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Urban tree design approaches for mitigating daytime urban heat island effects in a high-density urban environment

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ABSTRACT

Hong Kong suffers from an intense urban heat island (UHI) effect of up to 4 °C as a result of compact urban form and highly urbanized land cover. Enhancing the cooling efficiency of urban greenery is essential for improving the microclimate in high-density cities. This paper aims to delineate design strategies for urban greenery to maximize thermal benefits and mitigate the daytime UHI effect. Two site-specific design strategies for tree planting in the urban environment are proposed. The sky view factor (SVF)-based design approach and the wind-path design approach are evaluated in the neighbourhood scale in two climate-sensitive areas with different urban morphologies. Observed data and simulation results indicated that the cooling effect of urban trees is highly associated with SVF. Air temperature reduction (a 1.5 °C reduction) is the most profound for the high SVF scenario, whereas substantial radiation shading (T_{mrt} reduced to 34 °C) is detected in areas with medium-low SVFs. The modelling study also showed that the cooling of air temperature and sensible heat were twice as high for vegetation arranged in wind corridors than those for leeward areas. The study demonstrated that tree planting in conjunction with proper planning is an effective measure to mitigate daytime UHI.

1. Introduction

High population density and rapid urban growth increase the vulnerability of cities to climate change [1]. As one of the world's high-density cities, Hong Kong suffers from a severe urban heat island (UHI) effect. According to Siu and Hart [2], the annual UHI intensity in Hong Kong ranges from 2 °C to 4 °C. With the effect of climate change and high-density development, increasing heat stress would trigger health problems for the habitants [3]. A study of Hong Kong reported a 2% increase rate in heat-related mortality associated with a 1 °C increase of air temperature when the threshold of 28 °C is reached [4]. Moreover, thermal discomfort and heat stress would be more fatal to the elderly and those with chronic illness [5,6].

Urban greenery has been proposed as an effective measure to mitigate UHI in the city and improve the urban microclimate. Intra-urban measurement at the macro scale showed a 4 °C difference in the air temperature between the urban centre and a well planted area in the city [7]. Armson et al. [8] also showed that greenery could effectively cool urban surfaces by 20 °C, and that shading by trees could reduce the global temperature by 5 °C to 7 °C, thus providing a more comfortable microclimate in cities. The environmental effects of vegetation depend on foliage density [9] and the leaf area index (LAI)[1] and leaf area density (LAD)[2] proved to be important metrics in determining cooling outcomes [10]. A study on hot humid climates demonstrated that with maximum LAD being 1.0 m^2/m^3 and LAI value around 5, air temperature and surface temperature were reduced by 1.3 °C and 14.7 °C, respectively [11]. A modelling study for hot dry climates showed that 84% of free horizontal direct radiation was intercepted by tree canopy with a maximum LAD of 1.8 m^2/m^3 and LAI value of 3 [12]. The green coverage ratio in an urban area also significantly affected the air temperature distribution and UHI intensity [13]. A microclimate study of the building block scale revealed that a 10% increase in the green/built area ratio would create 0.8 °C cooling [14]. Observational studies of urban greenery further showed that urban parks would be 1 °C cooler than non-vegetated sites [15]. About 20% to 30% coverage of greenery has been proposed as a mitigation measure for newly built projects

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[1] LAI is defined as a dimensionless value for the total upper leaves area (one-sided) per unit planting ground area.
[2] LAD is defined as the total leaves area (one-sided) per unit layer volume of a tree's horizontal slices along the height of a tree [10].

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to improve the living environment in Hong Kong [16]. Achieving this standard greenery coverage in many urban areas is challenging because of intense urban land use and compact urban morphology. As cities continue to develop, their increasing density may result in environmental issues [17]. In this regard, strategies for optimizing greenery design with regard to the built environment and local climatic conditions can enhance thermal benefits of vegetation in urban areas [18,19]. Hence, further research on context-based planning and design strategies for greenery in high-density cities is necessary [15]. The present study evaluated two site-specific design approaches for urban trees on mitigating daytime UHI in a compact urban environment. The findings could quantify the cooling effect of different greenery design strategies at the site-level. Urban planners and designers can employ this knowledge to maximize the use of greenery design to improve daytime thermal comfort and mitigate the UHI effect in high-density urban environments.

2. Urban thermal environment and climatic planning

2.1. Sky view factor (SVF) as a thermal indicator

SVF is an important factor in morphology-related urban microclimate studies. Mills [20] reported that solar exposure and SVF are two key factors that determine the daily heat balance of building structures. Holst and Mayer [21] also investigated the thermal conditions in street canyons and observed a linear relationship between the mean radiant temperature (T_{mrt}) and SVF. Giridharan et al. [22] further reported that a 1% reduction in SVF would reduce the daytime UHI intensity by 1–4% under subtropical climatic conditions. However, the effect of SVF on UHI intensity was only evaluated within a small range (up to SVF = 0.4) in their study.

SVF is also associated with intra-urban temperature differences. Areal SVF average, as an indicator of the building geometry of urban areas, is linearly correlated with temperature variations in the city centre [23]. Chen et al. [24] reported an inversely proportional relationship between areal averaged SVF and daytime air temperature elevation in urban sites. They also found that the influence of SVF varied with building density. In the present study, SVF is the key variable to provide a comprehensive description of urban geometry [25,26], and the studied range of SVF is extended up to 0.8 in order to investigate morphology-based design strategies for urban greenery in improving the outdoor thermal environment.

2.2. Greenery cooling and wind effect

Several studies have indicated that the vegetation effect on the urban microclimate is associated with wind. Taha et al. [27] found that a tree could influence the downwind air temperature up to a distance of about five times its height. Parametric studies have shown that proper arrangement of trees with respect to wind could improve pedestrian thermal comfort around buildings [28]; nevertheless, the studies focused on a relatively small scale. Alexandri and Jones [29] studied the influence of wind direction on the cooling outcome of vegetation in street canyons, and pointed out that the influence was less significant when the wind speed was low. Dimoudi and Nikolopoulou [14] reported similar finding that the cooling effect in the downwind areas of an urban park was strongly subject to wind direction. Bruse [30] further demonstrated that urban greenery could generate substantial cooling in downwind areas, though this effect was compromised if the streets were not parallel to the wind direction. Ng [31] established planning guidelines for urban ventilation improvement and suggested combining urban greenery with major breezeways in the city for thermal comfort enhancement. To further study the influence of wind conditions on the cooling effect of urban greenery, the present study investigates the variation in cooling outcomes of trees when arranged at different angles to the wind direction. Strategies are also considered for utilizing the synergetic effect of greenery and wind to optimize the environmental benefits in high-density urban areas.

3. Methodology

3.1. Area studied and sensitivity test

This study considers two morphology-oriented design strategies for tree planting in high-density areas of Hong Kong. A SVF-based approach is proposed for urban areas with an irregular building layout and different building heights, while a wind-path approach is recommended for areas with regular building block arrays and a prevailing summer wind direction. Sensitivity test and modelling study are conducted to evaluate these two design approaches. Hong Kong is located at 22°16′42″ N 114°09′32″ E with a hot-humid subtropical climate. The daily maximum temperature exceeds 31 °C in the afternoon during summer (Hong Kong Observatory). The high-rise high-density urban form and decrease in vegetation cover intensify the UHI effect [32]. The Urban Climatic Map for Hong Kong was established and the city has been categorized into eight climatic classes based on a balanced consideration of local thermal load and wind potential [33]. Tsim Sha Tsui (TST) and Sham Shui Po (SSP) are two waterfront districts with high climate sensitivity. These two areas have been classified as ‘highly developed core areas with high thermal load’ zones on the Urban Climatic Map (Fig. 1b), and mitigation actions are essential and required in these areas. These two areas were selected as studied areas because of their representative urban morphology and areal climate characteristics.

The studied TST area has mixed land uses, and the combination of tall commercial towers and residential buildings also presents an irregular distribution. Total building volume in the area is about 11,718,000 m^3. The mean building height is 37 m with a standard deviation of 24 m. The SVF values at ground level vary from lower than 0.2 to near 0.8 in the studied area (Fig. 1c). In the first modelling study, the morphology-based method is tested with the morphology of the selected TST area. The cooling effects of the following design scenarios are compared:

1. Trees arranged in spots with low SVF (<0.2).
2. Trees arranged in spots with medium SVF (0.2–0.4).
3. Trees arranged in spots with high SVF (0.4–0.8).

The studied SSP area is a traditional residential district with regular block array geometry. The total building volume in the area is 16,722,000 m^3, and the average building height is 32 m with a standard deviation of 15 m. This area is next to the waterfront and the main streets in the selected site are parallel or 45° to the prevailing summer wind from the sea. A wind-orientated planning approach for tree arrangement is tested in the studied area using a simulation. The thermal performance of trees in the following design scenarios is analysed:

1. Trees arranged in streets parallel to summer wind direction (along wind path).
2. Trees arranged in streets perpendicular to summer wind direction (at sheltered position).
3. Trees arranged in streets aligned 45° to summer wind direction (smaller wind speed).

The guidelines of urban planning and building design established by the Hong Kong Planning Department suggest 20–30%

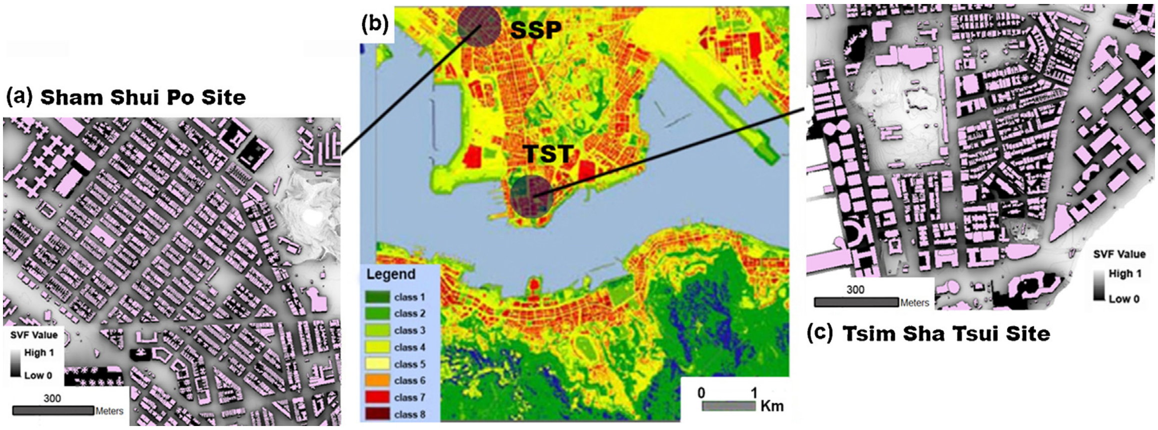

Fig. 1. (b) Locations of the selected sites on the Urban Climatic Map (UC-Map) of Hong Kong, zones with darker colour are highly developed areas with hot temperature and high thermal load; (a) and (c) building layout and spatial distribution of SVF in the studied areas of SSP (a) and TST (c). (based on Chen et al. [24]).

green coverage for individual sites in Hong Kong [34]. In the case study, a green ratio of 25% was adopted. For different design scenarios, the influence of trees on air temperature (T_a) and surface temperature (T_s), as well as on the radiant and convective environment, are compared to assess the performance in mitigating daytime UHI. It has been pointed out that T_{mrt} is a key parameter to assess the outdoor thermal environment in cities with hot climates [35,36]. The comfort range for T_{mrt} in the tropics and subtropics has been studied [37,38]. Hence, the cooling effect on T_{mrt} is also analysed to evaluate different design approaches.

A sensitive test with site measurement was conducted to compare the effect of trees under low and high SVF. The two survey sites were located in a public housing estate with limited traffic, one with 0.2 SVF and one with 0.8 SVF (Fig. 2). Measurements were performed on a sunny day in late June 2014 during 13:00–14:00, as the effect of trees is evident in the early-afternoon period [39]. The studied trees in the two sites were of the same species (*Ficus microcarpa*, 12–15 m high), and had similar solar transmissivity ratios around 0.06–0.07 (measured by thermopile-type pyranometer, see Fig. 2). Mobile measuring boxes that contained the HOBO sensors and the Testo measuring instrument were set at 1.5 m high under the canopy of the studied tree and in a nearby exposed reference point in the survey sites [8,40], and air temperature, relative humidity, and wind speed were recorded with a 10 s sampling interval, and the data were averaged for analysis. Globe temperature was also measured at each testing point with a standard-size black-globe thermometer using a 5 min mean [41]. Value of T_{mrt} was then calculated with the measured variables using the equation [41,42]:

$$T_{mrt} = \left[(T_g + 273.15)^4 + \frac{1.1 \times 10^8 \nu_a^{0.6}}{\varepsilon D^{0.4}} \times (T_g - T_a) \right]^{1/4} - 273.15 \quad (1)$$

where T_g and T_a represent the globe temperature and air temperature, respectively; ν_a is the air velocity, D and ε are the diameter and emissivity of the globe. To guarantee data representativeness, radiation record from the Hong Kong Observatory was referenced to check that the radiation level did not largely fluctuate 30–60 min before the measurement and during the measuring period. And to exclude the interference of upwind signals, only data collected under weak wind conditions (wind speed <1.5 m/s) were used for analysis.

3.2. Model validation and simulation setting

3.2.1. Model validation

The three-dimensional microclimate model ENVI-met (version 3.1) is used to analyse the proposed planning methods for tree planting in the two studied areas individually. The model simulates the micro-scale interactions among urban surfaces, vegetation, and the atmosphere. A vegetation scheme is included in the model, which calculates the turbulence acceleration, the additional exchange processes around vegetation, and the reduction in direct and diffuse radiation based on the leaf area index. A test run was conducted to validate the vegetation model of ENVI-met 3.1 with observed data. The data were collected between 13:00 and 14:00 on a clear sunny day in early July 2014. Fig. 3 shows the building layout of the survey site and the locations of the three trees being measured. It was a low-traffic residential area with trees of different species planted along the roadside. Thermal indicators were measured under the canopies of a *F. microcarpa*, a *Melaleuca cajuputi*, and a *Spathodea campanulata* and exposed reference points at 1.5 m high with HOBO sensors and Testo measuring instrument. The sampling interval was 10 s and a 15 min mean was recorded. T_{mrt} was calculated with the observed data using Eq. (1). With a FLIR thermography camera the surface temperatures of the road areas that were shaded by a tree and exposed to radiation were also recorded (Fig. 2). A self-developed leaf area density (LAD) profile was established for each measured tree (Fig. 4), based on

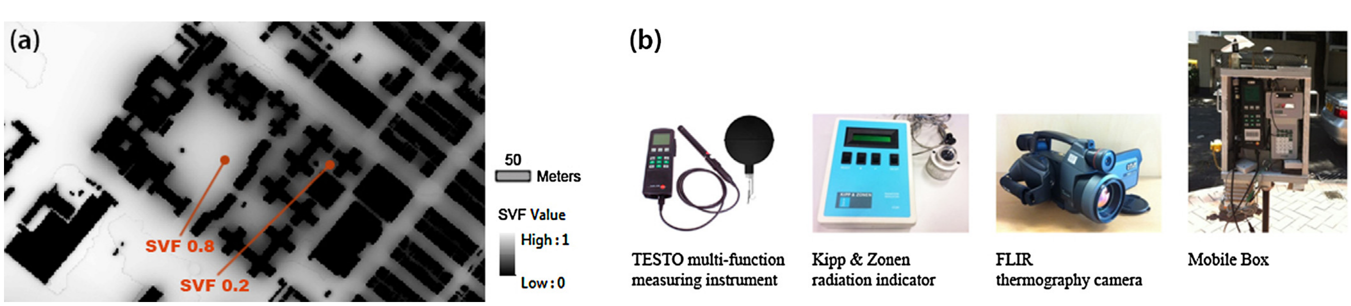

Fig. 2. (a) Selected site for sensitivity test; (b) measuring equipment for site survey.

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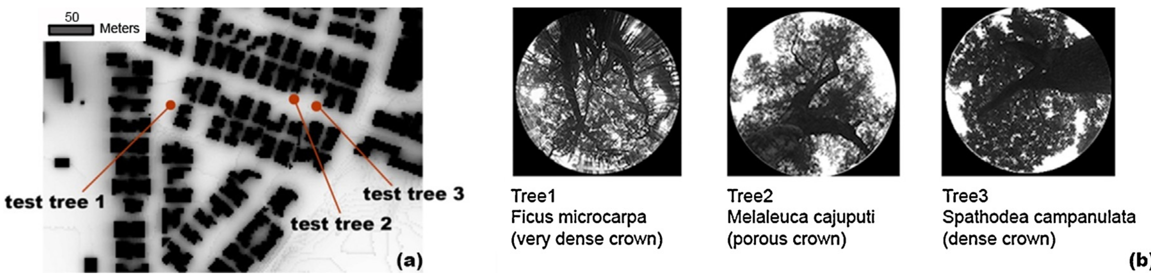
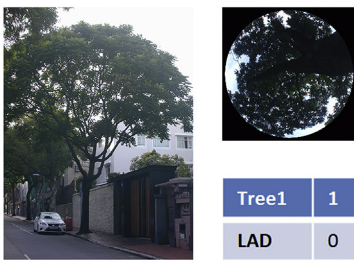


Fig. 3. (a) Measuring site of small-scale survey for model validation; (b) fisheye images of the measuring trees.



Tree1	1	2	3	4	5	6	7	8	9	10
LAD	0	0	0	0.07	0.35	0.75	0.75	1.05	0.95	0.86

Tree2	1	2	3	4	5	6	7	8	9	10
LAD	0	0	0	0.35	0.65	0.50	0.25	0.15	0.04	0.02

Tree3	1	2	3	4	5	6	7	8	9	10
LAD	0	0	0.75	0.75	1.05	1.75	1.35	1.05	0.75	0.35

Fig. 4. Leaf area density (LAD) profile was established for each measured tree based on canopy cover and vertical configuration of the tree.

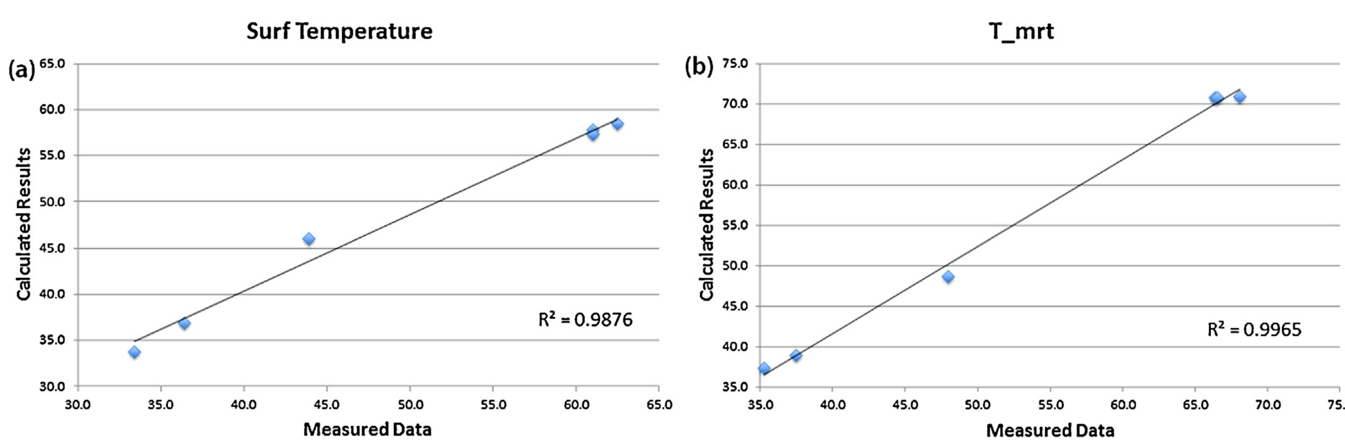


Fig. 5. Correlation coefficients between measured data and simulated results on surface temperature (a) and mean radiant temperature (b).

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Table 1
Input data for the modelling study.

Initial air temperature [K]	303	Relative humidity 2 m [%]	70
Factor of short-wave adjustment	1.2	Cloud cover	2/8
Heat transmission walls [W/m^{2}K]	2	Heat transmission roof [W/m^{2}K]	2
Albedo walls	0.2	Albedo roofs	0.3

Table 2
Observed data on tree effects in sites of low and high SVF.

	Low SVF (0.2)		High SVF (0.8)	
	Exposed	In shade	Exposed	In shade
Solar transmissivity	–	0.06	–	0.07
Air temperature	33.8	32.6	33.7	32.4
Surf temperature	47.7	31.8	52.8	34.1
T_{mrt}	55.3	34.0	62.1	36.2

fisheye lens images of canopy cover and observation of the vertical configuration of the tree [43]. These profiles were then input into the plant database of the ENVI-met model for calculation in the test run. Records from the nearest weather station from the survey site on the measuring day were also input as the initial meteorological setting. The simulation results are in close agreement with the measured data for T_a, T_s, and T_{mrt}. The observed ground-surface temperatures were higher than the calculated results for the exposed points, which could be attributed to the thermal property of the surface material (dark asphalt with high surface temperatures). Several shortcomings of the ENVI-met model as a microclimate analysis tool have been mentioned. One is that the buildings in the model are not parameterized as thermal mass and heat storage is not calculated. Moreover, the albedo and the thermal transmittance cannot be assigned to individual building element separately [44,45]. These disadvantages of the model limit its use to daytime situation and unsuited for nocturnal cooling and UHI analysis [46]. Despite the limitations, the strong correlation found between the measured values and test run results (Fig. 5) indicates that the ENVI-met model is a reliable tool for studying the thermal effects of trees on mitigating daytime UHI. The accuracy of ENVI-met in modelling the urban environment under Hong Kong's climatic conditions was also verified by a previous study [16].

3.2.2. Simulation setting

In the modelling study for the two investigated areas, the simulation setting adoptes a 250 × 250 × 30 grid version for the model domain. The grid sizes for the TST and SSP models are set to be 3 m and 6 m, respectively. As the study focuses on the outdoor thermal environment at the pedestrian level, denser vertical telescoping grids (3 layers) are set within the first 2 m to achieve more accurate results. Some of the input parameters are listed in Table 1. Most buildings in the city centre of Hong Kong are decades old with dark coloured facades; thus, the albedo values of the building surfaces are adjusted to low values (0.2 for walls and 0.3 for roofs) in the model. The air temperature and humidity input are mean values of the record from hot sunny days in August 2012 (SSP Station and TST Station, Hong Kong Observatory). Solar radiation adjustment factor is set to 1.2 to simulate the intense radiation level in a clear summer day in Hong Kong. Subtropical regions have cloudy summers [47]; a small amount of high-level clouds are common in sunny weather (cloud data 2001–2010, Hong Kong Observatory). A 2/8 fraction of high clouds is set for the simulation. Both of the selected sites are located in waterfront areas, so sea breezes and its directional effects are among the most essential climatic features in the district (Fig. 6). Input wind data, including wind direction and pedestrian wind velocity, can be extrapolated down from the 500 m height wind data of the district by using the wind profile power law expression:

$$\frac{u_{(z)}}{u_{ref}} = \left(\frac{z}{z_{ref}}\right)^{\alpha} \quad (2)$$

where $u_{(z)}$ and u_{ref} represent the mean wind speed at height z and at a suitable reference height, respectively. The roughness length is represented by α and is set to be 0.1 in this study because the upwind areas are waterfront open space with relatively low density [48]. The tree model input in the modelling study is profiled based on a 10 m-high *F. microcarpa* planted in the SSP area (see Fig. 7). *F. microcarpa* is widely planted in the urban areas of Hong Kong and has been frequently proposed in roadside tree planting plans [49]. And roadside trees 10 m high or below are commonly found in the city due to severely constrained growth space [50]. The maximum value in the LAD profile of the tree model is around 1.2 m^2/m^3. The LAI value of the tree model can be estimated by summing up the different LAD levels [51], which is about 4.5. The short-wave albedo of the leaf is assumed to have the default value 0.2.

It has been shown that urban greenery provides substantial cooling during the daytime [52]. The current study aims to evaluate the effect of urban trees on mitigating daytime UHI; hence, the period of simulation is set from 8:00 to 16:00.

4. Results and discussion

4.1. SVF-based approach

4.1.1. Sensitivity test

Table 2 presents the measured data from sites of low and high SVF during the early-afternoon period in summer. Ali-Toudert et al.

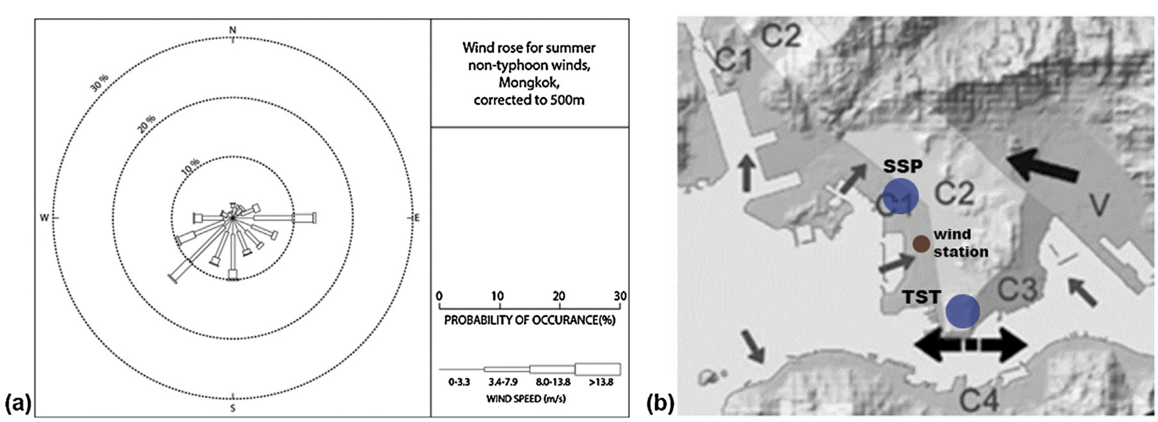

Fig. 6. (a) Summer non-typhoon wind data for the studied district (corrected to 500 m); (b) sea breeze direction during summer.

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	1	2	3	4	5	6	7	8	9	10
LAD	0	0	0	0.82	1.15	1.06	0.95	0.25	0.15	0.08

Fig. 7. *Ficus microcarpa* is popular species in Hong Kong (photo taken in the SSP area). A 10 m-high *F. microcarpa* is profiled and input to the model for simulation study.

[53] pointed out that the vegetation effect on T_{mrt} was more sensitive to building geometry than the effect on T_a. The observed data shows that the effect of trees on T_s and T_{mrt} exhibits a SVF-related pattern. T_s of the road area shaded by tree is reduced by 18.7 °C under 0.8 SVF and 15.9 °C under 0.2 SVF, comparing to the exposed point. Similarly, cooling in T_{mrt} is more significant under high SVF (26 °C) than low SVF (21 °C).

4.1.2. Modelling study

The SVF-based planning approach of tree planting is tested in the studied area of TST. A base case without greenery is simulated and a spatial correlation is found between SVF and distribution of T_s and T_a (Fig. 8). The contours of T_a/T_s become closer together when the SVF value changes (transforming in colour scale), indicating that SVF is a significant indicator of urban microclimate conditions.

In the first scenario, the trees are placed in the open space in the TST area with high SVF values ranging from 0.4 to 0.8. This type of concentrated green matrix usually exists as small parks in the city. As areas with high SVFs are exposed to solar radiation, the strong shade provided by the greenery can create substantial cooling. The before and after comparison using simulation results shows that for the road area shaded by trees, T_s is reduces by 10 °C in the morning and 13 °C in the afternoon. The effect is most significant at noon when T_s decreases from 49 °C to 31 °C – an 18 °C reduction. T_{mrt} under the tree canopy is reduced by 27 °C compared to the non-green scenario. These results are close to the observed values at noon in the sensitivity test. In the ENVI-met model, the turbulent fluxes are calculated as the result of the wind shearing and thermal stratification effect. In the base case without trees, the upward sensible heat flux from the ground reaches 380 W/m^2 at noon; in the vegetated scenario with the same weather condition, the sensible heat fluxes turn negative because of the presence of trees (Fig. 9). It indicates that the tree canopies are able to maintain the surface cooler than the air above. T_a is cooled by 1 °C at the pedestrian level (1.5 m) in the morning and by 1.5 °C in the afternoon.

In the second scenario, a similar number of trees are arranged in urban spaces with medium SVF ranging from 0.2 to 0.4. This arrangement is common in urban areas in the form of mid-size connected green spaces. Simulation results show that a considerable cooling effect is observed when trees are placed under medium SVF. T_s of the shaded road area is cooled by 15 °C at 13:00 and 5 °C at 16:00. Armson et al. [8] obtained similar results. The presence of trees significantly alters the long-wave radiation budget of the ground surface, and the emitted radiation is reduced from 20 to 40 W/m^2 to below 6 W/m^2 (Fig. 10) as indicated in the before and after comparison. A reduction in T_{mrt} is about 23 °C. The effect on T_a is less significant in the medium SVF scenario (about 0.3 °C). The first and second scenarios demonstrate that for green space of certain size, the most significant cooling is found in the midsections, which corroborates an earlier study by Shashua and Hoffman [54].

In the third scenario, the trees are arranged in urban areas with low SVF (<0.2). This arrangement usually exists as isolated inner gardens in high-density residential neighbourhoods or as small green fractions in compact commercial districts. The calculated cooling effects are similar to the medium SVF case, though modification of T_s and radiation budget are slightly lower in the low SVF scenario because of the shading effect of compact geometry.

These case studies indicate that the effects of trees on urban microclimate regulation are related to SVF. For urban areas with irregular building layouts, the SVF-based method can assist planners to cope with areal thermal stress through appropriate arrangement of street trees. Through a centralized arrangement of urban trees, cooling effects can be accumulated and profound reductions in T_a can be achieved in high SVF environments during the daytime. T_s and T_{mrt} are also substantially reduced. Several studies have demonstrated that building morphology has a significant influence on the radiant environment and outdoor thermal condition in low-latitude cities [53,55]. Therefore, the net shading effect would be different when trees are placed in urban areas with different SVF. Armson and Andreou [8,56] reached similar conclusions in their studies on the influence of vegetation in the built environment. The current study showed that due to the high solar angle in the subtropics, a substantial reduction in T_s and T_{mrt} can be achieved by arranging trees in areas with low to medium SVF during early afternoon, which has been verified by both simulation results and observed data in the present study. The finding of

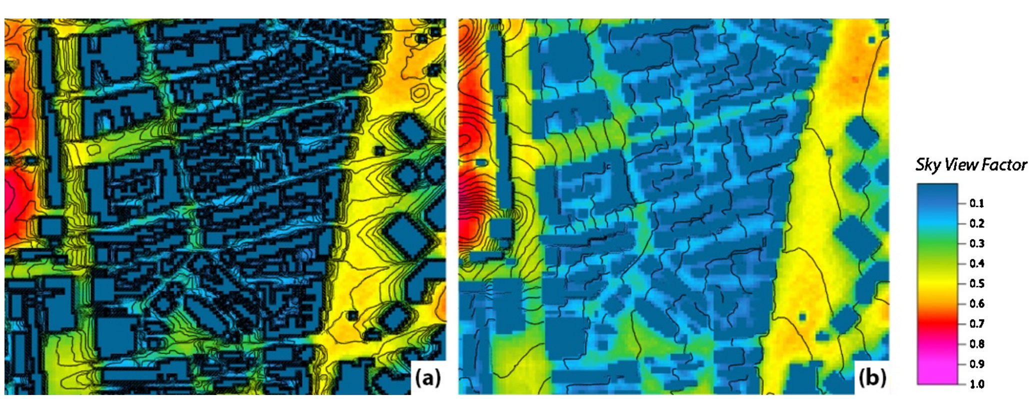

Fig. 8. Variation patterns of SVF comparing to spatial distribution of surface temperature (a) and air temperature (b). The colour scale indicates SVF values; the contour interval is 1 °C for surface temperature and 0.1 °C for air temperature.

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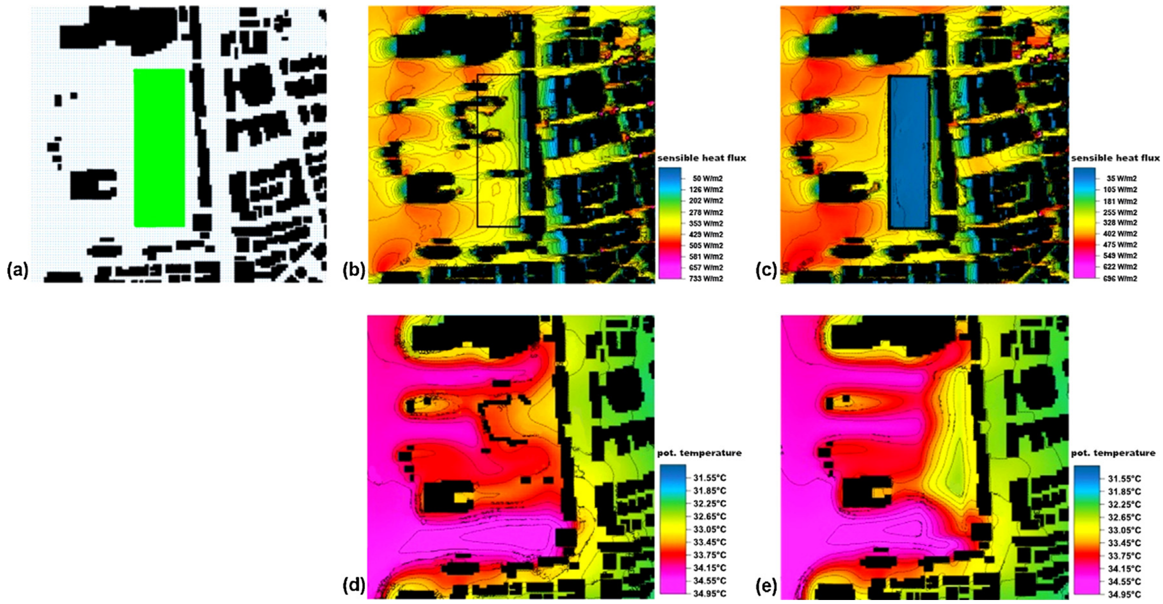

Fig. 9. (a) Concentrated tree arrangement in high SVF areas. Simulation results on the sensible heat flux with (c) and without (b) tree arrangement, and simulation results on air temperature distribution at 1.5 m with (e) and without (d) tree arrangement at 13:00.

Cheng et al. [42] suggested that the comfortable range for T_{mrt} is between 32 and 34 °C in the urban environment of hot subtropical cities. Records from the sensitivity test indicate that street trees can create a comfortable microclimate by reducing T_{mrt} to around 34 °C in some of the heavily built areas with low SVF.

4.2. Wind-path approach

The wind-path planning approach of tree planting is evaluated in the studied area of SSP. The simulation result for the based case shows that the wind speeds at the pedestrian level differ significantly among the streets at 0°, 45°, and 90° to the prevailing wind (Fig. 11). The wind speeds in 45° angled streets and leeward streets are 13% and 10% of the wind speed in the wind paths respectively.

In the first scenario, the trees are arranged in the main streets parallel to the prevailing wind and in the 45° angled streets two blocks away. By subtracting the calculated data of the vegetated layer from the base case layer, the analysis tool of ENVI-met provides the net effects of the tree arrangement (Fig. 12). Remarkable cooling is obtained when the trees are placed in the wind paths and T_a is reduced by 0.6 °C to 0.8 °C at the midsection during noon time. The cool air spreads to the leeward spaces connected to the main streets and is extended by about 30 m into the downwind areas. Similar levels of cooling were reported by Jauregui [58] and Crewe [59]. The cooling effect is small in the angled streets (0.2 °C

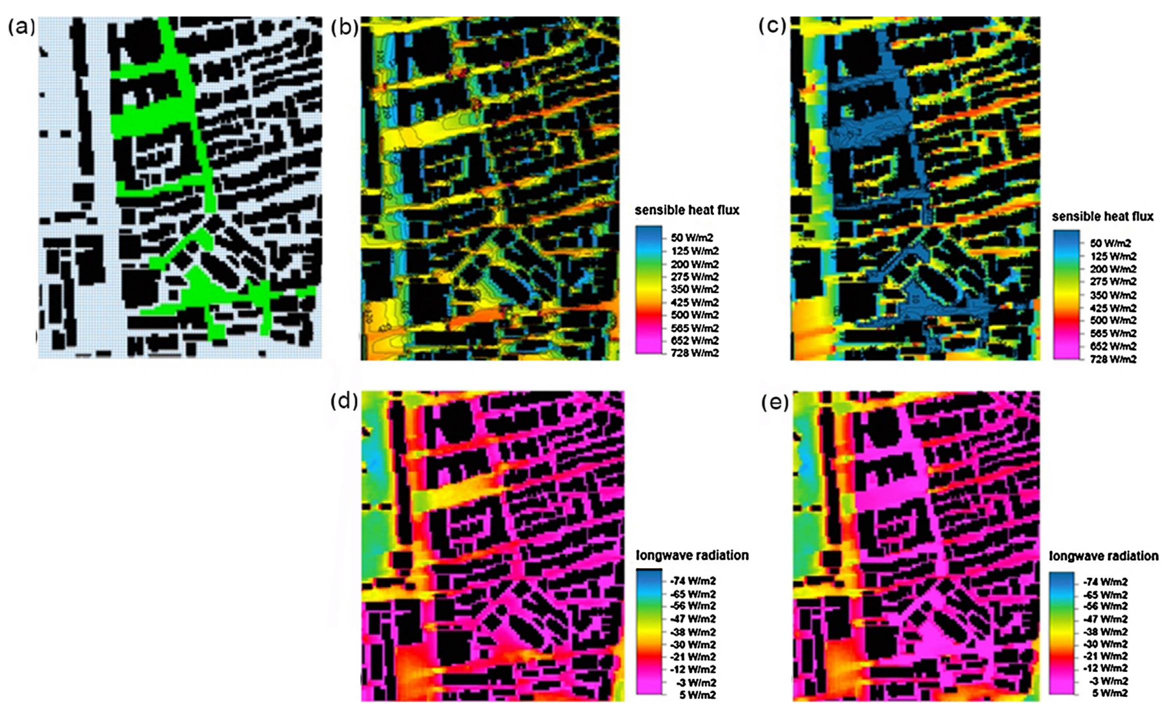

Fig. 10. (a) Connected green corridors in medium SVF areas. Simulation results on sensible heat fluxes above surface with (c) and without (b) tree arrangement, and simulation results on surface long-wave radiation budget with (e) and without (d) tree arrangement at 13:00.

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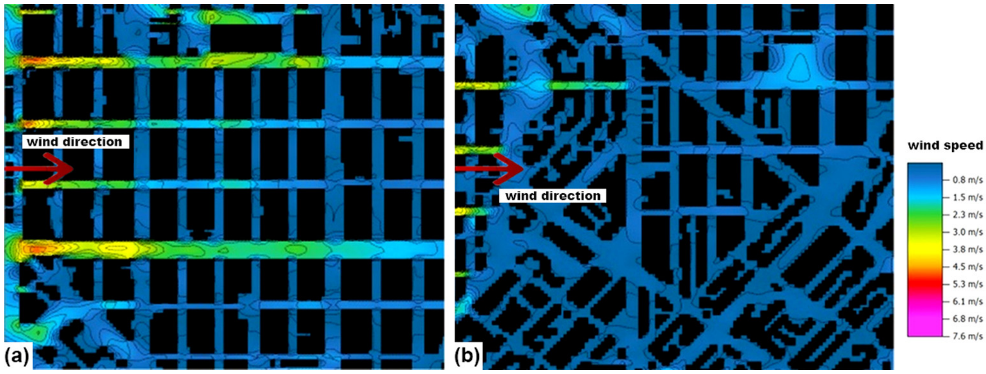

Fig. 11. Simulated wind field in the base case of the studied SSP area. Wind speed is about 2–4 m/s in streets parallel to areal wind direction; and reduces to less than 1 m/s in leeward streets and angled (45°) streets.

reduction in T_a). The synergetic effect is also detected in sensible heat reduction when greenery is combined with wind paths. The amount by which trees arranged in the streets parallel to wind direction reduced the sensible heat is twice that caused by trees in the angled streets. The cooling effects on T_s and T_{mrt}, which are sensitive to the surrounding building morphology [53], show less dependence on wind direction. The simulated cooling outcome on T_{mrt} reaches 27 °C in the wind path area and 30 °C in the angled streets.

In the second scenario, the same number of trees is placed in the streets perpendicular to the wind and in the leeward angled streets a couple of blocks away. Fig. 13 shows that reductions in T_a and sensible heat flux are much smaller when the trees are placed in the leeward areas than in the first scheme. T_a is decreased by 0.3 °C in the leeward streets at noon and by 0.2 °C in the morning and in the afternoon. Cooling by the trees in the leeward angled streets is minimal. Bruse [30] has concluded that the cooling effect of green spaces was reduced with decreased wind speed. The effect of trees on T_s and long-wave radiation remained substantial and at a similar level to the wind-path case.

Hong Kong is a coastal city that experiences onshore winds in the summer. In the waterfront areas where the regular block-array layout is commonly found, the wind channelling effect would be established in streets with small angles to the prevailing wind [57,60]. Simulation results also demonstrate that remarkable synergetic effects can be obtained when trees are placed in these wind paths, and the cooling effects on T_a and sensible heat can increase by a factor of two or three.

The study demonstrates that proper tree planning can be an effective measure to mitigate daytime UHI. Urban trees can also achieve cooling levels similar to those in other passive design strategies. According to the results of the present study, tree planting generates similar cooling outcomes to green roofs in terms of lowering surface temperature [52,61]. For air temperature cooling

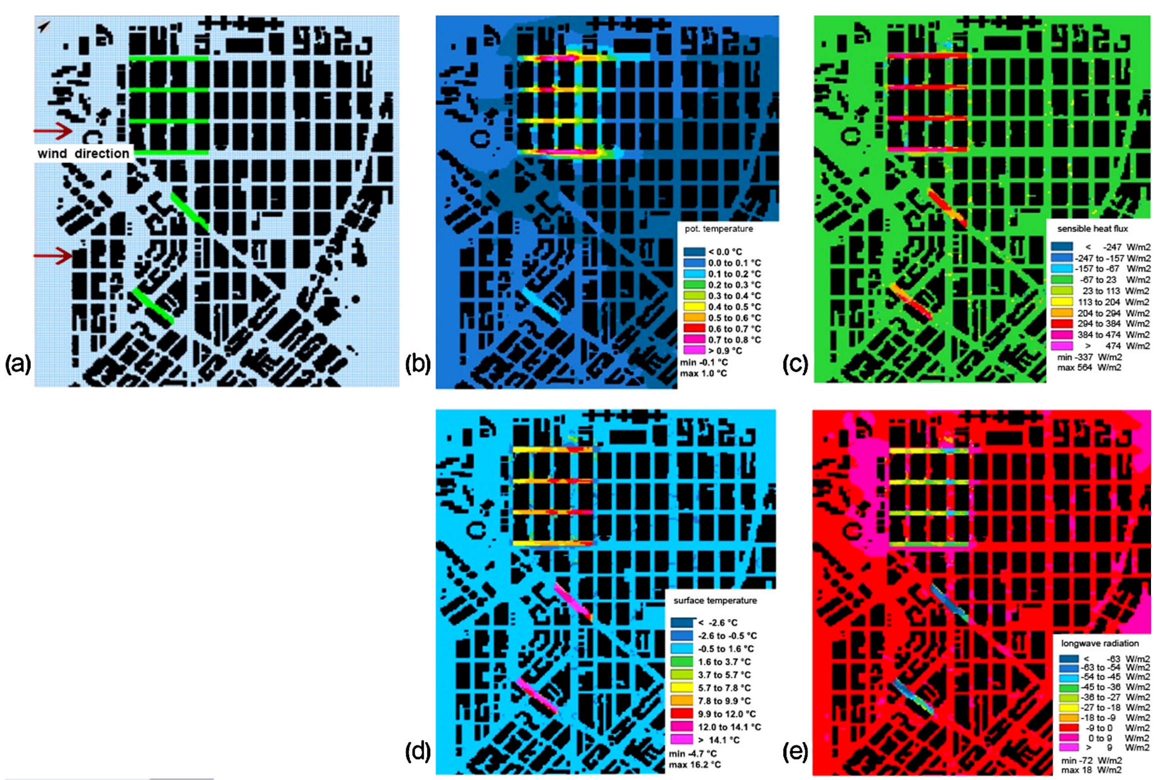

Fig. 12. (a) Street trees arranged in the wind paths and angled streets. Cooling magnitude on air temperature (b), sensible heat flux (c), surface temperature (d), and surface long-wave radiation budget (e) at 13:00.

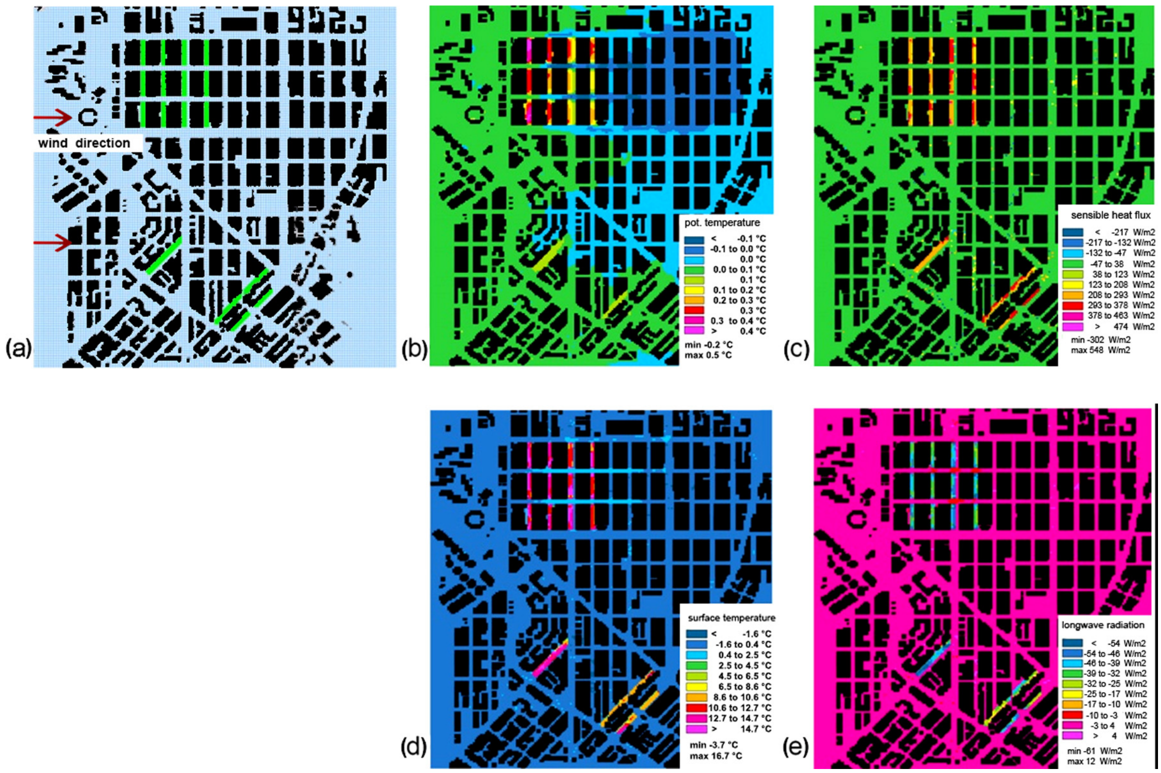

Fig. 13. (a) Street trees arranged in the leeward areas and angled streets. Cooling magnitude on air temperature (b), sensible heat flux (c), surface temperature (d), and surface long-wave radiation budget (e) at 13:00.

effect of trees is similar to the effect of altering the albedo value of built surfaces in the neighbourhood [62,63]. Therefore, urban greenery must be carefully planned to maximize its thermal benefits in cities.

5. Summary

In this study, optimized tree planning strategies for daytime UHI mitigation in high-density subtropical cities are investigated. Morphology-based planning approaches for tree planting are evaluated in two climate-sensitive waterfront areas of Hong Kong. The study demonstrates that small parks in the high SVF areas with highly localized tree planting significantly cools down the air temperature and mitigates daytime UHI effect in the urban centre. On the other hand, mid-size green space and small green fraction under medium and low SVF reduce the radiation load in the urban environment of low-latitude cities during the early-afternoon period. And a relatively comfortable mean radiant temperature is provided in the heavily built areas. For high-density residential blocks with low green space provision, it is recommended to plan the trees in the areal wind paths to enhance the cooling benefits in neighbourhoods.

The study has several limitations. In the simulation part, the study is limited to the cooling effect of one tree model. More work is needed to reveal the thermal performance of urban trees of various crown density, so that systematic evaluation and recommendation for tree species selection can be made for tree planting plans of the city. Moreover, analysis of the planning approaches is only limited to the impacts of tree planting on microclimate regulation. Urban trees have multiple ecological functions. Urban greenery can provide vast ecological networks and buffer areas in the built environment and support ecosystems in the city. Further study is recommended to investigate optimized planning strategies in relation to the multi-function of urban greenery in the built environment.

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