The effectiveness of shade trees for urban heat mitigation, a comparative numerical simulation study

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ABSTRACT

As a result of climate change, many regions are projected to see increases in air temperatures and extreme heat events over the coming decades. Since these trends are expected to exacerbate existing conditions in cities, urban heat mitigation will be one of the key challenges of the twenty-first century. A frequently advocated means of mitigating urban heat is through shade trees. Through the reduction of air and radiative temperatures trees not only improve outdoor human thermal comfort, but also reduce the cooling loads of buildings. This paper investigates the impact of different canopy cover ratios and tree layouts on the urban microclimate. The numerical simulation study utilizes four characteristic dense urban configurations from Budapest (Hungary) to assess the influences of these factors on the effectiveness of shade trees in mitigating urban heat.

The study applies ENVI-met for microclimate simulation and MATLAB for the analysis and visualization of the results. Microclimate conditions within the urban canopy layer are examined on the basis of diurnal air and mean radiant temperatures. Preliminary results indicate that the effectiveness of shade trees is the function of the urban configurations’ initial thermal performance. Since microclimate improvements by way of trees are primarily achieved through shading, greatest reduction in radiative temperatures is achieved in configurations with large open spaces. In the case of air temperature, increasing the canopy cover increases the added benefit of temperature reduction—indicating that reduced turbulence can in certain cases be beneficial.

Key Words: shade trees, canopy cover ratio, urban heat mitigation, mean radiant temperature, air temperature, numerical simulation, ENVI-met

1. INTRODUCTION

Regional climate projections for Central and Eastern Europe indicate a sharp increase in summertime temperatures and in the frequency of warm temperature extremes over the next century. According to the projections of the A1B scenario, summer temperatures Hungary will see a 1.7–2.6°C rise in the near future, and a 3.5–6.0°C increase by the end of the twenty-first century (Horányi 2011). Combined with existing urban heat island intensities, these projections are expected to make conditions in Hungarian cities worse. Since dense urban environments are most vulnerable to the influences of both climate change and urban heat island, identifying adequate heat mitigation strategies for these areas is of primary importance. Previous analyses indicate that shade trees are not only most effective in decreasing daytime temperature, but also influence nighttime urban temperatures favorably (Gál 2014c, 2015). The aim of this study is to assess the influence of various canopy cover ratios on the urban canopy layer (UCL) microclimate, along with the effect of different tree layouts.

2. MATERIALS AND METHODS

A numerical simulation study was carried out to assess the influence of shade trees on the canopy layer microclimate. The study utilized ENVI-met (Version 4.0 BETA II) for microclimate simulation (Bruse 2014) and MATLAB (Version 7.12) for the analysis and visualization of the
results. The key phases of the research methodology are (1) the selection of cases and input parameters for the numerical model, and (2) the analysis of the simulation results.

2.1 Model configuration

Four dense urban block typologies from Budapest are selected as cases for the study: the nineteenth-century configuration consisting of attached courtyard apartment buildings (T1), the perimeter block built up at its edges (T2), the Zeilenbau design of parallel rows of buildings (T3), and the hybrid form composed of a set of short towers placed atop of a unifying base (T4). These dense configurations are characteristic to the inner districts of Pest and are also found at certain parts of Buda.

The cases and their corresponding ENVI-met layouts are shown in Figure 1. The urban blocks are 78 m wide and 150 m long, and are separated by 18-meter wide roads. The buildings are uniformly 24 m tall, and the hybrid configuration's base is 6 m heigh. The models have a 6 m horizontal and 3 m vertical grid resolution. Two ground surface materials are used within the model: gravel asphalt for roads and unsealed silt-loam soil for the urban blocks. Each model domain consists of nine identical urban blocks arranged in a three-by-three grid layout, as shown in Figure 2.

The study utilizes the simple forcing feature introduced in ENVI-met 4.0 (Huttner 2012) with the diurnal air temperature and relative humidity cycles of a typical July day in Budapest (Bacsó 1959, Réthly 1947). The baseline model, which mimics background or rural conditions and thus supplies the necessary canopy layer conditions for the study, contains no buildings. ENVI-met is run for 48 hours from July 7th to the 9th in order to provide sufficient time for model spin-up.

This paper is set to evaluate the influence of different canopy covers and tree layouts through the lens of different urban block configurations. In the case of canopy cover, four scenarios with 10%, 20%, 30% and 40% coverage are evaluated for all four configurations. In the case of the layout study, T1 (the courtyard apartment block) and T3 (the Zeilenbau configuration) are selected for the analysis. The rationale for their selection is that they are the most dissimilar typologies in terms of built form, building surface fraction and building density. Two additional layout scenarios are developed for these configurations. In the case of the heavily built-up form of T1, the added benefits of placing trees to the sunlit parts of the model (mainly in front of western and southern facades) versus placing them into the shade are evaluated. Regarding the T3 configuration, the influence of trees placed next to the facades only versus distributing them evenly across the model is assessed. All schemes utilize London plane trees (Platanus × acerifolia) with 11-meter wide canopy, 1.1 LAD and 0.18 albedo. The height of the tree species is 18 m uniformly, except for the ones placed on top of the hybrid form's (T4) 6-meter tall elevated base. Here, 12-meter high species are utilized in order to match the overall height of the other, 18-meter tall species.

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1 expressed as the ratio of enclosed volumes in a given urban canopy
2.2 Method of analysis

The study follows established procedures in numerical modeling and analysis. First, in order to minimize the edge effect, the analysis is limited to the central area of each model. The evaluated space, which encompasses the central block in the three-by-three grid layout, consists of the canopy layer above the block itself and above half of the adjacent streets (see Figure 2). Second, due to the model’s long spin-up time, only the results of the second day are evaluated. Finally, in order to reduce systematic model errors results are reported in relative terms—either relative to the baseline case with no buildings (T0bl) or relative to the respective base configurations without trees (T1, T2, T3 and T4).

During clear and calm days, the key parameters governing human thermal comfort are radiation and air temperature. Thus, changes in the canopy layer microclimates are evaluated on the basis of potential air temperature and mean radiant temperature in this study. The analyses utilize three approaches to compare different scenarios across across the selected cases. To reveal differences between the diurnal cycles of cases and scenarios, the first approach computes and plots volumetric median UCL air temperature and MRT values for every half hour relative to the baseline case (T0bl).

The second approach is the areal median method introduced by the author to analyze urban canopy layer conditions in a concise manner (Gáll 2014a, 2014b, 2014c). In this process areal median values are calculated within the UCL for every half hour and elevation (see Figure 3). The obtained values, expressed relative to a baseline (T0bl), are then assembled into a matrix. The columns in these matrices represent different times, while the rows consist of median values calculated for specific elevations. The magnitude of the evaluated climate parameter is indicated by colors. This method provides a rather detailed overview of the diurnal evolution of microclimate conditions within the UCL, while retains the contiguity of neighboring air layers and thus reflects their interdependence.

The third approach is introduced for the cross-comparison of cases and scenarios. In order to represent multiple schemes on a single graph, overall mean values of the evaluated climate parameter are computed for a selected time period and are expressed relative to a selected baseline (T0bl or T1–T4). When the baseline case without buildings (T0bl) is used as reference, microclimate conditions across different cases and scenarios can be compared and the impact of shade trees (combined with that of the initial built form) can be assessed. This assessment aids the identification of vulnerable configurations that are least responsive to heat mitigation by way of
trees. When the respective base configurations without trees are applied as reference (T1, T2, T3 and T4), the effectiveness of shade trees can be assessed in absolute terms: the values express the added benefit of trees relative to the tree-less condition.

3. RESULTS AND DISCUSSION

3.1 The influence of form

Before delving into a detailed discussion on the influence of shade trees, it is necessary to clarify the effect of built form on the canopy layer microclimate. In order to achieve this, microclimate differences between the four selected cases without trees is discussed briefly below. The analyzed typologies have characteristic spatial arrangements that allow us to categorized them either as enclosed forms with courtyards (T1, T2) or as open configurations (T3, T4). Furthermore, T2 and T3 typologies are characterized by large open spaces, which facilitate the absorption short-wave and the dissipation of long-wave radiations. In contrast, in the case of T1 and T4, building masses are distributed more or less evenly in space. Characteristic physical measures of these cases are summarized in Table 1.

Table 1 Physical characteristic of urban block typologies (computed for gross urban block area)

<table>
<thead>
<tr>
<th></th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building surface fraction [%]</td>
<td>58</td>
<td>43</td>
<td>15</td>
<td>73</td>
</tr>
<tr>
<td>Impervious surface fraction [%]</td>
<td>27</td>
<td>27</td>
<td>27</td>
<td>27</td>
</tr>
<tr>
<td>Pervious surface fraction [%]</td>
<td>15</td>
<td>30</td>
<td>58</td>
<td>0</td>
</tr>
<tr>
<td>Complete aspect ratio(^a) [m2/m2]</td>
<td>2.69</td>
<td>1.85</td>
<td>1.12</td>
<td>1.95</td>
</tr>
<tr>
<td>Facade density(^b) [m2/m2]</td>
<td>4.34</td>
<td>2.00</td>
<td>0.82</td>
<td>1.38</td>
</tr>
<tr>
<td>Building mass density [m3/m2]</td>
<td>14</td>
<td>10</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>Mean sky view factor(^c)</td>
<td>0.35</td>
<td>0.46</td>
<td>0.67</td>
<td>0.49(^d)</td>
</tr>
</tbody>
</table>

a excluding vegetation
b sum of active facade areas/horizontal area of the canopy between the facades
c calculated at street level (1.5 m)
d the urban block entirely built up, hence is excluded from the calculation

Figure 4a illustrates the diurnal cycles of potential median canopy air temperatures relative to the baseline (T0bl). Two different trends can be distinguished: that of T3, which more or less follows the evolution of the background temperature, and that of the other models, which exhibit cooler temperatures during the day and warmer during the night. Daytime cooling—also referred to as the oasis effect or intra-urban cool island—is characteristic to deep urban canyons where shaded surfaces offset the warming of adjacent air layers and where the intermixing of the cooler canopy air with the warmer one above is reduced (Johansson 2006). The cool island effect is most pronounced at the courtyard configurations (T1, T2) where both shading and reduced turbulence are present. These results are in line with Berkovic et al. (2012), who found that courtyards without lateral openings have lower air and radiant temperatures. The mutual shading of towers in the case of T4 brings its daytime temperatures closer to that of the courtyard configurations during the warmest hours of the day.

In the case of open configurations, nighttime temperatures support the generally reported direct relationship between the SVF and the rate of cooling: the Zeilenbau (T3) with the highest SVF remains cooler at night than the hybrid form (T4). However, this correlation does not hold true for courtyard typologies: T1 with lower SVF remains cooler than T2. At night, between 21:00 to 6:00 LST, T1’s temperature pattern is nearly identical with that of the most open configuration, T3. It appears that as a result of daytime shading and reduced turbulence, dense configuration are able to extend the effects of daytime cooling well into the evening. Ali-Touder and Mayer (2006) reported a similar phenomenon in deep urban canyons with H/W = 4 or higher. Here, nighttime temperatures remained about 0.5–1°C cooler than at shallower canyons with higher SVF.
Figure 4b shows the diurnal course of median radiant temperatures in the UCL. The M-shaped curve is the outcome of the interplay between the street grid’s alignment with cardinal directions and that of low sun angles: at low altitude angles (up to about 20°) and before/after the solar azimuth angle is aligned with the east-west-oriented streets (around 6:00/18:00 LST), the canopy layer remains mostly shaded. As a result, median radiant temperature reduction peaks at 20–30 °C around these times. At noon, the greatest MRT reduction is provided by configurations with relatively evenly distributed building masses (T1, T4), while open configurations (T2, T3) maintain higher MRT levels for most of the day.

![Graph showing diurnal median UCL (a) potential air temperature and (b) mean radiant temperature cycles of non-vegetated configurations (T1, T2, T3 & T4) relative to the baseline without buildings (T0bl).](image)

Figure 4: Diurnal median UCL (a) potential air temperature and (b) mean radiant temperature cycles of non-vegetated configurations (T1, T2, T3 & T4) relative to the baseline without buildings (T0bl)

Figure 5a shows the diurnal cycle of the areal median potential air temperature relative to the baseline (T0bl). The presented trends are in line with previous observations: each configuration experiences daytime temperature reduction and nighttime temperature excess to a varying degree. Greatest deviations from background conditions are observed in cases with low SVF (T1, T2, T4). They are coolest during the day with temperature reductions exceeding 1.5°C at the pedestrian level and warmest at night by at least over 0.5°C. T3 typology modifies the background climate the least with areal median temperature changes remaining within the +/-0.5°C range. The configuration’s low building density and large SVF facilitate both radiative and convective cooling at night and contribute to higher temperatures during the day.

The influence of built form on the areal median MRT are presented in Figure 5b. The dark wedge-shaped areas early and late in the day are the outcomes of shortwave radiation obstruction at low solar altitude angles. In configurations with large open spaces shading from adjacent structures ceases during high sun hours. In the case of T4, the closely placed towers decreases radiant temperatures by 5–10°C between 10:00 to 17:00 LST to almost the entire depth of the canopy. MRT reduction is greatest in the configuration with small courtyards (T1).
3.2 The effect of canopy cover

The impact of five canopy cover ratios (0%, 10%, 20%, 30% and 40%) in four cases is compared by means of overall mean UCL air and mean radiant temperatures calculated for the daytime period. Air temperature values computed relative to the baseline case (T0bl) and to respective base configurations (T1 to T4) are shown on Figure 6a and 6b, respectively. As expected, increasing the canopy cover reduces temperatures in the UCL. However, this benefit varies by configurations. In absolute terms (Figure 6a), this heat mitigation strategy appears to be the most effective in the case of courtyard configurations (T1, T2) where reduced turbulence due to enclosure is already present.

In the case of T1’s cooling performance, the thermal advantage owing to preexisting shading and enclosure remains even when configurations are compared in relative terms without the impact of built form (Figure 6b). The influence of different canopy cover ratios in the case of configurations with large open spaces (T2, T3) are rather similar. The only exception is the 40% canopy cover
scenario where air temperature reduction in the Zeilenbau configuration (T3) lags behind that of the perimeter block (T2). The reduced heat mitigation performance of T3 is the result of the tree layout. An improved performance close to that observed at T2 can be achieved by a better spatial distribution of trees (compare T3 results on Figure 6 and Figure 11 and see the discussion on the role of tree layouts below). Cooling through increased canopy cover is least effective in the case of T4, a configuration that is characterized both by the lack of enclosure and by evenly distributed building masses that ensure an increased level of shading in the canopy.

Figure 6: Overall mean UCL potential air temperature (a) relative to the baseline case (T0bl) and (b) relative to base configurations without vegetation (T1, T2, T3 & T4) at 10%, 20%, 30% and 40% canopy cover calculated for the daytime period only

In order to find the canopy cover ratio at which the benefit of added trees start to taper off, a simple rate of mean UCL air temperature change at every added 10% canopy cover is calculated for the daytime period and presented on Figure 7. In the case of T1, T3 and T2 cooling peaks at 20% canopy cover, while in the case of T4 it occurs at 30%. Over 30% the impact of increased canopy cover decreases in all cases.

The impact of shade trees within the canopy layer is illustrated by means of areal median relative air temperatures, computed for T1 and T3 cases (Figure 8). With increasing canopy cover the cooling effect increases and extends both in space and time. While the greatest temperature reduction remains to be at the pedestrian level around 14:00 LTS, cooler temperatures increasingly dominate through a greater part of the canopy layer and a larger extend of the day. This effect is best illustrated by T1 configuration on Figure 8a, and is most evident in the 16:00 to 22:00 LTS period.
Figure 7: The rate of mean UCL air temperature change per 10% cc increase (daytime period)

Figure 8: Diurnal cycles of areal median potential air temperatures in the UCL relative to the baseline ($T_{0bl}$) for (a) $T_1$ and (b) $T_3$ configurations with increasing canopy cover ratios (10%, 20%, 30% and 40%, respectively)
Overall mean canopy layer MRTs calculated relative to the baseline case (T0bl) and to the respective base configurations for the daytime period are shown on Figure 9a and 9b, respectively. According to Figure 9a, increased canopy cover does not diminish the initial difference between the MRT's of different cases: T1 remains to be the most, while T3 the least shaded configuration. However, the reduction of mean MRTs decreases with each added 10% canopy cover. Compared in relative terms, without the initial effect of built form (Figure 9b), the effectiveness of shade trees in reducing radiant temperatures is the least in the case of configurations where considerable shading in the UCL is already present (i.e. in the case of T1). In this regard, the uniqueness of T1 in comparison to other configurations is best illustrated by the diurnal cycle of areal median MRT values in Figure 5b.

![Figure 9: Overall mean UCL MRT temperature (a) relative to the baseline case (T0bl) and (b) relative to base configurations without vegetation (T1, T2, T3 & T4) at 10%, 20%, 30% and 40% canopy cover calculated for the daytime period only](image)

The areal median MRT patterns within the UCL at 10%, 20%, 30% an 40% canopy cover ratios for T1 and T3 are shown in Figure 10a and 10b, respectively. The shading effect of trees is most pronounced in the 0–15 m region above ground. In the case of the relatively shaded configuration of T1, the canopy cover increase only slightly alters the diurnal MRT pattern. In contrast, the addition of shade trees considerably reduce radiant temperatures during the midday period in the case of T3. As a result of the growing canopy cover ratio, the MRT pattern of T3 increasingly resembles that of T1 (see Figure 10b). Minor differences and irregularities in the patterns of T1 and T3 at 40% canopy cover are the results of directionalities in the models (i.e. the alignment of building and tree layouts with the cardinal directions).
3.3 The role of the tree layout

The overall mean UCL air temperature values for two configurations (T1, T3) with two canopy cover and three layout scenarios are plotted on Figure 11. Values relative to the baseline case (T0bl) and relative to the respective base configurations are presented in Figure 11a and 11b, respectively. The dense and well shade configuration of T1 is sensitive to the increase in canopy cover (compare the different marks: circle to squares to triangles), but not to changes in tree layouts (compare identical marks with different colors). In contrast, overall UCL mean air temperatures are the function of both canopy cover and tree layouts in the case to T3—a typology characterized by large open spaces and low building surface fraction. Here, trees evenly distributed in space (magenta triangles and squares) achieve the greatest temperature reduction compared across identical canopy cover ratios (20% and 40%, indicated by triangles and squares, respectively). Placing shade trees along the facade (blue triangle and blue square) is the least effective approach to reduce air temperatures in the urban canopy. In the case of T3, placing trees
along the facade at 40% canopy cover results a similar mean cooling effect within the UCL as does a 20% canopy cover with trees distributed evenly in space (compare the magenta triangle and the blue square on the right-side columns in both Figure 11a and 11b).

![Graph showing overall mean UCL potential air temperature](image)

Figure 11: Overall mean UCL potential air temperature (a) relative to the baseline case (T0bl) and (b) relative to base configurations (T1, T3) over the daytime period only. Different shaped markers indicate different canopy cover ratios: circle (0%), triangle (20%) and square (40%). The colors refer to layout variations: black is the initial case taken over from the studies before; in the case of T1 blue is the layout with trees placed in next to eastern and norther facades and magenta is with trees next to south and west facing facades; whereas in the case of T3 blue is the layout with trees placed adjacent to facades while magenta is where trees are distributed evenly in space.

The diurnal cycle of median canopy air temperature at different canopy cover ratios and tree layouts for T1 and T3 are shown in Figure 12a and 12b, respectively. As noted above, tree layout does not influence canopy layer air temperatures in the case of T1. In contrast, the effect of vegetation layout is considerable in the case of T3. Differences are greatest in the afternoon, between 13:00 to 19:00 LTS. The other notable pattern that is well illustrated by Figure 11 is that the increasing canopy cover shifts the occurrence of the greatest median UCL air temperature reduction from noon or early afternoon to early evening in both cases. This trend is most evident in the case of T1, where the greatest diurnal temperature reduction shifts from 14:00 LTS (0%), to about 15:00–16:00 LST (20%) and then to 16:00–18:00 LST (40%).

The overall mean canopy layer MRTs of T1 and T3 configurations with different layouts and canopy cover ratios are presented in Figure 13. Values calculated for the daytime period relative to the baseline case (T0bl) and to base configurations are shown on Figure 13a and 13b, respectively. Similarly to overall air temperature reductions, T1 configuration is insensitive to changes in tree layouts. In the case of T3, the trends in radiation reductions are interlinked with those observed at the air temperature (Figure 11): radiant temperatures within the canopy are the function of both canopy cover ratios and shade trees layouts. As expected, the greatest MRT reduction in the UCL is achieved by distributing trees evenly in space. As noted at the canopy cover analysis earlier (Figure 9), in absolute terms T1 configuration provides greater radiant temperature reduction than the other cases. Nevertheless, the comparison in relative terms reveals that in the case of T1 the MRT reduction benefit decreases with increasing canopy cover (see Figure 13b and also Figure 9b).

The diurnal cycles of median canopy MRTs for the layout and canopy cover scenarios for T1 and T3 configurations are presented in Figure 14a and 14b, respectively. In both cases, increasing the canopy cover reduces midday MRT levels in the UCL and turns the initial M-shaped curve into a W. In the case of T1, the impact of layout change is little, and those differences decrease with increasing canopy cover. In the case of T3, the influence of both layout and canopy cover is significant. As noted, the impact of 20% canopy cover distributed evenly (dashed magenta line, Figure 14b) is comparable to that of 40% with trees placed along the facade only (dotted blue line, Figure 14b).
Figure 12: Diurnal cycle of median UCL potential air temperature for (a) T1 and (b) T3 layout and canopy cover scenarios. Line types indicate different canopy cover ratios: 0% (continuous), 20% (dashed) and 40% (dotted). The colors refer to layout variations: black is the initial case taken over from the studies before; in the case of T1 blue is the layout with trees placed in next to eastern and norther facades and magenta is with trees next to south and west facing facades; whereas in the case of T3 blue is the layout with trees adjacent to facades while magenta is where trees are distributed evenly in space.

Figure 13: Overall mean UCL mean radiant temperature temperature (a) relative to the baseline case (T0bl) and (b) relative to base configurations (T1, T3) over the daytime period only. Different shaped markers indicate different canopy cover ratios: circle (0%), triangle (20%) and square (40%). The colors refer to layout variations: black is the initial case taken over from the studies before; in the case of T1 blue is the layout with trees placed in next to eastern and norther facades and magenta is with trees next to south and west facing facades; whereas in the case of T3 blue is the layout with trees placed adjacent to facades while magenta is where trees are distributed evenly in space.
Figure 14: Diurnal cycle of median UCL mean radiant temperature for (a) T1 and (b) T3 layout and canopy cover scenarios. Line types indicate different canopy cover ratios: 0% (continuous), 20% (dashed) and 40% (dotted). The colors refer to layout variations: black is the initial case taken over from the studies before; in the case of T1 blue is the layout with trees placed in next to eastern and norther facades and magenta is with trees next to south and west facing facades; whereas in the case of T3 blue is the layout with trees placed adjacent to facades while magenta is where trees are distributed evenly in space.

4. CONCLUSION

This paper presents the results of a numerical simulation study evaluating the effect of different canopy cover ratios and the impact of shade tree layouts using four urban block typologies. The study assumes a typical summed day with anti-cyclonic conditions and depicts microclimatic changes within the UCL by means of potential air and mean radiant temperatures. The analyses indicate that effectiveness of shade trees as daytime heat mitigation measures is strongly influenced by the shape of the built environment. Spatial enclosures, such as courtyards, intensify the cooling effect of trees. As expected, increasing the canopy cover decreases air temperatures in the UCL and also extends this effect through space and time. The cooling benefit of an incremental 10% canopy cover increase tapers off beyond 30% canopy cover in all four cases. Trees are most effective in reducing mean radiant temperatures in urban canopies where shading is sparse (i.e. where large open spaces are present). The influence of tree layouts on UCL air and radiant temperatures is greatest in open configurations with low building surface fraction.

REFERENCES


