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THE INFLUENCE OF BUILT FORM AND VEGETATION ON THE CANOPY LAYER MICROCLIMATE WITHIN URBAN BLOCKS

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Summary: A numerical simulation study was conducted to reveal the effects of built form on the canopy layer microclimate at the scale of city blocks and to evaluate the role of vegetation in modifying these environments. The study took four metropolitan urban block typologies from Budapest as models and compared their microclimate dynamics with and without vegetation. Microclimate modeling was performed by ENVI-met (Bruse 2011), while MATLAB was utilized for the data analysis. The findings indicate that built form and vegetation are key factors governing the canopy layer microclimate. Their influence is primarily exerted through shading and enclosure.

Key words: urban block, typology, trees, mean radiant temperature (MRT), numerical simulation, ENVI-met

1. INTRODUCTION

Regional climate projections for Hungary indicate a rather sharp increase in summertime temperatures by the end of the next century. While the prognosis for the mid-century is a 1.7–2.6°C rise in temperatures, by the end of the twenty-first century, models signal a 3.5–6.0°C increase in summertime conditions (Horányi 2011). In line with these changes, the frequency of extreme warm temperature events are also expected to rise (Bartholy and Pongrácz 2011).

In light of these projections, the understanding of microclimate modification by means of built form and vegetation is of key importance to architects, planners and other professionals in developing effective mitigation strategies in the future. As part of a larger study, the aim of this paper is to assess the microclimate performance of built form at the scale of city blocks and to evaluate the role of vegetation in influencing the climate of these spaces.

Fig. 1 From left to right: the block of courtyard apartments, the perimeter block, the Zeilenbau configuration and the hybrid block typology (Google Maps 2010)

2. MATERIALS AND METHODS

A numerical simulation study was carried out to assess the impact of built form and vegetation on the microclimate within urban blocks. The study utilized ENVI-met (Version 3.1 BETA V) for microclimate simulation (Bruse 2011) and MATLAB (Version 7.12) for the analysis and visualization of the results. The adopted research methodology consisted of two distinct phases. During the first, the examined cases were developed as well as the baseline case without buildings. In the course of the second, numerical simulations were run and the results analyzed.

2.1. Numerical modelling

The study utilized a typological approach to assess the effect of built form. The cases examined were developed on the basis of Budapest's four metropolitan urban block typologies: the nineteenth-century configuration consisting of attached courtyard apartment buildings, the perimeter block built up at its edges, the Zeilenbau design of parallel rows of buildings, and the hybrid form composed of short towers on a unifying base (see Fig. 1). The corresponding layouts, adapted to ENVI-met, are illustrated in Fig. 2. The buildings are uniformly 24 meters high, except for the hybrid configuration's base, which is set to 6 m. The models have a grid resolution of 6 m horizontally and 3 m vertically.

The influence of vegetation on the microclimate within these typologies was also evaluated numerically. The analysis adopted a rudimentary approach to lay out greenery within the blocks. The guiding principles were as follows. First, 40% of the available open space within the blocks received vegetation. Second, vegetated areas consisted of deciduous trees only with medium dense canopy. Third, trees were primarily arranged in rows along facades (see Fig. 3). Fourth, the top of the tree canopy was set to 21 meters uniformly across typologies. In most cases this resulted in 21 m tall trees, except for the hybrid configuration, where 15 m tall trees were placed on top of the six-meter-high base.

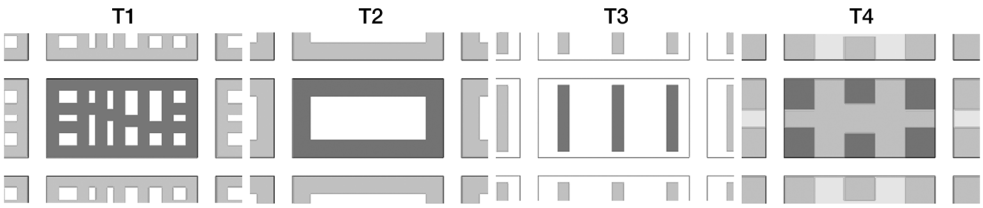

Fig. 2 The model equivalents of the four urban block typologies

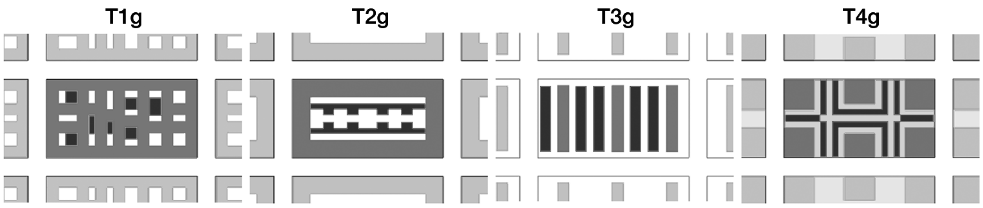

Fig. 3 The four model with trees (indicated by black patches within the blocks)

The baseline case without buildings was developed to emulate a typical July day in Budapest as described in the literature (Bacsó 1959, Réthly 1947). It both provided the climate parameters needed by the numerical model and the baseline canopy layer conditions applied as a reference. The air temperature and specific humidity cycles reproduced by the baseline configuration are plotted along with the reference data on Fig. 4. Further details on the development of the baseline case are discussed in Gál (2014).

The study follows a well-established procedure in numerical modeling. The digital model of each case consists of nine identical urban block configurations arranged in a three-by-three grid layout. In order to minimize the edge effect and to reduce the influence of bordering streets, the analyses only take the UCL above the central block into consideration. ENVI-met was run for 48 hours from July 7th. Due to the model's long spin-up time, only the results of the second day were evaluated. Additionally, to reduce systematic model errors, results are reported relative to the baseline conditions.

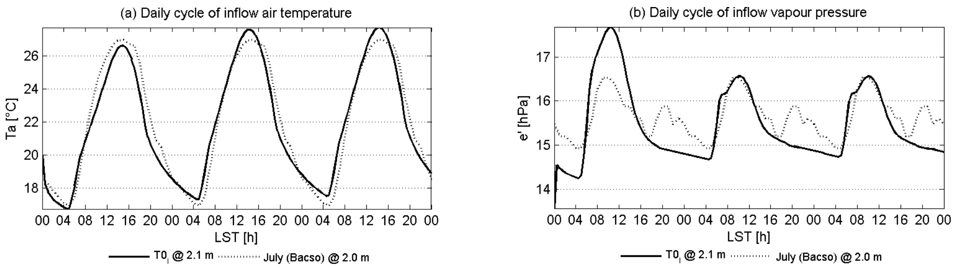

Fig. 4 Comparison of ENVI-met simulated (baseline case) and average July conditions in Budapest, Hungary (Bacsó 1959): (a) potential air temperature, (b) vapor pressure

2.2. Method of analysis

The present paper examines how built form and vegetation modify the microclimate within urban blocks. During clear and calm conditions, the key parameters governing the human thermal comfort and surface temperatures are radiation and air temperatures. Consequently, the study focuses on air temperature and MRT differences, with the latter used as an indicator of radiative conditions within the urban canopy. The presented analysis utilizes volumetric median air temperatures (ΔT_{UCL}) and mean radiant temperatures ($\Delta T_{MRT\text{-}UCL}$) calculated for UCL above the central urban block, relative to the baseline condition. For an ease of comparison, characteristic heat island measures calculated for the entire canopy are also reported.

In order to analyze UCL conditions in a concise manner, the study adopted a simple method based on areal average values (Gál 2014). The concept, illustrated in Fig. 5 briefly, consists of areal medians calculated for each elevation in the UCL and for every half hour of a diurnal cycle. Since results are reported relative to baseline conditions, areal values for the baseline model are derived from an identical canopy volume to that of the analyzed configuration. In other words, the volumes contained by buildings in a given model are first extracted from the canopy of the baseline, only then are areal medians calculated. The areal median canopy differences are subsequently assembled into a matrix, with different elevations arranged into columns and results from different times joined into rows. The magnitude of selected climate parameters is indicated by colors. This representation has the advantage of providing a more detailed overview of the diurnal evolution of UCL conditions, while retaining the relative positions of adjacent air layers.

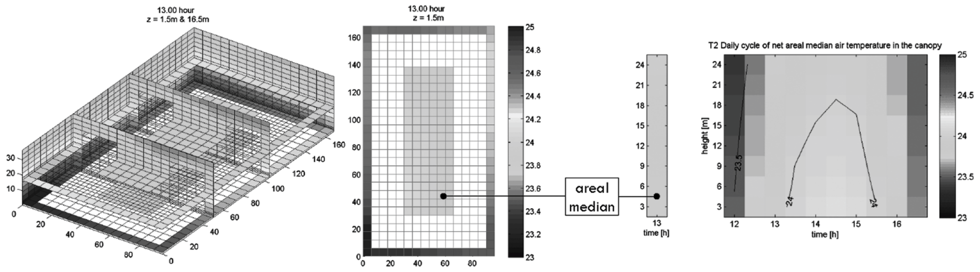

Fig. 5 The method of deriving an areal median matrix, illustrated on air temperature values

3. RESULTS AND DISCUSSIONS

3.1. The influence of form

The diurnal evolution of potential air temperatures relative to the baseline is presented on Fig. 6a. As a result of mutual shading, denser configurations remain about 1.5–2°C cooler than the baseline case during the warmest hours of the day. This phenomenon, called the intra-urban cool island, is characteristic to deep urban canyons where shaded cool surfaces offset the warming of the adjacent air (Johansson 2006). Besides shading, reduced intermixing – as a result of buoyancy difference between the cooler air of the canopy and warmer one above and likewise the consequence of the skimming flow that develops over densely built environments – also contributes to the emergence of this phenomenon (Johansson 2006). Among the denser typologies, lowest daytime temperatures are achieved in courtyard configurations. These results are in line with Berkovic et al. (2012), who found that courtyards without lateral openings have lower air and radiant temperatures. The role of courtyards in mitigating canopy layer temperatures is perhaps best represented by the comparison between the perimeter block configuration (T2) and the hybrid form (T4). While the two has the same building density, the canopy of T2 remains about 0.2°C cooler than T4 through the day.

In case of open configurations, nighttime temperatures confirm the generally reported inverse relationship between a configuration's rate of cooling and building density: the Zeilenbau (T3) with lowest density and building surface fraction cools down the most, while the hybrid form (T4) with the entire block covered remains the warmest configuration. The nighttime temperature difference between these two cases is nearly 1.5°C. According to the results, this correlation does not hold true for courtyard configurations (T1, T2). T1, which is the densest configuration and has the second greatest building surface fraction after T4, remains about 0.5°C cooler than its less dense courtyard counterpart, the perimeter block (T2). T1 also stays about 0.7°C cooler than T4. Ali-Touder and Mayer (2006) reported a similar relationship between nocturnal temperatures and high aspect ratios. According to their findings, deep urban canyons with H/W = 4, remained about 0.5–1°C cooler than comparable shallower configurations at 21:00 LST. These findings indicate that beyond a certain threshold of density (signaled by sky view factor or aspect ratio), the cooling effect from mutual shading extends into the night.

The diurnal course of mean radiant temperatures is presented in Fig. 6b. According to the results, large open spaces in T2 and T3 provide little to no protection from solar radiation during the day. In contrast, the mutual shading of towers in the case of T4 offers a 5–15°C radiant temperature reduction within the canopy. The greatest cooling is realized in typology T1, where small courtyards decrease MRT by over 25°C. The only time during the day when radiant temperatures in T1 approach baseline conditions is around noon, when the high sun is able to penetrate the small courtyards. Compared to daytime, the variation of nighttime radiant temperatures is much reduced. The microclimate dynamics of configurations are set apart by their openness: typologies with large open spaces (T2, T3) remain about 5°C cooler than the typologies with relatively evenly distributed building masses. While this difference confirms a better nighttime cooling due to greater sky view factors, the considerably reduced range of nocturnal MRT values might also be the sign of ENVI-met's limitation to account for the heat stored in building envelopes.

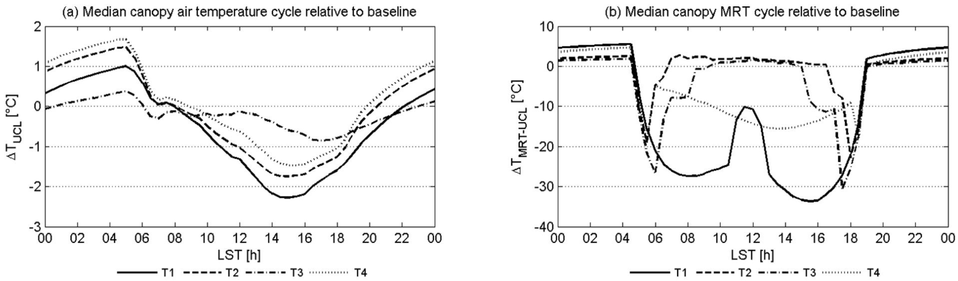

Fig. 6 Diurnal cycles of the UCL relative to the baseline, non-vegetated configurations: (a) potential air temperatures, (b) mean radiant temperatures

The diurnal spatial and temporal evolution of potential air temperatures within the UCL is shown in Fig. 7a. The presented trends are in line with previous observations: all typologies experience daytime temperature reduction and nighttime temperature excess to a varying degree. The daytime cool island intensity is greatest at configurations with courtyard (T1, T2). Since the heavier cold air of courtyards remains relatively separated from the well-mixed, but warmer air of streets, daytime cooling within these configurations lasts longer and affects the greater part of the canopy. During the hottest hours of the day, cooling intensity exceeds 3°C at the bottom of the small courtyards (T1). Among the typologies T3 interferes the least with the background climate, as both daytime temperature reduction and nighttime temperature excess remain below 1.2°C. Hence, the configuration's low building density and openness not only facilitate radiative and convective cooling at night, but also contribute to higher temperatures during the day: the lack of shading increases both surface and air temperatures, while the lack of enclosure ensures that the warm canopy air remains well-mixed and evenly distributed. In the case of T4, the mutual shading of towers decreases daytime, but increases nighttime temperatures.

The effects of built form on the radiation fluxes within the canopy are shown in Fig. 7b with deeper colors indicating greater radiation reductions. The dark tapered areas during early and late hours of the day, around 6:00 and 18:00 LST respectively, are the results of shortwave radiation obstructions at low sun angles. With increasing sun angles, the effect of mutual shading decreases. During high sun hours, shading completely ceases in configurations with large open spaces (T2, T3). At T4, the interference between the towers decreases radiant temperatures by over 10°C from approximately 10:00 to 18:00 LST. Solar obstruction is greatest at configuration with small courtyards (T1). Here, the icicle shape pattern around noon indicates the average depth that solar radiation infiltrates the courtyards. The relatively symmetrical MRT patterns in Fig. 7b are the outcome of spatial symmetries in configurations, as well as the alignment of typologies with cardinal directions.

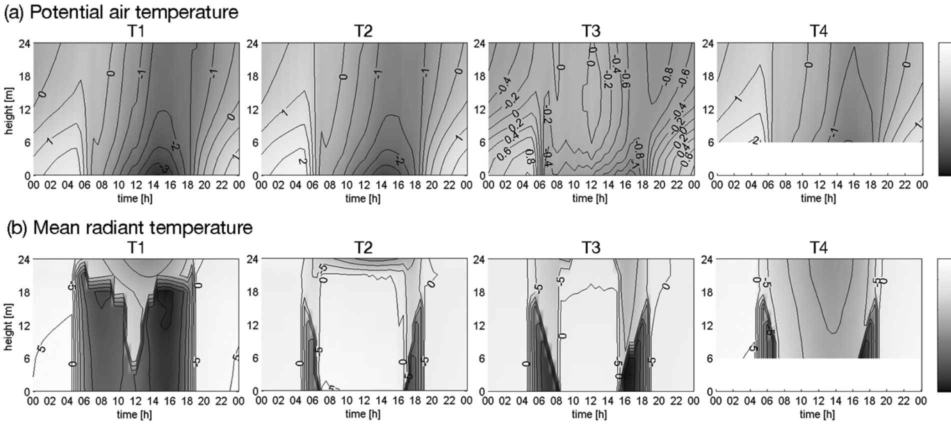

Fig. 7 Diurnal cycles of the UCL relative to the baseline, non-vegetated configurations: (a) potential air temperatures, (b) mean radiant temperatures

3.2. *The effect of vegetation*

The influence of greenery on the potential temperature cycle of typologies is shown in Fig. 8a. A comparison with non-vegetated conditions in Fig. 6a reveals that trees are most effective in configurations with large open spaces (T2, T3). At night, the Zeilenbau (T3) remains about 1°C cooler than the denser configurations. Except for a brief period between 12:00 to 16:00 LST, T3 also stays the coolest typology during the day. The likely reasons behind these cool conditions are the configuration's high green area ratio and low building surface fraction. In case of typologies with evenly distributed building masses, the effect of trees is largely limited to nocturnal temperatures. The nighttime temperature reduction is about 0.3°C and 1°C in the case of T1 and T3, respectively. Since ENVI-met cannot account for the heat stored in building envelopes, this difference is likely the result of the reduced heat stored in the ground due to shading. According to the new thermal dynamics of typologies, the temperature cycles of courtyards configurations (T1, T2) stand apart. They are characterized by a nearly 1°C smaller diurnal range. The perimeter block (T2), characterized by a larger green area ratio and a smaller building surface fraction than T1, remains about 0.2–0.4°C cooler through the day. In contrast, while the temperature cycles of open configurations are likewise nearly identical, their canopy temperatures remain about 1°C apart over the day.

The effect of vegetation on the evolution of relative MRT cycles is presented in Fig. 8b. With its well-distributed building mass and lowest amount of greenery, T1 is the typology least affected by trees. In this case, the only noticeable outcome of shading is the disappearance of extreme radiant temperatures around noon (see Fig. 6b). With regard to other typologies, vegetation resulted a MRT cycle similar to that of T1. The irregularities and minor differences between the four typologies are due to the directionalities present in the combined layout of buildings and vegetation.

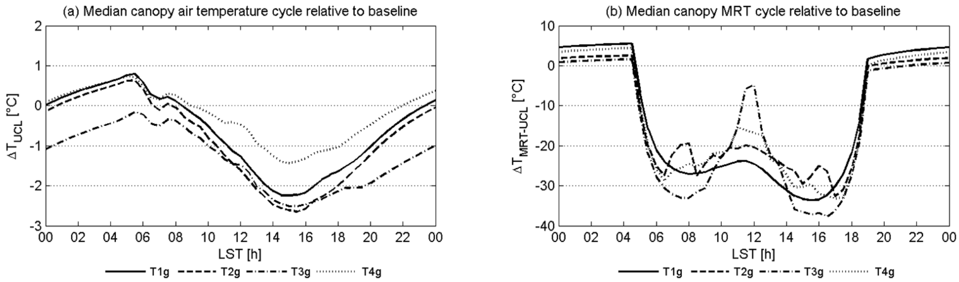

Fig. 8 Diurnal cycles of the UCL relative to the baseline, vegetated configurations: (a) potential air temperatures, (b) mean radiant temperatures

Fig. 9a presents the influence of vegetation on the distribution of relative potential air temperatures within the UCL. With the introduction of trees, the configurations with large open spaces (T2, T3) became the coolest ones. During the day, the greatest absolute cooling is achieved by T2 with over 3.5°C reduction near the ground, while the most prolonged and spatially extensive cooling within the canopy is realized by T3. In contrast, at configurations where mutual shading was already present (T1, T4) vegetation increased median canopy temperatures by 0.1–0.2°C during the day. This increase is likely the result of decreased turbulence, an effect that was also reported experimentally by Park et al. (2012). Similarly to the non-vegetated state, T3 cools down the most at night, while T4 remains the warmest configuration.

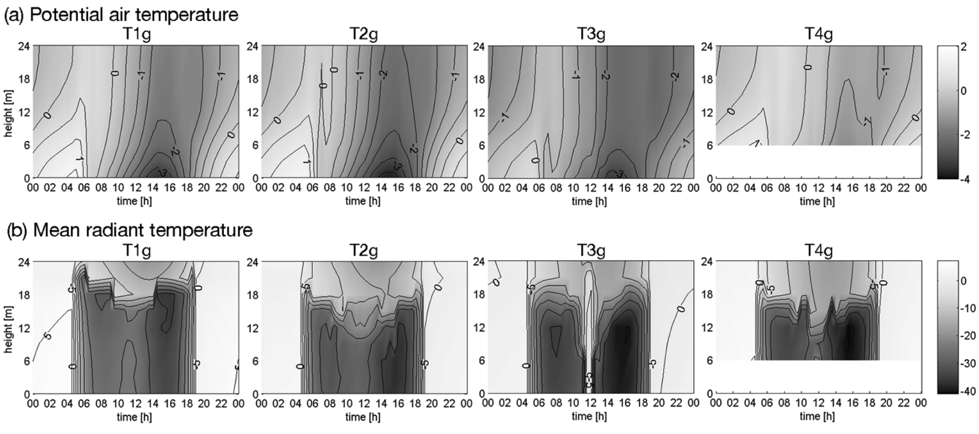

Fig. 9 Diurnal cycles of the UCL relative to the baseline, vegetated configurations: (a) potential air temperatures, (b) mean radiant temperatures

The relative MRT patterns within the canopy are shown in Fig. 9b. At 3 m vertical grid resolution, the introduced trees with medium canopy density result in a transitory MRT zone between the elevations of 15 to 21 meters. Only below this zone does the shading effect of vegetation come into full force. As already noticed above, the introduction of greenery results in radiant temperature patterns akin to the initial T1 configuration (see Fig. 7). The minor differences and apparent irregularities are the results of combined directionalities in models. The interference between building and tree layouts is best illustrated with the MRT patterns of T2 and T3. In the case of the latter, the lack of radiation reduction at noon is the outcome of the parallel north-south oriented paths between the rows of trees and buildings. When aligned with the solar azimuth angle, these spaces became fully irradiated. At T2, the slight decrease of shading during the morning and afternoon hours, around 9:00 and 15:00 respectively, are the result of the east-west oriented paths along the facades. These places became irradiated when the sun is aligned with the cardinal east-west direction. Since T4 has both north-south and east-west oriented paths, it carries the MRT pattern characteristics of both previous cases, although with smaller differences.

Fig. 10 summarizes the influence of built form and vegetation on canopy layer temperatures. Typologies without vegetation (black bars) can be divided into two groups by their microclimate dynamics. In contrast to T3, dense configurations are characterized by greater temperature range reductions, nighttime heat island magnitudes and daytime cooling (see Fig. 10a, 10b and 10c respectively). With the introduction of trees (white bars), the division between the thermal behaviors of typologies becomes more nuanced. While nighttime heat island magnitudes remained to be governed by building densities (Fig. 10b), the diurnal temperature reduction on Fig. 10a indicates a new division along the openness of typologies. In case of courtyard configurations, the diurnal temperature range of the canopy is about 1°C smaller. With regard to heat island magnitudes, the presence of vegetation decreased nocturnal values in all cases and increased daytime cool island intensities in configurations with large open spaces (T2, T3). As noted above, daytime cooling decreases slightly with the addition of vegetation to typologies where mutual shading is already present (T1, T4). These results are in line with other studies that found the ability of trees to reduce daytime temperatures limited or controversial (Ali-Toudet and Mayer 2007, Emmanuel and Fernando 2007, Spangenberg et al. 2008, Park et al. 2012).

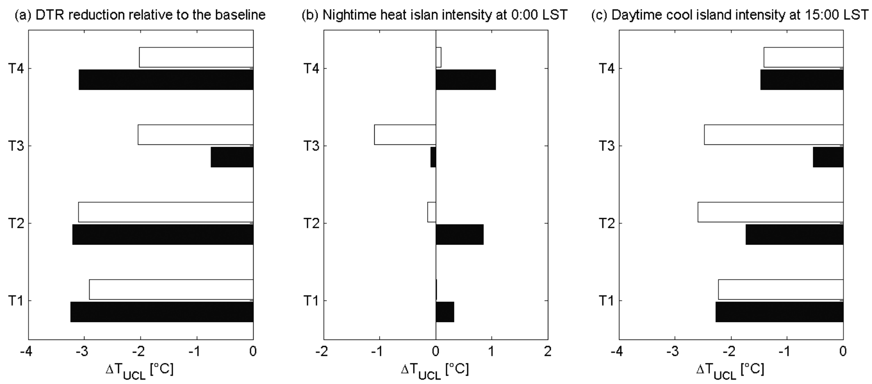

Fig. 10 UCL temperature characteristics for non-vegetated (black) and vegetated (white) configurations: (a) DTR reduction, (b) daytime UHI, (c) nighttime UHI

4. CONCLUSIONS

This paper presented the result of a numerical simulation study performed to reveal the influence of built form and vegetation on the canopy layer microclimate. The boundaries of the study were set by the identified metropolitan blocks of Budapest and by the characteristic summer climate of the city. The analysis on the role of built forms indicated the importance of building density, which, given uniform building heights, is interchangeable with building surface faction within the confines of this study. While low building density is generally associated with low nocturnal heat island intensity, if left unprotected, these areas warm up the most during the day. In reducing daytime air and radiant temperatures, shading and semi-enclosure (i.e. the effect of courtyards) were found to be effective strategies. Out of the two, shading is of primary importance in dense urban environments, since its effect may extend into the evening. According to the findings, canopy layer mean radiant temperatures are more responsive to the influences of built form. During the day, configurations with large open spaces (T2, T3) had the highest radiant temperatures, while the effect of mutual shading decreased default values by 10 to 30°C in the case of T1 and T4.

The rudimentary approach adopted to evaluate the role of vegetation confirmed that microclimate improvements by way of trees are primarily achieved through surface shading. The greatest reduction in daytime air and radiative temperatures were achieved in configurations with large open spaces (T2, T3). Although the introduction of trees slightly increased daytime temperatures at typologies where mutual shading was already present (T1, T4), it nevertheless reduced nighttime temperatures by offsetting the amount of energy intercepted by and stored in the urban texture. The controversies around the use of trees, on one hand, signal the limits of the vegetative approach to daytime temperature mitigation. The results, on the other hand, show that trees are beneficial in situations where shading is scant.

Finally, some remarks on the results and the adopted approach in evaluating the role of greenery. The effectiveness of trees to mitigate heat stresses in the built environment depends not only on the amount of vegetation (the green area ratio), but also on the plant characteristics of the adopted species (i.e. canopy geometry, height, LAD, LAI) and on the layout and distribution of greenery (e.g. Ali-Toudert and Mayer 2005, 2007, Spangenberg et al. 2008, Park et al. 2012). Although important, these parameters were not addressed by the current study. Nevertheless, the author believes that the main issues surrounding the urban use of greenery for microclimate mitigation were illustrated by this concise study. The initial assumption of 40% vegetation over the unbuilt areas of urban blocks, consisting of fully-grown trees, is certainly an optimistic one. First, 21-meter tall trees are less common in cities primarily due to the conflicts with above- and underground infrastructures, and also due to the extreme heat and drought conditions that often characterizes urban environments. Second, green roofs are rarely built with adequate supporting structures to accommodate large trees. As a consequence, the obtained results likely overestimate the effects of greenery, and point towards the decisive role of built form in shaping daytime temperatures within the UCL. These findings are in line with the results of Middler et al. (2014).

To conclude, built form and vegetation are principal factors in governing UCL microclimates. They act by means of shading and enclosure. At uniform building height, the key spatial parameters are influencing the climate between buildings are: building density (or in this special case, the building surface fraction), the openness of the configuration (i.e. the presence or absence of courtyards), and the distribution of building masses (which is signaled by the range of sky view factors calculated for the lowest points of the canopy). Given ENVI-met's limitation to account for the heat stored in building envelopes and the assumptions made in MRT calculation by the model (Ali-Toudert 2005, Huttner 2012, Kántor and Unger 2011), further investigations are needed to refine and validate the findings of this study.

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