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Enhancing Outdoor Comfort and Climate Resilience with Mitigation Strategies: Optimized Planning Methods for Tree Planting in Subtropical High-Density Cities

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ABSTRACT

The hot, humid summers of subtropical Hong Kong cause thermal discomfort, which is further intensified by the urban heat island (UHI) effect in heavily built-up areas. Urban greenery has been proposed as a mechanism for microclimate regulation, yet the thermal impact of such greenery in the high-density urban environment has seldom been discussed. This study reviewed outdoor thermal comfort criteria in the hot-humid subtropics, and evaluated the environmental effects of trees in urban areas with different urban morphology.

The study evaluates the performance of urban trees in mitigating urban heat island (UHI) effect and optimized planning methods are proposed for heavily built districts with most intense UHI. The prevailing summer weather in the hot-humid subtropics is cloudy, and will be more dominant due to climate change. It will be of regional significance to include cloudy conditions in the study of mitigation strategies to increase climate resilience in these areas. Site surveys are conducted in urban areas with sky view factor (SVF) range between 0.2 and 0.8 in both sunny and cloudy conditions. Measurements show building geometry has profound influence on the net effects of trees in cloudy condition. With modelling study, SVF-based planning method of tree planting in district scale is tested with the existing building geometry in high-density urban areas of Hong Kong. Furthermore, optimized planting locations in districts with different orientations are analysed with regards to the subtropical sun angles.

The study demonstrates that with trees planted under low SVF (<0.2), PET values is maintained in the comfort range during the most critical hours in the green spaces. More diverse outdoor thermal environments are created by arranging trees in low SVF areas, which provides the possibility for adaptive comfort and promotes resilience to a changing climate. Furthermore, the optimized solar orientations for tree planting were determined, taking into account the subtropical sun angles. Combining the optimized solar orientations with the areal wind paths can achieve maximum cooling effect and a comfortable microclimate is created during most of the summer. Findings of the study assist planners in developing greening framework at district scale and identifying optimized planting locations in the core urban areas of subtropical cities.

Key Words: UHI mitigation, tree planting, outdoor comfort, climate resilience

1. INTRODUCTION

Givoni noted that one of the objectives for urban design in hot-humid regions is minimizing thermal discomfort and reducing the heat island effect in very dense urban areas (1998). It has been noted that high population density and rapid urban growth increase the vulnerability of the subtropical regions to climate change (Patz, Campbell-Lendrum, Holloway, & Foley, 2005; Rosenzweig, Solecki, Hammer, & Mehrotra, 2011). Additionally, cities located in hot regions are at higher risk of being affected as temperatures climb (Yahia, 2014). Hong Kong suffers from an intense urban heat island (UHI) effect of as much as 2-4°C (Siu & Hart, 2013). With the effect of climate change and high-density development, increasing the heat stress would trigger health problems for the inhabitants (Goggins, Chan, Ng, Ren, & Chen, 2012). A study in Hong Kong reported a 2% increase rate in heat-related mortality associated with a 1°C increase in air temperature when reaching a threshold of 28°C (Chan, Goggins, Kim, & Griffiths, 2012). Moreover, thermal discomfort and heat stress would be more life threatening to the elderly and those with chronic illness (Chau, Chan, & Woo, 2009; Luber & McGeehin, 2008).

Passive urban design primarily by proper planning is climatically appropriate in the hot subtropical regions (Givoni, 1998). Less systematic research is available for the hot climates, especially the subtropical hot-humid, than for other climate types (Roth, 2007). Several measures including greening the city have been proposed to mitigate UHI effects (McPherson, Nowak, & Rowntree, 1994; Shashua-Bar & Hoffman, 2004; Zinzi & Agnoli, 2012). Macro-scale intra-urban measurements showed a 2-4 °C air temperature difference between urban areas and green areas in tropical and subtropical cities (Chow, Pope, Martin, & Brazel, 2011; Hamada & Ohta, 2010; Wong & Chen, 2005). Ng et al. (2012) revealed that green coverage greater than 33% would substantially reduce the thermal load in the urban areas. The existing green coverage ratio, however, is much lower than the recommended value in many core developed areas including high-density residential districts (Hui, Lam, & Ho, 2006; Jim, 1999). The problem is shared with other high-density cities in the regions, where urbanization generates significant tension in terms of vegetation cover and green space (Mensah, 2014; Nagendra, Sudhira, Katti, Tengö, & Schewenius, 2014). With low vegetation coverage ratios in heavily built urban areas, tree planting as mitigation strategies should be planned and designed properly to improve the outdoor thermal environment and enhance human comfort. Optimally planned tree planting that responds to the built environment and local climate can enhance the thermal benefits and provide a solution for highly developed areas (McPherson et al., 1994; Shashua-Bar & Hoffman, 2004). As previous findings of urban greenery studies in temperate climates with the urban sprawl forms of western cities may not be fully applied here (Jim, 2000), site-specific planning research for planting trees in high-density subtropical cities is urgently needed.

2. URBAN MORPHOLOGY AND MITIGATION EFFECTS OF GREENERY IN BUILT ENVIRONMENTS

The sky view factor (SVF) has been shown to be a key parameter to be considered in morphology-oriented studies of urban thermal environments. Unger (2009) studied the relationship between intra-urban temperature differences and areal means of SVF in a European city and noted that the areal averaged SVF would better predict the temperature differences between sites compared with point values. Studies in tropical and subtropical areas have shown that the SVF influences the thermal performance of building groups (Mills, 1997) and significantly affects the outdoor thermal comfort of residents (Krüger, Minella, & Rasia, 2011; Lin, Matzarakis, & Hwang, 2010a). A 1% reduction in the SVF was found to reduce the daytime UHI intensity by 1% to 4% in subtropical Hong Kong (Giridharan, Ganesan, & Lau, 2004). Chen et al. (2012) studied the relationship between the areal averaged SVF and the daytime air temperature increase in urban sites of the city and noted that the influence of the SVF varied with building density.

Several studies have investigated the mitigation effects of urban greenery, and the influence on human comfort in built environments. A 2.3°C cooling in air temperature was reported with 64% tree coverage in the streets with aspect ratios of 0.2-0.6 (Shashua-Bar, Hoffman, & Tzamir, 2006). Ali-Toudert and Mayer (2007) revealed that cooling in a radiant environment by vegetation was more sensitive to canyon geometry comparing to the cooling on air temperature, and a 2°C difference in the cooling magnitude on PET was found for streets with aspect ratios of 1 and 2. Shashua-Bar et al. (2012) summarized that the cooling efficiency of vegetation in an urban canyon was highly related to canopy coverage. As SVF provides a comprehensive description of urban morphology, it is necessary to study the mitigation effects of urban trees under different building geometries with SVF as an indicator.

3. METHODOLOGY

The present study investigates the mitigation impact of roadside trees, and evaluate the impact on outdoor comfort within the context of highly developed urban environments with subtropical hot-humid climate. With site survey, the study first compares the thermal effects of trees under low and high SVFs. Based on the survey results, numerical modelling is conducted to study the mitigation impact of trees in low-SVF areas in highly developed urban districts, as these areas are associated with remarkable UHI effects (Arnfield, 2003; Oke, 1981). Climatic planning strategies are then explored to provide comfortable spaces in heavily built urban areas with tree planting.

Hong Kong is a subtropical city with hot-humid climate (Hong Kong Observatory, 2015). Due to the high humidity in the subtropics, cloudy conditions dominate the weather during summer in Hong Kong, especially at noon and in the early afternoon (Giridharan, Lau, Ganesan, & Givoni, 2008). Cloudy conditions when the cloud amount reaches 6 Oktas or above occur around 70% of the summer time between 12:00 to 15:00 (HKO Cloud data 2001–2010). Furthermore, the increasing occurrences of both extreme hot weather and low-level clouds are expected in the subtropics as the result of climate change (Field & Barros, 2014). To address the “critical” and “prevailing” thermal issues in subtropical cities such as Hong Kong (Ng, 2009), this study investigates the mitigation impact of trees in built environments in both sunny and cloudy conditions. Kowloon Peninsula is among the most highly developed urban areas in the city (Planning Department, 2003), and most of the urban areas in Kowloon Peninsula have been classified as “highly developed core areas with high thermal load” on the Urban Climatic Map of Hong Kong (Fig.1). Night time UHI effect was about 3°C in Hong Kong, and ASTER data illustrated that the highest temperature occurred in the high-density urban areas on Kowloon Peninsula (Nichol & To, 2011). Therefore, Kowloon Peninsula is selected as studied area.

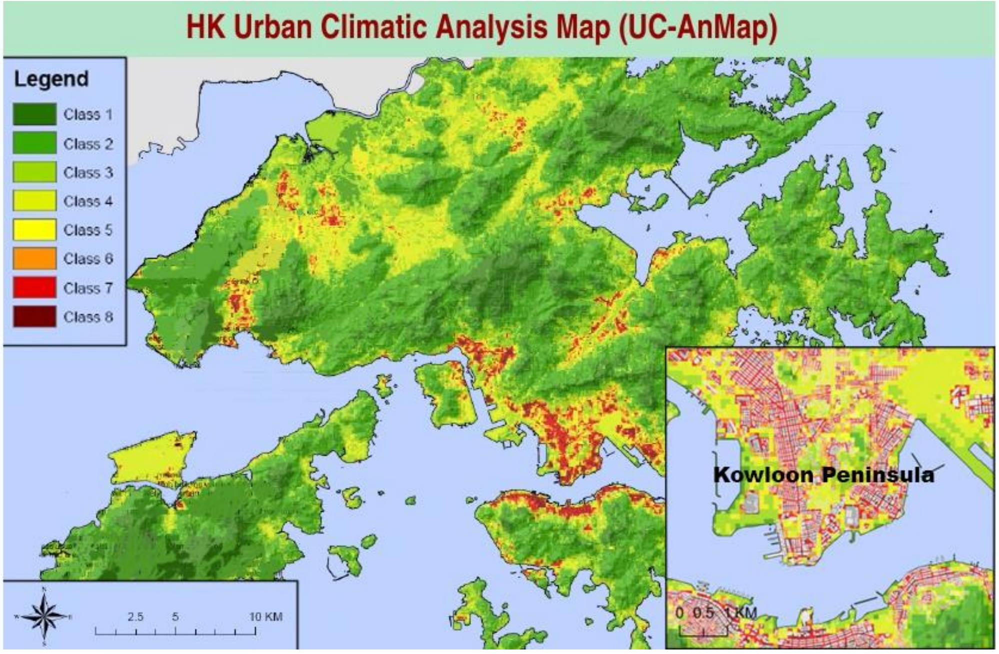


Figure 1: Kowloon Peninsula in the urban climatic map of Hong Kong

Research focused on the tropic and subtropics show that the comfort range in the regions differs from the temperate climate and has a higher threshold (Ali-Toudert & Mayer, 2006). To remain comfortable in subtropical outdoor environments in hot-humid summers, PET should not exceed 32°C and T_{mrt} should not exceed 34°C (Cheng, Ng, Chan, & Givoni, 2012; Srivanit & Auttarat, 2015). To assess the planning method in optimizing the mitigation impact of trees and improving pedestrian comfort, the comfort thresholds are adopted.

3.1. Measurement Methodology

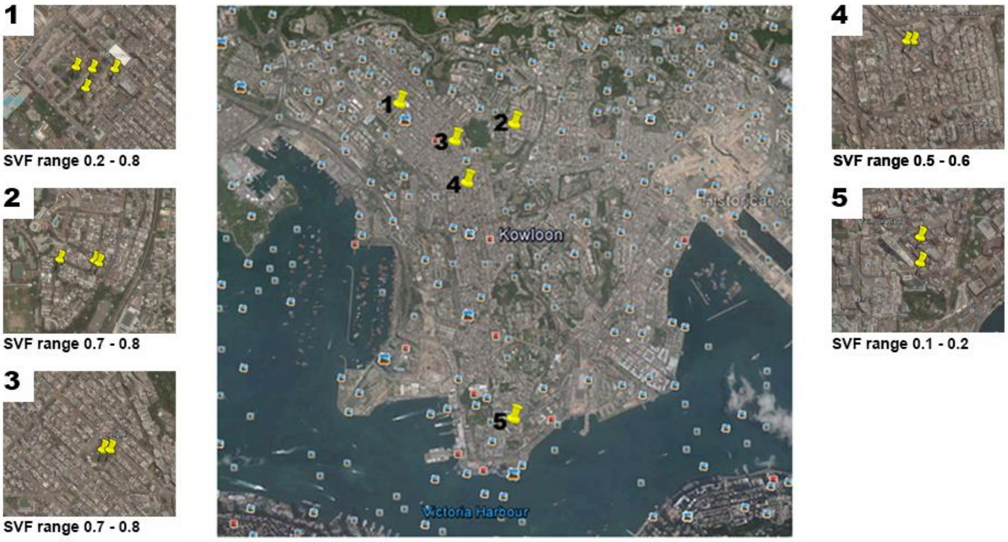


Figure 2: Measurement sites in the urban areas of Kowloon Peninsula

TESTO multi-function measuring instrument
Kipp & Zonen radiation indicator
FLIR thermography camera
Mobile Box

Figure 3: Measurement equipment

Small-scale site surveys were conducted to reveal the mitigation impact of urban trees under low and high SVF. Urban areas in Kowloon Peninsula with SVFs ranging from 0.2 to 0.8 were selected as sites to be measured (Fig. 2). For each pair of low and high SVF sites that were compared, the studied trees have similar solar transmissivity ratios (estimated by the ratio of downward radiation under a canopy and on an exposed location, measured by the thermopile-type pyranometer). Environmental variables are measured under the tree canopy and on a nearby exposed reference point at the height of 1.5 m (Armson, Stringer, & Ennos, 2012; Konarska, Lindberg, Larsson, Thorsson, & Holmer, 2014; Shashua-Bar & Hoffman, 2000). A mobile measuring unit containing an HOBO sensor and Testo400 measuring instrument was set at each measuring point to record the downward solar radiation, air temperature, relative humidity, and wind speed at a 10-sec sampling interval; the data were then averaged for analysis (Fig. 3). The globe temperature was also measured with a standard globe thermometer (diameter D = 0.15 m, emissivity ε = 0.95) using a 5-min mean (Thorsson, Lindberg, Eliasson, & Holmer, 2007). Tmrt values were then calculated with the recorded measurements (Cheng et al., 2012; Thorsson et al., 2007). The measurements were conducted from 12:30-14:00 under both clear and cloudy conditions in July and August 2014. As the measurements were conducted on different days, the background radiation was at the same range for each measured weather type. For sunny conditions, the globe radiation amounts reached 800-1000 W/m^2 and the diffuse radiation was at a low level of approximately 100-200 W/m^2. For cloudy conditions, the diffuse radiation accounted for a large fraction and remained at high levels of 350-400 W/m^2. For data representativeness, the weather criteria were set for data collection as follows: 1) the solar radiation should remain at a constant level 30-60 min before measurements and during the measurement period (referencing the solar radiation records from HKO). 2) To exclude the interference of upwind signals, only data collected under weak wind conditions (wind speeds <1.5 m/s) would be used for analysis.

3.2. Numerical Modelling

Based on the measurement results, numerical modellings were conducted to explore the climatic planning method for tree planting in the compact urban areas with low SVFs. Two densely built districts on Kowloon Peninsula with profound UHI effects were chosen to be the studied areas. Mong Kok (MK) is a highly developed urban district with an extremely high population density of 130000/km^2 (Yuan & Ng, 2012). The area has mixed land-use, and the combination of tall commercial towers and residential buildings formed a geometry that can be characterized as LCZ-1 (compact high-rise) (Stewart, Oke, & Krayenhoff, 2014). The studied MK area has an average SVF value of 0.14, with standard deviation of 0.15 (Fig. 2-6). Study (Wong & Lau, 2013) revealed that Mong Kok has the strongest UHI effect due to the existence of high-density building morphology, and that urban greenery offers a practical solution for the area. The second studied site is in Sham Shui Po (SSP), a densely built residential district (39905/km^2). The mean SVF value in the studied area was 0.23 and the related standard deviation was 0.24. The geometry of the SSP site can be characterized as a mixture of LCZ-1 (compact high-rise) and LCZ-2 (compact mid-rise). The two districts present different solar orientations in the urban context.

The three-dimensional microclimate model ENVI-met is an effective tool for micro-scale urban climate analysis (Ali-Toudert & Mayer, 2006; Ng et al., 2012), and was used in the simulation study. The accuracy of the ENVI-met model in simulating cloudy and sunny conditions was verified with measured data. For air temperature, surface temperature, and T_{mrt}, the simulated results closely matched the observed data for both clear and cloudy conditions. Average deviations between measured and simulated air temperature values were less than 0.4 °C. Moreover, strong correlations were found between the measured and simulated values of surface temperature and T_{mrt} (Fig.4).

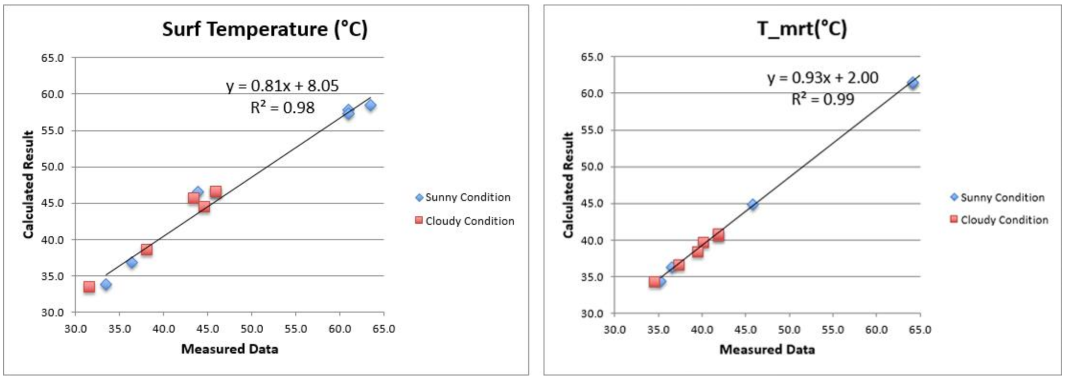


Figure 4: Correlation coefficients between measured and simulated results in different weather conditions

For simulation setting, 250 × 250 × 30 grid version was adopted for the model domain in the case study. The grid sizes were set 4 m × 4m. For both cases, there were four grid layers in the first 2m height to offer high resolution at the pedestrian level. From above 2m, the telescoping factor was set 18%. The studied sites and surrounding environments 3-times the site area were set up in the building domain. The meteorological inputs are shown in table 1. The air temperature, RH data were the averaged records of a weather station near the studied areas (August 2012). The factor of shortwave adjustment was increased to 1.2, reflecting the high radiation level in the subtropics. To simulate the clear sky condition, 2 Oktas (of a maximum of 8) of high clouds were set up in the cloud section. For the cloudy condition, 2 Oktas of medium clouds and 4 Oktas of low clouds were set for the run. The input wind data were extrapolated down from the 500 m height records of the district using the wind-profile power-law expression, with the roughness length set to be 0.1 considering the relatively low density in the upwind waterfront areas (Ng *et al.*, 2005). In the simulations, the tree model was profiled with an existing tree species in the studied area (Fig.5).

The maximum LAD of the tree model profile was 1.65 m^2/m^3 and the LAI value was 8.0. Based on the local guidelines and references (Ng et al., 2012; PNAP APP-152), the green coverage was set to 33% in the design schemes. To evaluate the mitigation impact of tree planting in heavily built districts, the 33% areas with lowest SVF values in both studied sites were identified with ArcGIS platform (Fig. 6), and trees models were arranged in these areas in the design schemes.

Table 1 Input parameters for numerical modelling

Initial Air Temperature [K]	303	Relative Humidity 2 m [%]	70
Factor of shortwave adjustment	1.2	Cloud Cover	2/8(sunny) 6/8(cloudy)
Heat Transmission Walls [W/m2K]	2	Heat Transmission Roof [W/m2K]	2
Albedo Walls	0.2	Albedo Roofs	0.3

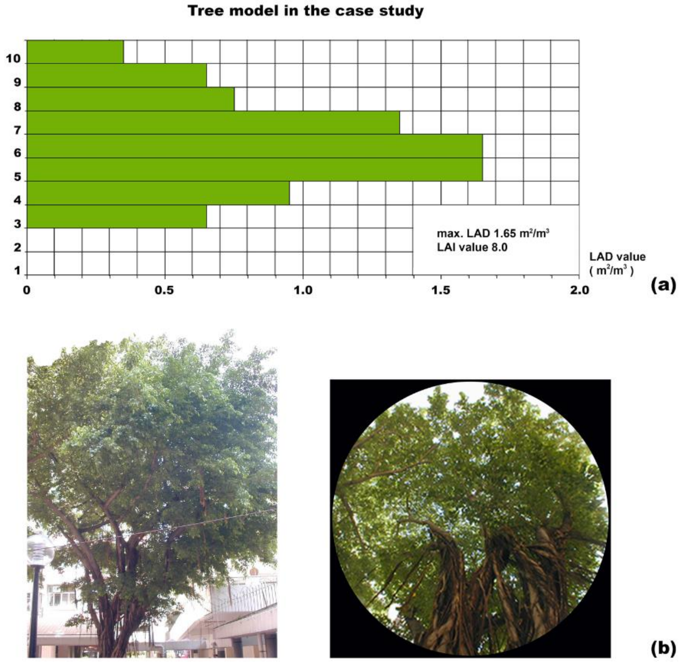


Figure 5: Tree model used in the simulation (a), profiled based on a tree species in the existing urban environment of the studied district (b)

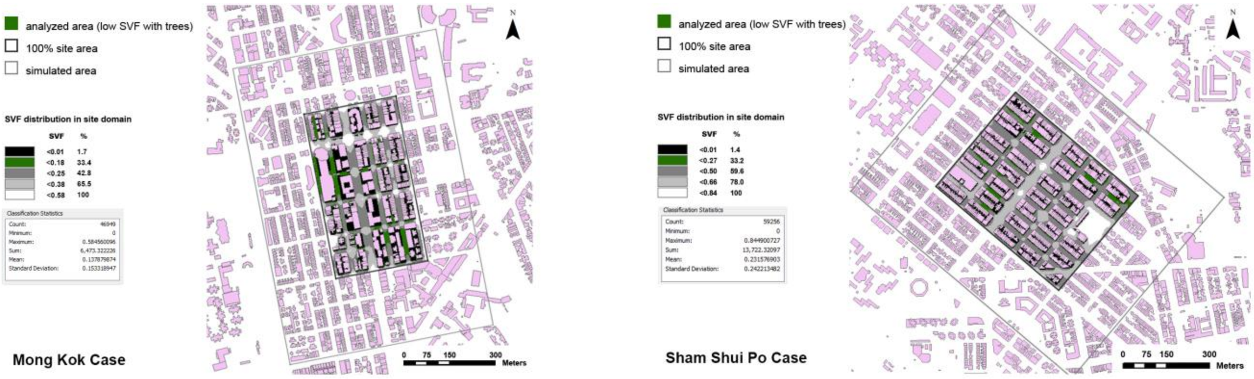


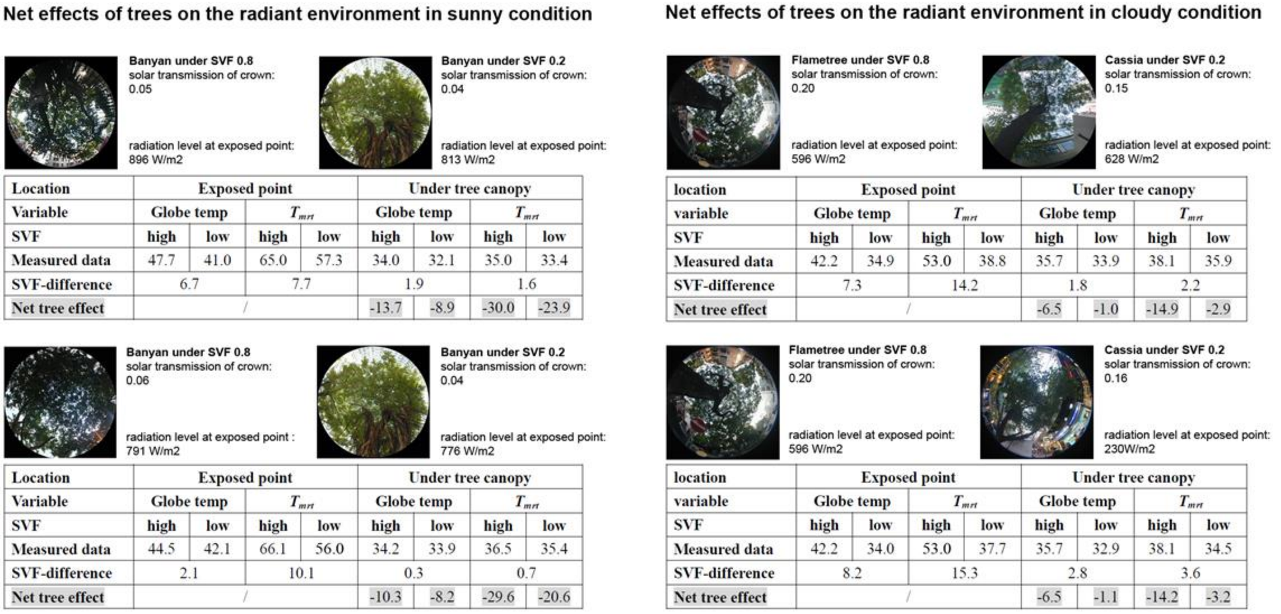
Figure 6: Areas with the lowest SVFs in both sites are identified with ArcGIS and set as green spaces

4. RESULT AND DISCUSSION

4.1. Measurement Result

The measured data show that the mitigating effects of trees are SVF-related. The measured data show that when trees of close solar transmission ratios are planted individually in urban sites with similar SVF values, equivalent cooling outcome in T_{mrt} can be achieved under similar background radiation levels. T_{mrt} reductions by trees at sites of 0.52 SVF and 0.50 SVF, were 21.7°C and 21.6°C respectively. The difference was only 0.1°C (radiation level at exposed point range between 790 W/m^2 to 820 W/m^2, tree crown solar transmission ratios around 0.08). T_{mrt} reductions by trees of 0.06 solar transmission ratio at sites of 0.73 SVF and 0.70 SVF were 17.5°C and 17.0°C, a small difference of 0.5°C (radiation level at exposed point range between 790 W/m^2 to 820 W/m^2, tree crown solar transmission ratios around 0.06).

The measurement also compared the cooling effects of trees under low SVF and high SVF to evaluate the impact of building morphology. The physical environmental variables were measured at sites with SVF values of 0.2 and 0.8 individually in sunny and cloudy conditions. In both sunny and cloudy conditions, there are significant differences in the net environmental effects of trees planted under low SVF and high SVF (see Fig. 6). The net cooling effects on T_{mrt} under high SVF and low SVF were about 30°C and 23°C, respectively; the difference was about 7°C in sunny weather. For cloudy conditions, the cooling magnitude reduced to 15°C under high SVF and 3.0°C under low SVF, the difference increased to 12°C. The results indicate that larger cooling magnitudes in globe temperature and T_{mrt} were observed at the high SVF sites comparing to the low SVF ones. As the influence of background weather, the cooling effects of urban trees were more significant during sunny days. On the other hand, the influence from building morphology, which was assessed by the difference of net cooling magnitude of trees under low and high SVF, was more evident under cloudy weather. In cloudy conditions, the diffuse radiation comes from different parts of the sky hemisphere and is more uniform over the sky, compared to a sunny case during the early-afternoon period (Noorian, Moradi, & Kamali, 2008). Therefore, given the same background radiation level and the transmissivity of tree canopies, the cooling effects of trees in reducing T_{mrt} would be subject to the fraction of the sky being obstructed by the crowns under cloudy weather, which varies with the SVF value of the site.



Location	Exposed point				Under tree canopy			
Variable	Globe temp		T_{mrt}		Globe temp		T_{mrt}	
SVF	high	low	high	low	high	low	high	low
Measured data	47.7	41.0	65.0	57.3	34.0	32.1	35.0	33.4
SVF-difference	6.7		7.7		1.9		1.6	
Net tree effect	/				-13.7	-8.9	-30.0	-23.9

Location	Exposed point				Under tree canopy			
Variable	Globe temp		T_{mrt}		Globe temp		T_{mrt}	
SVF	high	low	high	low	high	low	high	low
Measured data	44.5	42.1	66.1	56.0	34.2	33.9	36.5	35.4
SVF-difference	2.1		10.1		0.3		0.7	
Net tree effect	/				-10.3	-8.2	-29.6	-20.6

location	Exposed point				Under tree canopy			
variable	Globe temp		T_{mrt}		Globe temp		T_{mrt}	
SVF	high	low	high	low	high	low	high	low
Measured data	42.2	34.9	53.0	38.8	35.7	33.9	38.1	35.9
SVF-difference	7.3		14.2		1.8		2.2	
Net tree effect	/				-6.5	-1.0	-14.9	-2.9

location	Exposed point				Under tree canopy			
variable	Globe temp		T_{mrt}		Globe temp		T_{mrt}	
SVF	high	low	high	low	high	low	high	low
Measured data	42.2	34.0	53.0	37.7	35.7	32.9	38.1	34.5
SVF-difference	8.2		15.3		2.8		3.6	
Net tree effect	/				-6.5	-1.1	-14.2	-3.2

Figure 7: Comparison between reductions on globe temperature and T_{mrt} under low SVF and high SVF

The measurement results indicates that the impact of building morphology on the net effect of trees is more evident under cloudy conditions. Such results emphasize the significance of studying morphology-based planning strategies for roadside tree design in subtropical cities, because a large part of the region is dominated by cloudy weather during summer. Based on the results, further studies with numerical modelling were conducted to investigate that in the heavily built urban areas with low SVFs, how the spatial relationship between buildings and the subtropical sun angle and areal wind direction influence the thermal effects of roadside trees.

4.2. Simulation Result

In the simulations, roadside trees were arranged in the 33% of the areas with the lowest SVF values (i.e., the analysed areas) in both of the studied districts. Simulation results for the early-afternoon period were used for analysis. For the MK site, trees were placed in areas with SVF values of 0.18 or below. For the SSP site, areas with SVF values lower than 0.28 were designed as green space.

The simulation results showed that in the base case (without trees) of MK, the T_{mrt} values were between 35–40°C under the shades of buildings, and were close to 50°C in exposed spots in the analysed areas during cloudy conditions. For the sunny conditions (cloud fraction 2/8, high-level clouds), the T_{mrt} values were between 43–47°C in shade and above 60°C in exposed spots. Similar high values were recorded in the urban areas of subtropical cities in summer (Lin, Matzarakis, & Hwang, 2010b; Ng & Cheng, 2012). In the greening scheme, the T_{mrt} values were lowered to 32–34°C in most of the green space during cloudy conditions. For the sunny conditions, the T_{mrt} values were 35.5–38.4°C in the analysed areas with trees (Fig. 8). In the base case of SSP, the T_{mrt} values exceeded 50°C in the hot spots in the analysed areas in the cloudy condition. Fig. 8 presents the spatial distribution of T_{mrt} for the greening design scheme with the SVF contours. In the green space with tree planting, low T_{mrt} values of 31.1–32.8°C were obtained in areas with low SVF. In the analysed areas with SVF values around 0.3, the T_{mrt} values under tree canopy were between 34.3–36.4°C, close to the comfortable range (Fig. 9). The above results demonstrated that the SVF-oriented planning method for tree planting could create comfortable radiant environments in compact districts of subtropical cities in nearly 70% of sunny periods.

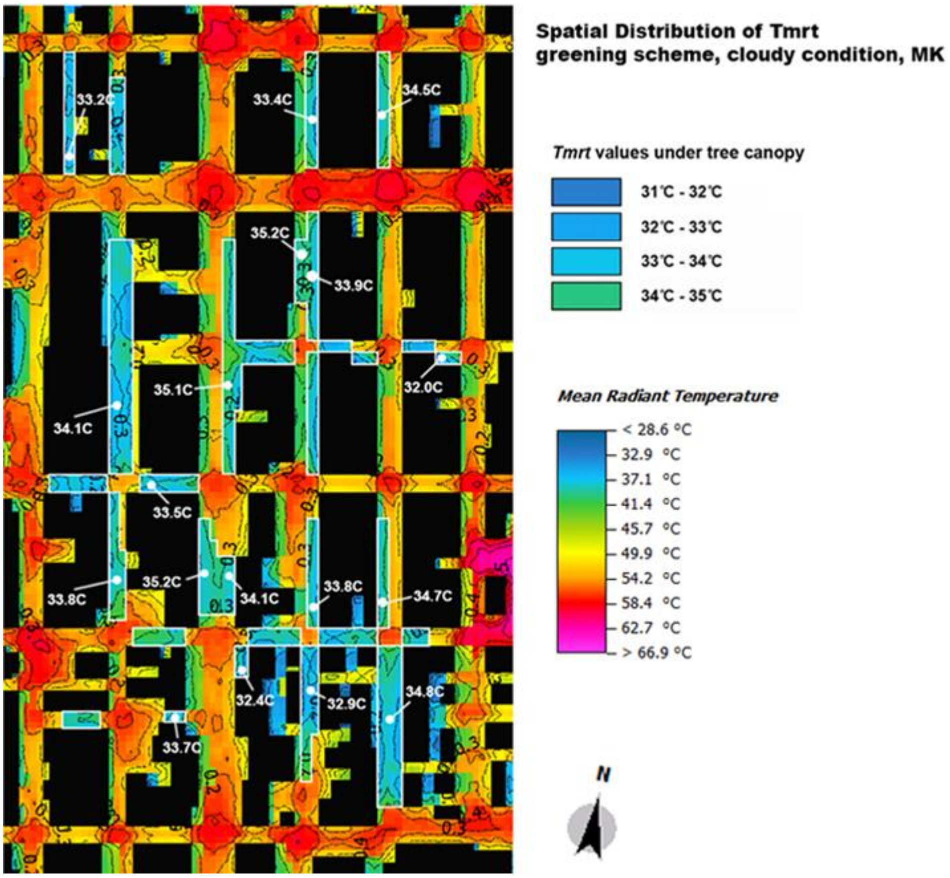


Figure 8: Spatial distribution of T_{mrt} for the greening scheme in cloudy condition, MK (SVF values are represented by contour lines with 0.1 intervals; white frames indicate the analysed areas with trees)

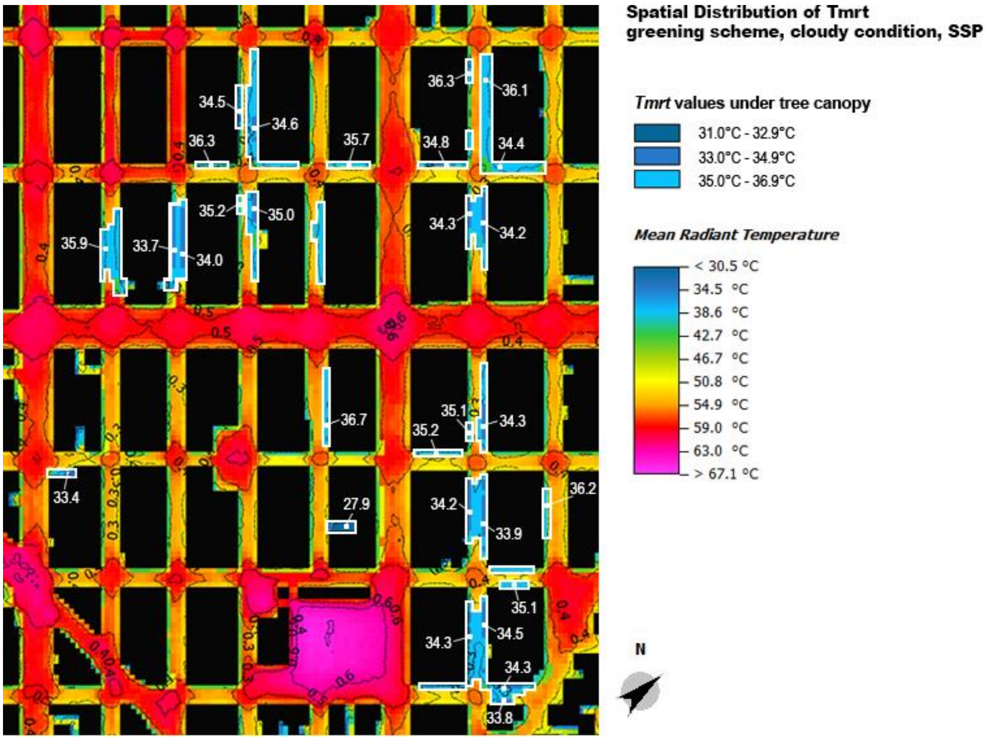


Figure 9: Spatial distribution of T_{mrt} for the greening scheme in cloudy condition, SSP (SVF values are represented by contour lines with 0.1 intervals; white frames indicate the analysed areas with trees)

The adjacent shading effects of building blocks in subtropical areas were determined by the sun position during specific periods (Chan, 2012), which also causes spatial diversity in the thermal effects of roadside trees at a particular site. The studied MK site in offered an example of sites that are N-S and E-W orientated or slightly rotated. The T_{mrt} values in the base case were compared with the greening case and the results for early afternoon hours indicate that the roadside trees have their maximum benefits achieved, when planted on when planted on the northern and southern sides of the buildings, i.e. the E-W orientated areas, and on the western sides of the building blocks in N-S orientated areas (reductions of T_{mrt} reached 12.8–14.8°C). Cooling effects on surface temperature had similar pattern. The reduction on the surface temperature of ground surface under tree canopy was about 8-13°C at the above orientations. The studied SSP site presents an example of sites with intermediate orientations. The building blocks are 50° rotated from the N-S orientations and the green spaces are NW-SE and SW-NE orientated at the studied site of SSP district. Roadside trees arranged on Southwestern sides of buildings in NW-SE oriented areas, and north-western sides of buildings in SW-NE oriented areas, have profound thermal effects and the T_{mrt} values at pedestrian level were reduced by 12–16°C. These results showed that in terms of reducing radiative heat load in urban areas, optimized tree-planting location can be determined considering the spatial relationship between buildings and the subtropical sun angles at a particular site (Fig. 10-11).

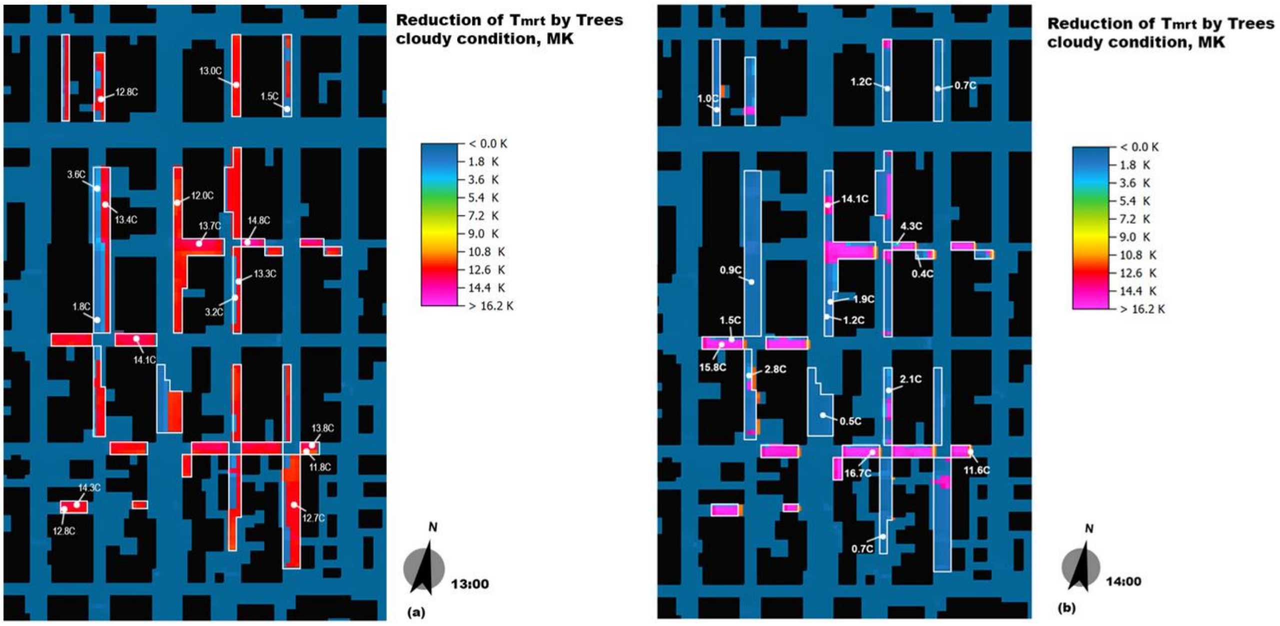


Figure 10: Spatial distribution of T_{mrt} reduction for the greening scheme in cloudy condition, MK

Figure 11: Spatial distribution of Tmrt reduction for the greening scheme in cloudy condition, SSP

In terms of PET values, with the existing building geometry in MK, the PET values in the analysed areas were 31.9–38.7°C in the cloudy conditions and 34.5–40°C (under shades of the buildings) or even above 50 °C (in exposed spots) in sunny conditions. Such high values are not unusual in subtropical cities with hot-humid climate (Spagnolo & De Dear, 2003). With the trees arranged in areas with low SVFs (<0.18), PET values at 1.5-m height were below 32°C in most of the analysed areas during cloudy conditions, with minima at around 28.8°C in several cool spots. For green spaces that have higher PET, the values were mostly 32–33°C, very close to the comfort range. The PET values were also substantially reduced to 33.2–37.8°C in the sunny condition. Building geometry in SSP is less compact compared to MK. Fig. 12-b shows the spatial distribution of PET in the green scheme of SSP. As the trees are arranged under higher SVF compared to MK, the PET values are higher. However, main streets in the SSP site are parallel to areal wind direction (see Fig. 12-a), and PET values in green spaces on the wind paths were obviously lower than those at leeward positions. Simulation results also showed that substantial cooling effects in PET values were achieved by trees planted on the southwestern sides of the building blocks in the NW-SE oriented streets (Fig. 13-a), which can be explained by the profound effects in T_{mrt} reduction results from optimized planting orientation. And in those locations that integrate the optimized planting orientation and wind paths (Fig. 13-b,c), 7–8°C cooling in PET was created and a comfortable microclimate was offered in these green spaces in cloudy condition (with PET=31.7°C). The result agrees with Ng and Cheng (2012) on the comfort criteria in the urban environment in a subtropical hot-humid climate.

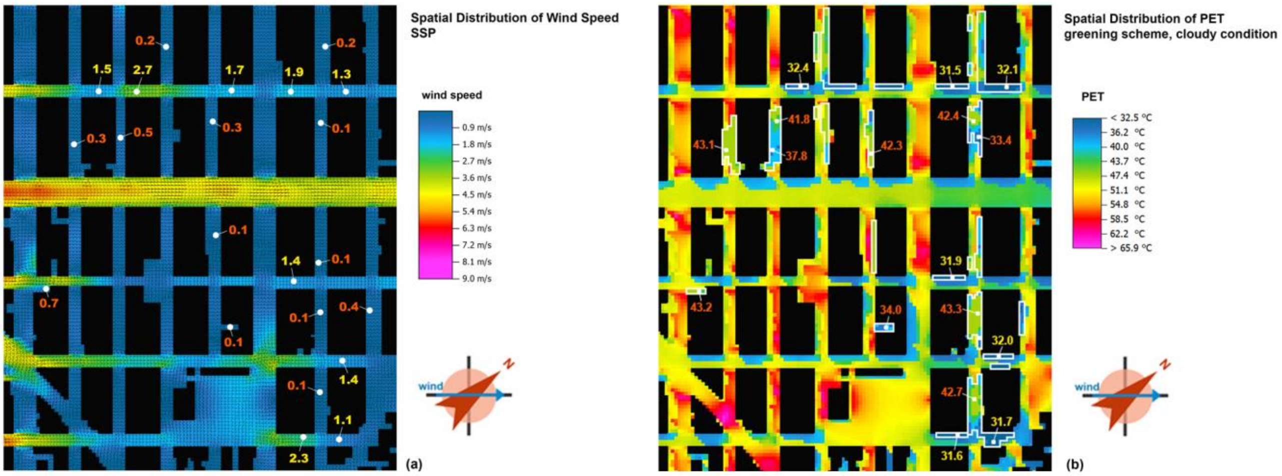


Figure 12: (a) wind speeds in wind paths and leeward areas in base case of SSP and (b) spatial distribution of PET in the greening scheme, cloudy condition

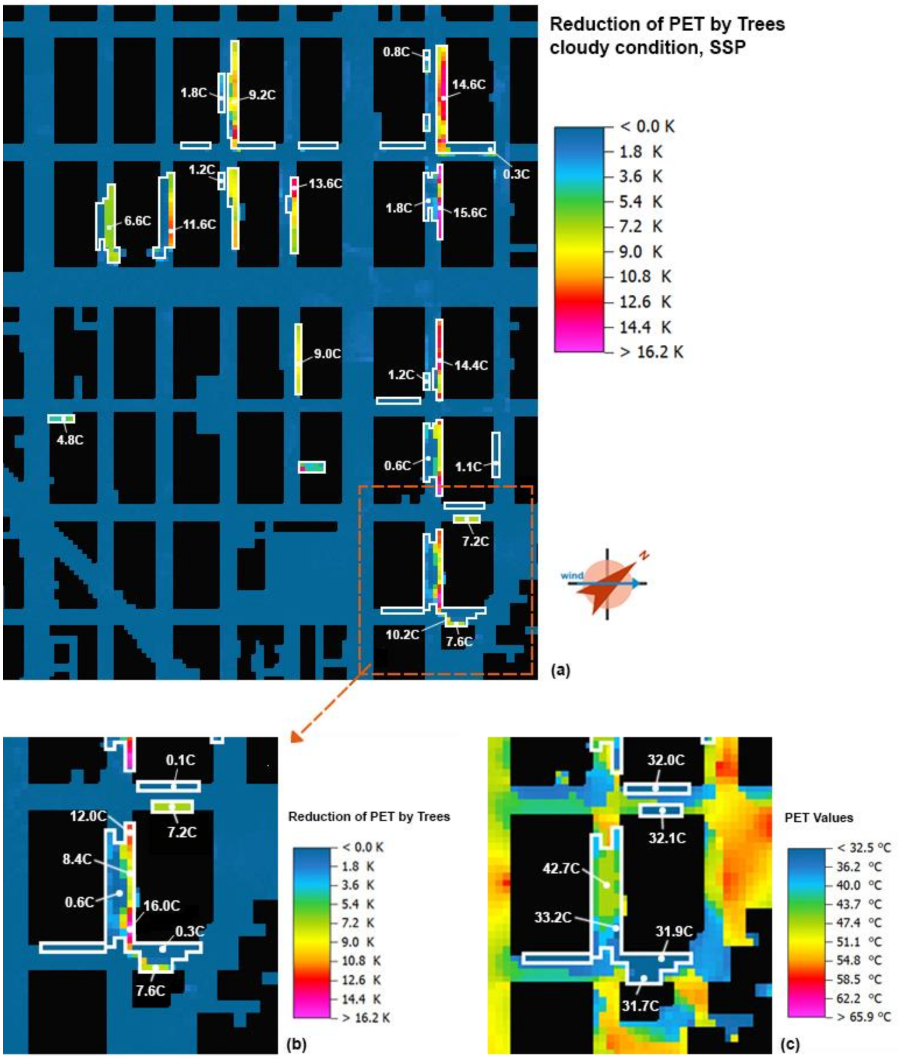


Figure13: (a) and (b) spatial distribution of PET reduction for the greening scheme in cloudy condition, SSP. (c) PET values at pedestrian level in the green areas presented in (b)

4.3. Planning Implication for Roadside Tree Planting in Subtropical High-Density Districts

Ali-Toudert and Mayer (2007) noted that it is difficult to achieve a comfortable outdoor environment with passive design strategies during summer in the subtropics. Therefore, it is essential to study planning method that responds to the built environment and local climate, so that the benefits of tree planting can be optimized in subtropical. Measurement results indicate that the influence of building geometry is more evident under cloudy conditions than sunny conditions. Both measured data and simulation results indicated that by tree planting only, a comfortable microclimate was provided in those heavily built urban areas with low SVF during most of the summer in the subtropics. In his recent study, de Dear (2011) proposed the concept thermal alliesthesia. Instead of avoiding thermal stress and providing uniform neutral sensation in urban space, he suggested designing for thermal pleasantness that would be stimulated by a dynamic anisothermal environment and spatial diversity. Moreover, thermal diversity in urban environment helps to build resilience and to increase adaptive capacity to climate change in a region (Kwok & Rajkovich, 2010; Nicol & Humphreys, 2002). Therefore, at district-level planning, planning of roadside trees planting is advisable to consider urban areas with low SVF, to increase spatial diversity and enhance contrast in thermal sensation. While at more detailed site-specific planning, priority in tree planting should be given to low-SVF areas with optimized orientations and/or those located on areal wind paths.

5. CONCLUSION

The study provided quantitative data on the mitigating impact of roadside trees in highly developed urban areas, and addressed the “critical” and “prevailing” thermal issues in the subtropics by assessing the thermal effects of trees under both sunny and cloudy conditions. Furthermore, the study has resulted in SVF-oriented planning recommendations for roadside tree planting at district scale, as well as site-level climatic planning strategies for tree arrangement in heavily built urban environments with profound UHI effects.

Urban greenery has multiple ecological functions in the urban environment. Only the aspects of microclimate regulation and outdoor comfort enhancement of urban trees is discussed in this study. In future studies, planning consideration of other ecological functions, such as supporting the ecosystems in the city, accessibility of urban green space for different age groups, and aesthetic and psychological benefits of urban greenery to urban landscaping, should be linked judiciously and taken into account for developing greening master plans at the city scale.

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