University of Szeged
Doctoral School of Geosciences

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

Summary of PhD Thesis

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1. Introduction

The 21st century brought the spread of cities, the increasing number of city-dwellers and the gigantic transformation of our environment. Nowadays, approximately 51% of the total population lives in cities, that is to say, in urban environment, and this figure has not halted to grow so far. The climate change and the increasing number of city-dwellers worldwide place a heavy burden on both the theoretical urban ecology and the design practice. Consequently, more and more studies reflecting on temporal and spatial processes of the environmental factors are needed. Due to the challenges of global climate change, more and more research focuses on measuring and modeling of phenomena regarding urban climate and on the role of urban vegetation (such as climate modifying effect) to protect and expand green areas.

At the same, however, the complex climate modifying effects of the urban trees under Central European circumstances are still to be unearthed both at local (city, district of a city) and at micro (particular public areas) levels, and no comprehensive Hungarian survey has been carried out so far.

As more and more light is shed on the harmful effects of urbanization and the problem of global climate change, the more and more attention is focused on urban vegetation, more precisely, on the services provided by trees. The comfort level of the urban public areas may significantly be improved and the summer thermal stress may considerably be reduced by the adequate application of tree vegetation (due to their shading and evapotranspiration). Besides the reducing thermal stress, the trees also ease other harmful effects of urban living areas (noise and air pollution), ameliorate urban water balance diminish (reduce flood risk after heavy rainstorms), fix carbon dioxide and emit oxygen. In addition to these direct ecosystem services, the urban vegetation contributes indirectly to the well-being of city-dwellers as well. Since the urban green infrastructure, namely, the woody vegetation, is one of the most multi-faceted factors regarding adaption to the harmful effects of the climate change, studies on this subject has become of significance.

Field surveys on microclimatic effects and numerical models have demonstrated that trees mainly ease the heat stress on the human body via shading. The efficacy of reducing sunshine may be described by foliage transmissivity (solar permeability) that varies not only by species but also by the seasonal change and health condition of the tree crown. The morphological features of a tree (density, closing, size, shape, state and structure of leaves of the foliage) define the actual quantity of sunlight transmitted by the foliage. Trees with wide and low foliage have a not very diversified shade pattern compared to the tall and narrow trees. Leaves are transparent to a certain extent, hence transmit sunlight, whereas twigs and branches are not transparent at all. From perspective of facilitating the design practice, determination of the constantly changing transmissivity values of urban species in accordance with the seasons and the thermal stress reducing capability of certain species would be of significance.

During my research, I studied the micro-meteorological modifying effect, especially, the solar radiation modification of popular Hungarian urban tree species. The methodological experience gained at on-site measuring is hard to find. This is particularly true for long term surveys carried out in several seasons. Such results are scarce even at international level.

<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 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. Databases and research methods

Tree stand surveys

In 2012, the Department of Climatology and Landscape Ecology of University of Szeged (in collaboration with the Environmental Management Office of Szeged) set forth establishing a detailed tree cadastre that, by providing up to date information, facilitates the everyday duties of the maintainer and creates a database that makes the scientific examination of the trees possible. I was able to join such work with multiple tasks (data confirmation and survey of new ones), eventually I coordinated the field works and their registry to the geoinformatics system (Greenformatic).

The surveyed tree stand varies by species and the tree cadastre was of great help to select the species (and survey sites) for the micrometeorological examination to be carried out later.

Micrometeorogical measuring

To calculate the value of transmissivity, I chose four tree species that are popular in urban environment in Central Europe: small-leaved linden (*Tilia cordata)*, pagoda tree (*Sophora japonica)*, common hackberry (*Celtis occidentalis)* and horse-chestnut (*Aesculus hippocastanum)*. Upon selecting the examined trees and study areas, I opted for healthy and well-developed specimens and placed special emphasis to avoid the shading effect of other objects (other trees or buildings) during the measuring period (between 10:00 and 16:00).

To acquire the transmissivity value of the examined trees, the measuring of global radiation (short wave radiation from the upper hemisphere) was required on the one hand below the foliage (transmitted global radiation – G_{trans} [W/m^2]), and, on the other hand, at a nearby site free of sky restrictions (actual value of global radiation – G_{act} [W/m^2]). The field surveys were carried out by two special mobile urban climate stations suitable for bioclimatic experiments owned by the Department of Climatology and Landscape Ecology. The actual value of global radiation was acquired from different sources during the survey series of 2014 and 2015.

During the first series of surveys, I used the global radiation values measured by the pyranometer located on the rooftop of the Ady square –

building of the University of Szeged. This allowed parallel measurements with the two mobile devices under two tree specimens at the same time. However, based on the experience gained in the first year, I had to make changes in my measurement design. Due to the 1-2 km distance between the survey points and the rooftop reference station, the actual value of global radiation might be different at the reference point than above the surveyed trees during cloudy weather. This problem caused sometimes the unexpected raising of the transmissivity values.

In 2015, to acquire more reliable values, I omitted the data measured by the pyranometer located on the rooftop of the university building, and I measured the actual transmissivity at an open point of the surveyed area with high sky view factor on which no shadow was casted during the measurement period. One station was located on a shady site of the area 2 meters north of the tree, whereas the other equipment was placed on a sunny spot.

The devices (Vaisala WXT 520 and net radiometer by Kipp & Zonen) locating at 1.1 and 1.2 m height above ground level recorded the meteorological data (air temperature, relative humidity, wind speed) and the components of radiation budget (short and long wave radiation flux densities from the upper and lower hemisphere) in each minute. The radiometers were faced southward and were leveled. In the basic settings of the net radiometer, one pyranometer and one pyrgeometer detected the short and long wave radiation from the upper hemisphere, while another pyranometer and pyrgeometer carried out the same task from the lower hemisphere. The transmitted radiation data measured by the upper pyranometers were applied when defining the transmissivity values of tree foliages.

For the duration of the series of surveys covering almost one and a half years (between June 2014 and October 2015), I always intended to carry out the measurements during daytime and sunny periods at least once a month in order to capture the effect of the yearly foliation-defoliation cycle as well. I have data for 13 days from 2014 and 36 days from 2015. Unfortunately, it happened very often that the clear sky did not last until the end of measuring hours in the summer of 2014.

For data processing, statistical examination and displaying the results, Microsoft Excel, SPSS Statistics 20, ESRI ArcGIS 10.3 and CorelDRAW X3 software were applied.

Since transmissivity measurements sometimes resulted in very high values (due to the sudden transmission of the direct sunlight for a short time) and the majority of results tended to group around the lower values, I assumed that the usage of percentage values would be more appropriate than the commonly applied arithmetical mean.

3. Results and conclusions

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.

Publications related to thesis

1. ***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.

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

3. ***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.*

4. ***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.

5. ***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.

6. ***Takács Á****, Kántor N, Gulyás Á, Kiss M* (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, 571–587.

7. ***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, 6 p.

8. *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.

Additional relevant publications

1. ***Takács Á****, Gál CV, Gulyás Á, Kiss M, Kántor N* (2017): Radiation conditions at a central European square in a hot summer day – a case study from Szeged, Hungary. In: *97th AMS Annual Meeting and 13th Symposium of the Urban Environment*. Seattle, 1372.
2. *Kántor N, Kovács A,* ***Takács Á*** (2016): Small-scale human-biometeorological impacts of shading by a large tree. *Open Geosciences 8*, 231-245. (IF_{2016}: 0,475)
3. *Kántor N, Kovács A,* ***Takács Á*** (2016): Seasonal differences in the subjective assessment of outdoor thermal conditions and the impact of analysis techniques on the obtained results. *Internacional Journal of Biometeorology 60*, 1615-1635. (IF_{2016}: 2.204)
4. *Kiss M,* ***Takács Á****, Pogácsás R, Berkes L, Gulyás Á* (2015): Klimatológiai vonatkozású városi ökoszisztéma szolgáltatások értékelése Szeged példáján. *Természetvédelmi Közlemények 21***,** 130-138.
5. *Kiss M,* ***Takács Á****, Gulyás Á* (2015): Evaluating climate-related ecosystem services of urban tree stands in Szeged (Hungary). In: *ICUC9 extended abstracts*. 9th International Conference on Urban Climate, Toulouse, 6 p.
6. *Kiss M,* ***Takács Á****, Pogácsás R, Gulyás Á* (2015): The role of ecosystem services in climate and air quality in urban areas: Evaluating carbon sequestration and air pollution removal by street and park trees in Szeged (Hungary). *Moravian Geographical Reports 23*, 36-46. (IF_{2016}: 2.149)
7. *Égerházi LA, Kovács A,* ***Takács Á****, Égerházi L* (2014): Comparison of the results of two microclimatological models and measurements. *Acta Climatologica et Chorologica 47-48*, 33-42.
8. ***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.
9. ***Takács Á****, Tanács E, Kiss M, Gulyás Á* (2014): Urban tree crown projection area mapping with object based image analysis for urban ecosystem service indicator development. In: *Gavril Pandi, Florin Moldovan* (szerk.) Air and Water Components of the Environment. Cluj-Napoca, Románia, 486 p.

In addition, existing urban species structure and composition can help mitigate urban heat islands, and thereby reduce greenhouse gas emissions. However, as climates change, the species composition and structure of urban forests may also change. This presentation will explore existing urban tree composition, species richness, and diversity in several cities; how trees affect urban heat islands; the potential to alter vegetation structure and composition in cities to cool air temperatures and provide other ecosystem services; and the potential effect of climate change on future species tree com University of szeged doctoral school of geosciences investigation of shading efficiency of popular urban tree species based on examples from szeged neÌpszeruÌ‹ vaÌROSI fafajok aÌrnyeÌkoloÌkeÌpesseÌGEÌnek vizsgaÌlata szegedi peÌldaÌk alapjaÌn. 2018. View 1 excerpt. Cites background. Within-Class and Neighborhood Effects on the Relationship between Composite Urban Classes and Surface Temperature. UHI energy efficiency. â€¢ Urban heat island â†' summer heat stress â†' health problems. â€¢ Trying to create a tolerable indoor comfort â†' mechanical cooling â†' drastic increase of electricity-use during the summer period. â€¢ EU aims to mitigate energy consumption in building sector (EPBD recast: nZEB, EED). â€¢ Green Infrastructure development goals (EU Biodiversity Strategy 2020). Analysis. Aims: â€¢ investigate the importance of shading effect of alley trees on indoor thermal comfort â€¢ analyse species-dependence of the effect â€¢ form a base for targeted model development/ adaptation (e.g. i-Tree). Field m