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PASSIVE COOLING POTENTIAL OF ALLEY TREES AND THEIR IMPACT ON INDOOR COMFORT

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Abstract: The significance of vegetable shading is, that it can minimize the risk of overheating and also the negative effects of urban heat island. The aim of the paper is to analyze more precisely the shading effect of alley trees, and their impact on indoor comfort.

The shading efficiency of trees is a species-specific attribute, because of the varying crown structure and leaf density. The analyses aimed the quantification of the transmissivity of characteristic individuals of three frequently planted species. On the base of measured data the cooling load of the buildings and the risk of summer overheating are calculated.

Keywords: Urban microclimate, Indoor comfort, Energetic effects of vegetation, Energy-efficiency

1. Introduction

The negative effects of climate change on human thermal comfort occur heavily in the anthropogenically modified urban environment. Several climatic parameters are influenced by the high proportion of artificial, impervious surfaces, the complex surface geometry, and by the anthropogenic (industry, traffic, heating) heat surplus and air pollutant emissions [1], [2]. One of the climatic parameters is the temperature increase compared to the nearby rural areas, which phenomenon is considered as the Urban Heat Island (UHI) effect [3], [4]. One of its main consequences is the extreme heat stress during the summer period, not only changing the utilization of recreational areas [5], [6], nevertheless increasing mortality in numerous cities around the world [7], [8]. Considering the growth of urban population and the mentioned problems, urban planners have to face the challenge of creating a livable and climate conscious urban environment.

Besides the characteristics of outdoor human thermal comfort the indoor circumstances are also changing in this respect because of the above-mentioned effects. Due to the increased cooling demand of buildings, the phenomena of urban climate have considerable energetic effects as well. The effects of UHI are especially unpleasant in summer, when the heat becomes unbearable for city dwellers. Lately many have decided to install air condition systems in order to create a better indoor comfort. This way of cooling down the indoor areas escalates the heating outdoors and also consumes plenty of energy and money. According to European Union Directive 'Energy Performance of Buildings' by 2020 'nearly Zero Energy Building' should be implemented in the national regulation of all EU countries. The tendency of the last decades showed that energy-efficiency in architecture means a well-insulated and airtight building shell, however these features although provide a good indoor thermal comfort in the wintertime, also increase the risk of overheating during the summer. This leads to the more frequent use of air conditioning devices providing a self-generating process from the urban heat island point of view - what is more - it also increases the energy-consumption during the summer season. In order to achieve a high energy performance architects have to make efforts to improve natural ventilation, evaporative cooling and to achieve energy-efficiency. As it is proved the idea of nearly zero energy building can be put into practice only if the summer cooling demand of buildings can be mitigated at an urban scale.

One of the best solutions for climate sensitive urban design regarding indoor and outdoor thermal comfort and energy-conscious architecture is the application of different types of plants near buildings [9], [10]. The shading effect of tree canopies decrease the solar radiation input. This ameliorates human thermal comfort through the modification of the mean radiant temperature (T_{MRT}), which is one of the most important parameter of thermal sensation. Furthermore, the energy access of walls and windows is decreased as well, modifying the indoor thermal comfort and cooling demand. The near-surface air temperature of shaded places is lower by 0.8-1.7 °C than the ambient air temperature. The T_{MRT} is decreased by a higher extent reaching possibly 15-30 °C [11]. The two main components of evapotranspiration is the direct movement of water from different (soil, water, canopy interception) surfaces (evaporation) and the conversion of water within the leaf to water vapor, released to the atmosphere through the stomata (transpiration). Evapotranspiration has a cooling effect on the leaf and the surrounding microclimate. Evapotranspirative cooling also has an important share in modifying the microclimate near buildings [12]. Urban vegetation, especially trees have several other climate-related ecosystem services. The sequestration of carbon dioxide may be a significant share in the greenhouse gas budget of the city [13], which is to be considered indispensable, regarding the actual policy targets of creating climate-friendly cities. The removal of air pollutants of traffic and industrial origin can be detected in the health state of inhabitants (mortality statistics in particular) and their economic consequences [14]. In those cities where intense rain events occur, a huge amount of water can be intercepted in tree canopies mitigating storm-water runoff and thus help to decrease property damages [15]. Trees and larger green spaces provide aesthetic values and recreational possibilities for the inhabitants. These functions are not easy to quantify, but property value benefits of urban parks can be expressed easily as a monetary value [16]. Targeted models have been developed to evaluate some of these services [17], [18], and the importance of green infrastructure is more and more acknowledged in national and international policy processes. A high number of evaluations plan and planting guides have been published around the world, with emphasis on the multi-functionality of urban vegetation [19], [20], [21]. In 2013, a 'Green Infrastructure Strategy' was approved in the European Union, the referring communication of the Commission ('Green Infrastructure - Enhancing Europe's Natural Capital') propose the incorporation of green infrastructure development goals in planning and development processes.

Climate-related ecosystem services of urban green spaces are highly influenced by the characteristics of the study areas (mainly climatic parameters and the attributes of the dominant species). For that reason, the above-mentioned evaluation methods and models have to be adapted for use in other areas. If building energy and indoor thermal comfort evaluations are aimed adaptation is necessary due to significant differences in building characteristics between countries and geographical regions. There are very little experiences on these effects from the Central Eastern European region. There are numerous published studies worldwide about the effects of different tree species their ability to modify radiation [22], temperature as a consequence of shading [23], [24], and analyzing results of complex measurement campaigns [24]. As the energy budget of buildings is a result of many effects of a complicated system, many studies are carried out with measurements on test walls [25]. In planning-oriented studies model applications are widely used to evaluate the effects of tree shading [26], [27], [28]. By using models with suitable parameters, different types of tree stands on different locations can be evaluated. If the assessment of a larger number of buildings, the evaluation of the shading effect on a wider scale is targeted, empirical, statistical models are used, with the consideration of as many of the influencing factors as possible [29], [30].

There is a lack of knowledge about these effects among the climatic circumstances and building characteristics of Central Eastern Europe. Therefore, the paper presents present the first results of an integrated analysis of some frequent urban tree species in Hungary, from the point of view of indoor thermal comfort effects of vegetable shading. The targeted model-based evaluations need field-based measurements of the main parameters connected with the shading effect. That is why, in the first part of this study, the results of field-based transmissivity measurements in summer are presented, carried out near some real buildings in the downtown area of a Hungarian city.

2. Data and methods

Creating good indoor comfort depends to a great extent on the effectiveness of shading, mitigating the solar access of walls and transparent surfaces. Thus it is an essential issue - regarding the scale of building and plants nearby - to quantify the amount and ratio of the obstructed solar access by the vegetation. In order to be able to make clear the shading effect of often used Hungarian urban trees measurements were carried out in case of three species. The three species analyzed were: *Celtis occidentalis*, *Sophora japonica*, and *Tilia cordata.* All selected trees were in good condition and were typical for their species. In *Table I* some data are to seen about the trees investigated.

Table I

Measures of the trees

	Total height of tree [m]	Height of tree trunk [m]	Radius of canopy [m]	Coordinates	Orientation of wall behind
Celtis occidentalis	15.5	2.4	6.55	46.2601°; 20.1405°	130°
Tilia cordata	9.6	2.3	3.65	46.2577°; 20.1448°	130°
Sophora japonica	8.1	2.4	2.85	46.2607°; 20.1604°	100°

In *Fig. 1* the situation of the three measured trees can be seen. The trees were selected so that the orientation of the façades behind is similar (nearly southwest, with the aim of the longest irradiation that is achievable) and there are no objects to shade the tree during the day (the trees are situated in wide avenues). The distance of the trees and the buildings behind them is identical in the case of *Celtis occidentalis* and *Tilia cordata* - measuring 4.5 meters; in the case of *Sophora japonica* the distance between the wall and the tree is 5.2 m.

a) b) c)

Fig. 1. Pictures of the trees investigated respectively:
a) Celtis occidentalis, b) Tilia cordata, c) Sophora japonica

Fig. 2 shows the positions of the trees in the city centre of Szeged.

Solar irradiance is the most important factor in forming the buildings' microclimate, thus the investigations on the possibilities of natural shading and the measurements of the main parameters describing the effect is one of the main tasks in integral, model-based assessments as well. A simple parameter of the shading performance is transmissivity, which is the ratio of irradiance passing the tree crown to that measured in an un-shaded point. This parameter is frequently used in measurement campaigns and model-based human bio-climatological investigations, referring to horizontal surfaces. However, due to the structure of foliage (which is different in the case of different species), the leaf area index, which is in strong connection with transmissivity, have different values measured vertically or horizontally.

Fig. 2. Map of Szeged with the position of the trees

The measurements were carried out with Kipp&Zonen CNR 1 and 2 pyranometers, in two clear sunny days at every tree species. The instruments were placed at 1 m distance from the wall, at a height of 1.1 m (standard measurement height in human bio-climatological investigations). The measurement design (approximate duration of the measurements, places of instruments) was helped with preliminary modeling of the time course of the shade in Ecotect software, based on size parameters of the trees and on the orientation of the buildings. Transmissivity was calculated from 10 minutes averages of irradiance data.

As described transmissivity data obtained from field measurements were used for further modeling in order to give more general approach of the shading effect of alley trees. Modeling was carried out with Autodesk ECOTECT software. ECOTECT is a sustainable design tool which makes possible a detailed building energy analysis from building to city scale. As ECOTECT is capable for detailed solar simulation too, we found it suitable for our modeling aims.

The main aim of the modeling was to provide more general results about the shading effect of the trees and their impact on the buildings' solar gain. For that purpose it was best to carry out measurements on an ideal model, as the modeling results of the real houses near the examined trees could not show the tendency of the shading effect clearly. The model consists of a cubic room 12 meters long, 6 meters deep and 4 meters high. A perspective view is seen in *Fig. 3.* In the model materials were used, which were similar to the real cases. The wall is a thin brick structure covered with plaster; the windows are single glazed, timber framed window. Although researches have shown the importance of using heavy- or light-weight structures [31], this study focuses on the effect of tree shading

Trees are approximated as nearly spherical polygons, and the transparency of the canopy material is taken from the pyranometer measurements.

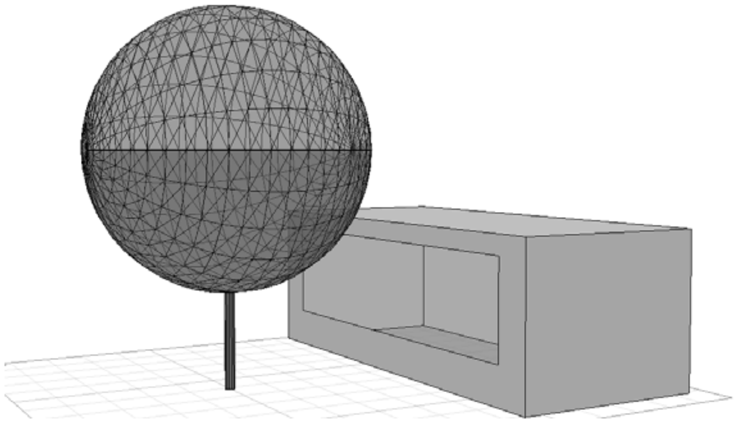

Fig. 3. Perspective view of model made in ECOTECT

Modeling was carried out in summer period. Metrological data were taken from Szeged meteorological center and imported to ECOTECT.

3. Results

Diurnal courses of radiation are presented in *Fig. 4* (shaded and reference point), the mean and standard deviation of the values are shown in *Table II*.

The diurnal course of the radiation values measured in the un-shaded place follow bell-shaped curves, the small drops refer to the short cloudy periods. The variability of the values of transmitted radiation is a consequence of the (species-specific) structure and the movement of the foliage.

As it can be seen in *Fig. 4* the three trees investigated showed a difference in transmissivity. Apart from the evidence that transmissivity's dependence from species, the reason for the difference could be also due to some anomalies in tree condition and dimensions. As the biggest of all studied trees was the Common hackberry (Celtis occidentalis) with thick branches and a rich canopy. Opposite to that the Japanese pagoda (Sophora japonica) was the smallest with loose foliage, which is also very typical for the species. The best transmissivity values were given by the Common hackberry (Celtis occidentalis), and the Japanese pagoda (Sophora japonica) showed the worst shading performance. The transmissivity value of the Small-leaved lime (Tilia cordata) showed to be nearer to the Japanese pagoda (Sophora japonica). Exact results for transmissivity values are seen in *Table II*.

As *Table II* shows different species have a high variability of transmissivity values. Besides the obvious factors of density of the canopy and the leaf area index, tree condition also influences the transmissivity values of the tree.

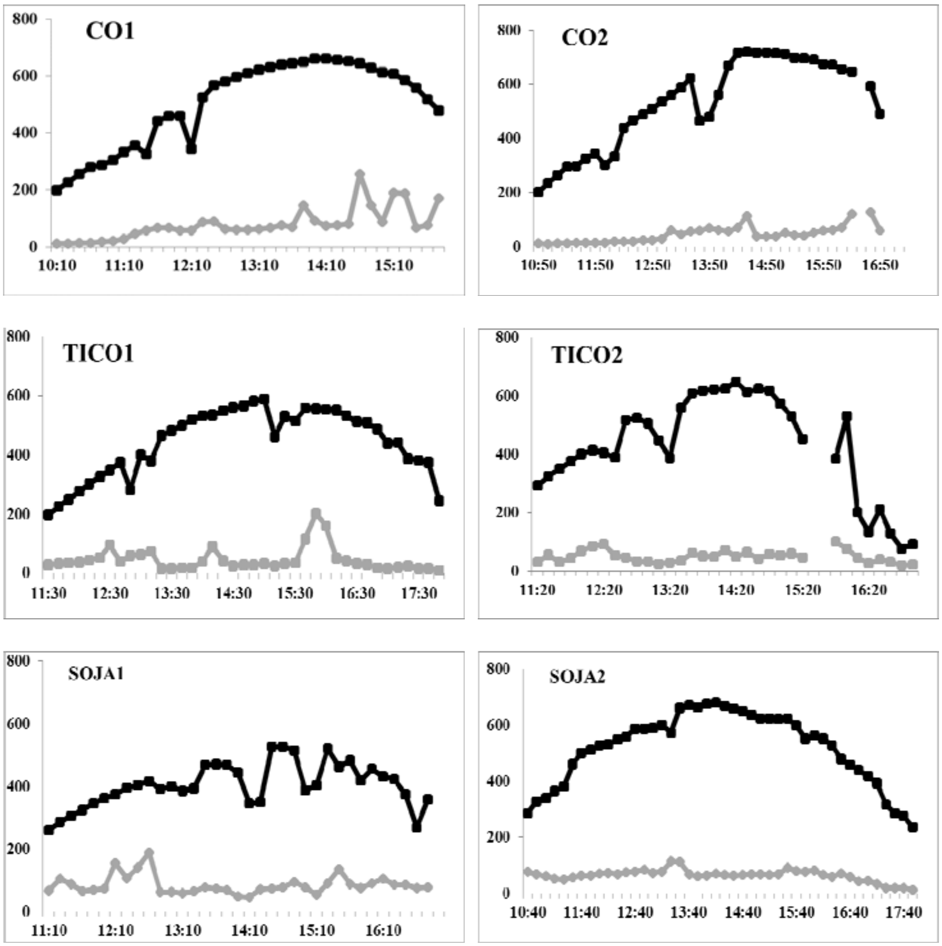

Fig. 4. Course of global solar radiation at non-shaded (reference) and at shaded (below canopy) point of the investigated trees

Table II

Mean (τ) and standard deviation (σ) of the transmissivity of the studied trees

Species	τ (%)	σ (%)
Celtis occidentalis	11.3	7.5
Sophora japonica	16.6	7.6
Tilia cordata	12.0	7.6

As it mentioned, further modeling was carried out in ECOTECT. On the base of the created model severe analysis were carried out in order to investigate the trees' effect on indoor and outdoor climate. The paper focuses on the results of solar analysis, which was carried out for both horizontal and vertical surface (façade). The aim of analysis of solar access on the façade aims primarily to examine how trees - depending on species - mitigate the heating up of building structures. Regarding that mainly solar gain (mainly through transparent structures) is responsible in the risk of summer overheating; the importance of the simulation is obvious.

In the below table (*Table III*) result of the analysis of trees' shading effect on vertical surface is showed. The data are taken from each cell of the analysis grid. Cells are 0.25 x 0.25 m big; the grid covers the whole façade of the model (12 x 4 m). Approximately the 80 per cent of the façade is transparent to be able to show more precisely the shading effect. The horizontal analysis grid is in 1.1 m high above the floor level, which is approximately the height of the head of a sitting person. The next two tables show the results of described model runs.

Table III

Trees' effect on direct solar gain on vertical surface
(daily values, modeling results from ECOTECT)

	Case without tree	Shadowed by Common hackberry	Shadowed by Japanese pagoda	Shadowed by Small-leaved lime
Average	1.98	0.81	1.60	1.49
Minimum	1.72	0.46	1.18	1.05
Maximum	2.00	1.28	1.92	1.90
Rate of reduction in per cent	0%	60%	19.30%	24.80%

The horizontal analysis grid is in 1.1 m high above the floor level, which is approximately the height of the head of a sitting person (*Table IV*).

Table IV

Trees' effect on direct solar gain on horizontal surface
(daily values, modeling results from ECOTECT)

	Case without tree	Shadowed by Common hackberry	Shadowed by Japanese pagoda	Shadowed by Small-leaved lime
Average	0.74	0.52	0.67	0.60
Minimum	0.46	0.46	0.46	0.46
Maximum	1.99	0.97	1.79	1.74
Rate of reduction in per cent	0%	29%	9%	18%

Understanding the results of *Table III* and *Table IV* it comes clear, that trees' impact is more effective on vertical surface than on horizontal. But it is also obvious that the effect of tree shading indoors is not less valuable, than outdoors. The solar gain of a shaded façade can be ~20-60 per cent less, and 10-30 per cent less in case of indoors horizontal surface - depending on species, transmissivity and canopy size. Obstructing solar gain on the façade has especially big importance in case of transparent surfaces (windows). As transparent surfaces highly influence the temperature of indoor thermal environment, the shading effect of a tree can mitigate the risk of summer overheating and energy demand too.

After investigating the mitigation of solar gain in case of each species a further step was to find out changes in indoor temperatures. The simplified model could show the tendency that during the day indoor temperatures are lower, but during the night a slight rise is observable.

Fig. 5 represents indoor temperatures in two cases:

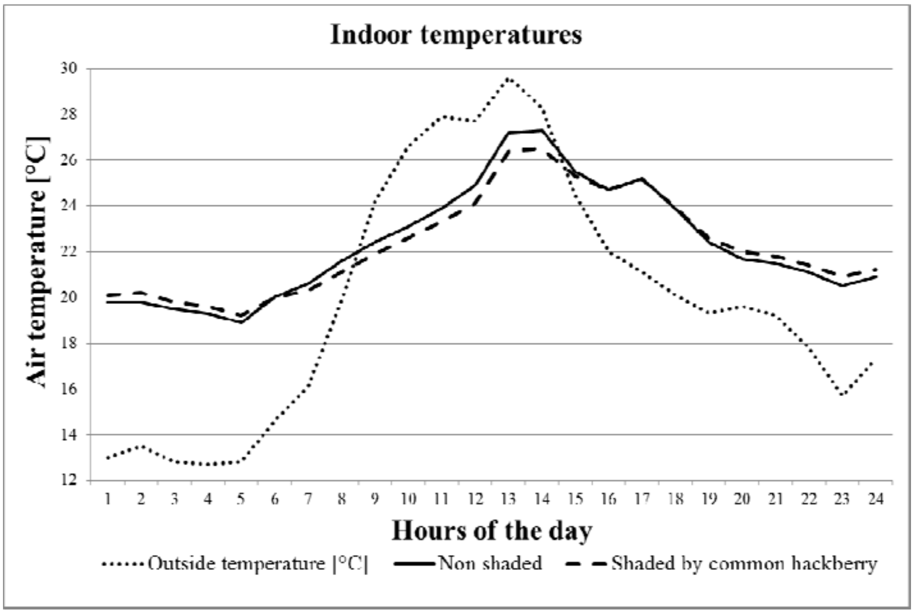

Fig. 5. Indoor operating temperatures on a typical summer day with (solid line) and without (broken line) shading by Common hackberry. Dotted line represents outdoor temperature

The modeling results have shown that on a typical summer day Common hackberry had a bigger shading effect, as in this case a mitigation of indoor temperature of 0.6°C was observed. In the case of Small-leaved lime and Japanese pagoda the mitigation of indoor temperature were 0.3 and 0.2°C respectively. These values can vary if other structure is used, but the tendency shows, that the effectiveness of shading depends not only on the transmissivity but also on the diameter of the canopy.

Concluding can stated, that the measurements and modeling could prove that the shading effect of trees have a major impact not only on outdoor but also on indoor comfort. Modeling has shown that trees can indeed improve indoor comfort. Further modeling is planned in order to give more precise results of shading effect of each species. An important result of our investigation is that with the usage of vegetation a better indoor comfort can be created in summer and this is a non-mechanical way to cool building surfaces.

4. Conclusion

The study described the investigations and their first results of street trees on indoor thermal comfort, for frequently used tree species and building characteristic of Central Europe. The main focus of our study was the shading effect, for which its main indicator, the transmissivity was investigated. Based on the results of the field measurements, that transmissivity is characterized with a very high variability, as a consequence of the structure of the crown and weather circumstances. Meanwhile, clear differences could be observed between species in terms of average transmissivities, the species with worst shading potential was Sophora japonica, the best shading potential was observed at Celtis occidentalis. In the second part of the study, the effects of these differences were investigated in terms of differences in irradiation on model buildings. These effects were also found to be quite considerable, though the indoor comfort conditions are obviously also affected highly by the physical characteristics of buildings. To aid planning and decision-making on different levels, further targeted investigations are needed.

References

[1] Unger J. Urban-rural air humidity differences in Szeged, Hungary, *International Journal of Climatology,* Vol. 19, 1999, pp. 1509–1515.

[2] Liu W., You H., Dou J. Urban-rural humidity and temperature differences in the Beijing area, *Theoretical and Applied Climatology,* Vol. 96, 2009, pp. 201–207.

[3] Unger J. Heat island intensity with different meteorological conditions in a medium-sized town: Szeged, Hungary, *Theoretical and Applied Climatology,* Vol. 54, 1996, pp. 147–151.

[4] Rozwan A. M., Dennis L. Y. C., Liu C. A review on the generation, determination and mitigation of urban heat island, *Journal of Environmental Sciences,* Vol. 20, 2008, pp. 120–128.

[5] Kántor N., Égerházi L., Unger J. Subjective estimations of thermal environment in recreational urban spaces, Part 1, Investigations in Szeged, Hungary, *International Journal of Biometeorology*, Vol. 56, 2012, pp. 1075–1088.

[6] Kántor N., Unger J., Gulyás Á. Subjective estimations of thermal environment in recreational urban spaces, Part 2, International comparison, *International Journal of Biometeorology*, Vol. 56, 2012, pp. 1089–1101.

[7] Smargiassi A., Goldberg M. S., Plante C., Fournier M., Baudouin Y., Kosatsky T. Variation of daily warm season mortality as a function of micro-urban heat islands, *Journal of Epidemiology and Community Health,* Vol. 63, 2009, pp. 659–664.

[8] Tan J., Zheng Y., Tang X., Guo C., Li L., Song G., Zhen X., Yuan D., Kalstein A. J., Li F., Chen H. The urban heat island and its impact on heat waves and human health in Shanghai, *International Journal of Biometeorology,* Vol. 54, 2010, pp. 75–84.

[9] Hunter Block A., Livesley S. J., Williams N. S. G. *Responding to the urban heat island: A review of the potential of green infrastructure,* Victorian Centre for Climate Change Adaptation Research, Melbourne (Australia), 2012.

[10] Szkordilisz F. Mitigation of urban heat island by green spaces, *Pollack Periodica,* Vol. 9, 2014, pp. 91–100.

[11] Takács Á., Kiss M., Gulyás Á. Some aspects of indicator development for mapping micriclimate regulation ecosystem service of urban tree stands, *Acta Climatologica et Chorologica,* Vol. 47-48, 2014, pp. 99–108.

[12] Shahidan M. F., Jones P. J., Gwillam J., Salleh E. An evaluation of outdoor and building environment cooling achieved through combination modification of trees with ground materials, *Building and Environment*, Vol. 58, 2012, pp. 245–257.

[13] Baró F., Chaparro L., Gómez-Baggethun E., Langemeyer J., Nowak D. J., Terradas J. Contribution of ecosystem services to air quality and climate change mitigation policies: The case of urban forests in Barcelona, Spain, *AMBIO,* Vol. 43, 2014, pp. 466–479.

[14] Nowak D. J., Hirabayashi S., Bodine A., Greenfield E. Tree and forest effects on air quality and human health in the United States, *Environmental Pollution,* Vol. 193, 2014, pp. 119–129.

[15] Kirnbauer M. C., Baetzb B. W., Kenneyc W. A. Estimating the storm-water attenuation benefits derived from planting four monoculture species of deciduous trees on vacant and underutilized urban land parcels, *Urban Forestry and Urban Greening,* Vol. 12, 2013, pp. 401–407.

[16] Sander H., Polasky S., Haught R.G. The value of urban tree cover: A hedonic property price model in Ramsey and Dakota Counties, Minnesota, USA, *Ecological Economics,* Vol. 69, 2010, pp. 1646–1656.

[17] i-Tree (2014): i-Tree Eco User Manual v5.0 (online, 2014). http://www.itreetools.org/resources/manuals/Eco_Manual_v5.pdf (last visited 19 August 2015).

[18] Liu C. F., He X. Y., Chen W., Zhao G. L., Li L., Xu W.D. Ecological benefit evaluation of urban forests in Shenyang City based on QuickBird image and CITYgreen model, *Chinese Journal of Applied Ecology*, Vol. 19, 2008, pp. 1865–1870.

[19] Rogers K., Jarratt T., Hansford D. Torbay's urban forest - Assessing urban forest effects and values (online, 2011), http://www.torbay.gov.uk/tuf.pdf (last visited 19 August 2015).

[20] City and County of San Francisco 2014, *San Francisco Urban Forest Plan*.

[21] Grant J., Gallet D. The value of green infrastructure, A guide to recognizing its economic, environmental and social benefits, *Center for Neighborhood Technology*, Chicago, 2010, http://www.cnt.org/sites/default/files/publications/CNT_Value-of-Green-Infrastructure.pdf (last visited 19 August 2015).

[22] Heisler G. M. Effects of individual trees on the solar radiation climate of small buildings, *Urban Ecology,* Vol. 9, 1986, pp. 337–359.

[23] Balogun A. A., Morakinyo T. E., Adegun O. B. Effects of tree-shading on energy demand of two similar buildings, *Energy and Buildings,* Vol. 81, 2014, pp. 305–315.

[24] Papadakis G., Tsamis P., Kyritstis S. An experimental investigation of the effect of shading with plants for solar control of buildings, *Energy and Buildings*, Vol. 33, 2001, pp. 831–836.

[25] Berry R., Livesley S. J., Aye L. Tree canopy shade impacts on solar irradiance received by building walls and their surface temperature, *Building and Environment,* Vol. 69, 2013, pp. 91–100.

[26] Chagolla M. A., Alvarez G., Simá E., Tovar R., Huelsz G. Effect of tree shading on the thermal load of a house in a warm climate zone in Mexico, *Proc. of the ASME 2012 International Mechanical Engineering Congress & Exposition IMECE2012,* Houston, Texas, USA, November 9-15, 2012, pp. 761–768.

[27] Simpson J. R., McPherson E. G. Simulation of tree shade impacts on residential energy use for space conditioning in Sacramento, *Atmospheric Environment,* Vol. 32, 1998, pp. 69–74.

[28] Hes D., Dawkins A., Jensen C., Aye L. A modeling method to assess the effect of tree shading for building performance simulation, *Proc. of Building Simulation 2011, 12th*

Conference of International Building Performance Simulation Association, Sydney, Australia, 14-16 November, 2011, pp. 161–168.

[29] Pandit R., Laband D. N. Energy savings from tree shade, *Ecological Economics,* Vol. 69, 2010, pp. 1324–1329.

[30] Donovan G. H., Butry D. T. The value of shade, Estimating the effect of urban trees on summertime electricity use, *Energy and Buildings,* Vol. 41, 2009, pp. 662–668.

[31] Szkordilisz F., Heeren N., Habert G. Energetic and comfort benefits of composite buildings, Learning from vernacular techniques: Section 16, In: Creating New Resources, Conference Proceedings: Session 16, *World Sustainable Building Conference* (WSB14), Barcelona, Spain, 28-30 October 2014, Green Building Council, Espana, 2014, pp. 9–15.