*, Sydney, 2711–2717.

Ng E (2009): Policies and technical guidelines for urban planning of high-density cities – air ventilation assessment (AVA) of Hong Kong. *Building and Environment 44*, 1478–1488.

Nouri H, Beecham S, Kazemi F, Hassanli AM, Anderson S (2013): Remote sensing techniques for predicting evapotranspiration from mixed vegetated surfaces. *Hydrology and Earth System Sciences Discussions 10*, 3897–3925.

Nowak DJ, Crane DE, Stevens JC (2006): Air pollution removal by urban trees and shrubs in the United States. *Urban Forestry & Urban Greening 4*, 115–123.

Nowak DJ, Crane DE, Stevens JC, Hoehn RE, Walton JT, Bond J (2008): A ground-based method of assessing urban forest structure and ecosystem services. *Arboriculture and Urban Forestry 34*, 347–358.

Nowak DJ, Heisler GM (2010): Air quality effects of urban trees and parks. National recreation and park association, Ashburn, 48 p.

Nowak DJ, Greenfield EJ, Hoehn RE, Lapoint E (2013): Carbon storage and sequestration by trees in urban and community areas of the United States. *Environmental Pollution 178*, 229–236.

Nowak DJ, Hirabayashi S, Bodine A, Greenfield E (2014): Tree and forest effects on air quality and human health in the United States. *Environmental Pollution 193*, 119–129.

Oke TR (1989): The micrometeorology of the urban forest. Philosophical transactions of the Royal Society of London. Series B, *Biological Sciences 324*, 335–348.

Papp N (2013): A városi fás vegetáció hatása a termikus komfortviszonyokra Szeged példáján (The impact of urban woody vegetation on thermal comfort conditions through the example of Szeged). MS Thesis, University of Szeged, 69 p.

Páldy A, Bobvos J (2014): Health impacts of climate change in Hungary – a review of results and possibilities to help adaptation. *Central European Journal of Occupational and Environmental Medicine 20*, 51–67.

Pearlmutter D, Krüger EL, Berliner P (2009): The role of evaporation in the energy balance of an open-air scaled urban surface. *International Journal of Climatology 29*, 777–789.

Pelzer K, Tam L (2013): 8 shades of green infrastructure. SPUR. http://www.spur.org/news/2013-08-08/8-shades-green-infrastructure

Perrings C, Duraiappah A, Larigauderie A, Mooney H (2011): The Biodiversity and ecosystem services science-policy interface. *Science 331*, 1139–1140.

Péczely Gy (1979): Éghajlattan. Tankönyvkiadó, Budapest, 336 p.

Pongrácz R, Bartholy J, Bartha EB (2013): Analysis of projected changes in the occurrence of heat waves in Hungary. *Advences in Geosciences 35*, 115–122.

Potchter O, Cohen P, Bitan A (2006): Climatic behaviour of various urban parks during hot and humid summer int he mediterranean city of tel Aviv, Israel. *International Journal of Climatology 26*, 1695–1711.

Potchter O, Ben-Shalom HI (2013): Urban warming and global warming: Combined effect on thermal discomfort in the desert city of Beer Sheva, Israel. *Journal of Arid Environments 11*, 113–122.

Robitu M, Musy M, Inard C, Groleau D (2006): Modeling the influence of vegetation and water pond on urban microclimate. *Solar Energy 80*, 435–447.

Ronczyk L, Czigány Sz, Horváth M, Lóczy D (2015): Urban stormwater runoff and pressure on the sewerage system in Pécs, Southwest-Hungary. *CSE Journal City Safety Energy 2,* 32–43.
Rosenthal JK, Kinney PL, Metzger KB (2014): Intra-urban vulnerability to heat-related mortality in New York City, 1997–2006. *Health & Place 30*, 45–60.
Sailor DJ, Hutchinson D, Bokovy L (2008): Thermal property measurements for ecoroof soils common in the western U.S. *Energy and Buildings 40,* 1246–1251.
Saito I (1990-91): Study of the effect of green area on the thermal environment in an urban area. *Energy and Buildings 15*, 493–498.
Schwarz N, Bauer A, Haase D (2011): Assessing climate impacts of planning policies – An estimation for the urban region of Leipzig (Germany). *Environmental Impact Assessment Review 31*, 97–111.
Shahidan MF, Shariff MKM, Jones P, Salleh E, Abdullah AM (2010): A comparison of Mesua ferrea L. and Hura crepitans L. for shade creation and radiation modification in improving thermal comfort. *Landscape and Urban Planning 97*, 168–181.
Shashua-Bar L, Hoffman ME (2000): Vegetation as a climatic component in the design of an urban street – an empirical model for predicting the cooling effect of urban green areas with trees. *Enery and Buildings 31*, 221–235.
Shashua-Bar L, Potchter O, Bitan A, Boltansky D, Yaakov Y (2009): Microclimate modelling of street tree species effects within the varied urban morphology in the mediterranean city of Tel Aviv, Israel. *International Journal of Climatology 30*, 44–57.
Shashua-Bar L, Tsiros IX, Hoffman ME (2010): A modeling study for evaluating passive cooling scenarios in urban streets with trees. Case study: Athens, Greece. *Building and Environment 45*, 2798–2807.
Shashua-Bar L, Pearlmutter D, Erell E (2011): The influence of trees and grass on outdoor thermal comfort in a hot-arid environment. *International Journal of Climatology 31*, 1498–1506.
Spronken-Smith RA, Oke TR (1998): The thermal regime of urban parks in two cities with different summer climates. *International Journal of Remote Sensing 19*, 2085–2104.
Spronken-Smith RA, Oke TR (1999): Scale modeling of nocturnal cooling in urban parks. *Boundary-Layer Meteorology 93*, 287–312.
Stathopoulos T, Wu H, Zacharias J (2004): Outdoor human comfort in an urban climate. *Building and Environment 39*, 297–305.
Streiling S, Matzarakis A (2003): Influence of single and small clusters of trees on the bioclimate of a city: a case study. *Journal of Arboriculture 29,* 309–316.
Sun R, Chen L (2012): How can urban water bodies be designed for climate adaptation? *Landscape and Urban Planning 105*, 27–33.
Taha HG, Akbari H, Rosenfield A (1989): Vegetation canopy micro-climate: A field project in Davis, California. *Journal of Climate and Applied Meteorology*. Lawrence Berkeley Laboratory, Report Number: LBL-24593.
Takács Á, Kiss M, Gulyás Á (2014): Some aspects of indicator development for mapping microclimate regulation ecosystem service of urban tree stands. *Acta Climatologica et Chorologica 47–48,* 99–108.
Takács Á, Kiss M, Tanács E, Varga L, Gulyás Á (2015a): Investigation of tree stands of public spaces in Szeged. *Journal of Environmental Geography 8,* 33-39.
Takács Á, Kiss M, Kántor N, Gulyás Á (2015b): A városi fás vegetáció humán bioklimatológiai jelentősége – gyakori szegedi fafajok árnyékhatásának vizsgálata. In: *Keresztes G.* (szerk.) Spring Wind 2015 Conference book [Tavaszi szél 2015 Konferenciakötet]. Doktoranduszok Országos Szövetsége, Eger, Budapest, 571–587.

Takács Á, Kiss M, Gulyás Á, Kántor N (2015c): Microclimate regulation potential of different tree species: transmissivity measurements in Szeged, Hungary. In: ICUC9 extended abstracts. 9th International Conference on Urban Climate, Toulouse, 6p.

Takács Á, Kiss M, Gulyás Á, Tanács E, Kántor N (2016a): Solar permeability of different tree species in Szeged, Hungary. *Geographica Pannonica 20*, 32–41.

Takács Á, Kiss M, Gulyás Á, Kántor N (2016b): Népszerű városi fafajok árnyékolóképességének vizsgálata Szegeden. *Tájökológiai lapok 14*, 21-32.

Takács Á, *Kovács A, Kiss M, Gulyás Á, Kántor N (*2016c): Study on the transmissivity characteristics of urban trees in Szeged, Hungary. *Hungarian Geographical Bulletin 65, 155-167.*

Takács Á, Kiss M, Hof A, Tanács E, Gulyás Á, Kántor N (2016d): Microclimate modification by urban shade trees – an integrated approach to aid ecosystem service based decision-making. *Procedia Environmental Sciences 32*, 97–109.

TEEB – The Economics of Ecosystems and Biodiversity (2011): TEEB Manual for Cities: Ecosystem Services in Urban Management. www.teebweb.org.

Thorsson S, Lindberg F, Holmer B (2007): Different methods for estimating the mean radiant temperature in an outdoor urban setting. *International Journal of Climatolology 27,* 1983–1993.

Thorsson S, Rocklöv J, Konarska J, Lindberg F, Holmer B, Dousset B, Rayner D (2014): Mean radiant temperature – A predictor of heat related mortality. *Urban Climate 10*, 332–345.

Tyrväinen L, Silvennoinen H, Kolehmainen O (2003): Ecological and aesthetic values in urban forest management. *Urban Forestry & Urban Greening 1*, 135–149.

UN (2014): World Urbanization Prospects: The 2014 Revision, Highlights (ST/ESA/SER.A/352). United Nations, New York, 32 p.

UNFPA (2011): The State of World Population 2011. Report of the United Nations Population Fund. UNFPA, New York, 132 p.

Unger J, Sümeghy Z (2002): Környezeti klimatológia. JATEPress, Szeged, 202 p.

Unger J, Sümeghy Z, Kántor N, Gulyás Á (2012): Kisléptékű Környezeti Klimatológia SZTE TTIK (egyetemi jegyzet), JATEPress, Szeged, 221 p.

van Oudenhoven APE, Petz K, Alkemade R, Hein L, de Groot RS (2012): Framework for systematic indicator selection to assess effects of landmanagement on ecosystem services. *Ecological Indicators 21*, 110–122.

Vidrih B, Medved S (2013): Multiparametric model of urban park cooling island. *Urban Forestry & Urban Greening 12*, 220–229.

WHO (2004): Heat-waves: risks and responses. Health and Global Environmental Change,Series, No 2. WHO Regional Office for Europe, Copenhagen.

WMO (1996): Climatological Normals (CLINO) for the period 1961-1990. WMO/OMM-No 847. Secretariat of the World Meteorological Organization, Geneva, 768 p.

Xiao Q, Mcpherson EG, Simpson JR, Ustin SL (1998): Rainfall interception by Sacramento's urban forest. *Journal of Agriculture 24*, 235–244.

Xu Z, Sheffield PE, Hu W, Su H, Yu W, Qi X, Tong S (2012): Climate Change and Children's Health – A Call for Research on What Works to Protect Children. *International Journal of Environmental Research and Public Health 9*, 3298–3316.

Yang X, Zhao L, Bruse M, Meng Q (2013): Evaluation of a microclimate model for predicting the thermal behavior of different ground surfaces. *Building and Environment 60*, 93–104.

Yu C, Hien WN (2006): Thermal benefits of city parks. *Energy and Buildings* 38, 105–120.

Zhang Z, Lv Y, Pan H (2013): Cooling and humidifying effect of plant communities in subtropical urban parks. *Urban Forestry & Urban Greening 12*, 323–329.

Zuvela-Aloise M, Bokwa A, Dobrovolny P, Gál T, Geletic J, Gulyás Á, Hajto M, Hollosi B, Kielar R, Lehnert M, Skarbit N, Stastny P, Svec M, Unger J, Vysoudil M, Walawender JP (2015): Modelling urban climate under global climate change in Central European cities. *Geophysical Research Abstracts 17*, EGU 2015-1594.