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A study on the cooling effects of greening in a high-density city: An experience from Hong Kong

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ABSTRACT

Greening is a useful mitigation strategy for planners mainly from a visual perspective. For high-density urban living environment such as Hong Kong, urban greening helps cooling the air and providing shade; it also helps lowering building energy consumption by providing a better outdoor boundary condition. Many researchers have also suggested that greening may be employed as a strategy for combating the ill effects of urban Heat Island (UHI). Working towards a set of better greening guidelines for urban planners, the current paper first provides a comprehensive review of planning with urban greening. It then describes parametric studies that have been conducted to investigate the preferred location, amount, and types of vegetation for urban planning. The parametric studies employed the numerical model ENVI-met, verified using field measurements, to simulate 33 cases with different combinations of factors. For benefiting urban activities, ambient air temperatures at the pedestrian level are compared among different greening strategies and building heights. For a city such as Hong Kong, which has a high building-height-to-street-width (H/W) ratio, the present study reveals that roof greening is ineffective for human thermal comfort near the ground. Trees are also suggested to be more effective than grass surfaces in cooling pedestrian areas. The amount of tree planting needed to lower pedestrians level air temperature by around 1 °C is approximately 33% of the urban area. The present study allows urban planners to identify more precisely the greening principles, amount and policies necessary for better urban living environment in high-density cities.

1. Introduction

1.1. Urban morphology and urban planning in Hong Kong

Hong Kong has a population of seven million and an area of 1104 km^2. Located just south of the Tropic of Cancer with a latitude of 22° 15′ N and a longitude of 114° 10′ E, Hong Kong endures a humid sub-tropical climate influenced by monsoons due to its proximity to the sea. As a metropolis in Asia, the city is especially characterized by a hot and humid summer. June–September are the hottest months of the year, with daily average temperatures ranging from 27.6 °C (September) to 28.7 °C (July), daily maximum temperatures ranging from 30.2 °C (September) to 31.3 °C (July), and a relative humidity of around 80% [1]. High temperatures of over 30 °C and high humidity result in an extremely high heat index. Moreover, Hong Kong has a high-rise high-density morphology with tall buildings (Fig. 1). On the one hand, this compact urban form helps minimize transportation costs and thus conserve energy use. On the other hand, however, its urban ventilation potential is reduced and open green spaces are limited.

1.2. Urban planning and greening issues

Hong Kong's urbanization in the last century has undergone several population booms, especially after the World War II. The process exerted a large amount of stress on urban development due to insufficient buildable land resources. Although land reclamation had been continuously conducted in the past, population growth in such limited urban areas inevitably led to compact city morphology, a unique feature in many Asian cities. This compact urban morphology can cause thermal heat stress, especially during the hot and humid summer months.

On the whole, only less than 25% of Hong Kong's landmass is developed, and about 40% of the remaining area is reserved for country parks and nature reserves [2]. Hong Kong is therefore unique in that it has maintained a large green area of its territory that buffers the high-density urban areas and provides a glimpse of the natural environment to its inhabitants. However, the average

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Fig. 1. Typical Hong Kong urban morphology and buildings.

per capita green space provision within an urban area of 2 m^2 that can be easily accessed [3] is low compared with other Asian cities such as Singapore (10 m^2) [4], Tokyo (7 m^2) [5], and Shanghai (12.5 m^2) [6]. The low average is partially due to the high population density, and also due to the fact that greenery was not a key consideration when the high-density urban areas were planned and built.

Following the 1999 Policy Address, which stated that the government would strive to make Hong Kong a green model for Asia, the Hong Kong SAR Government embarked on a planting programme. Thus, a total of over 100 million trees had been planted over the past 10 years. Furthermore, according to the *First Sustainable Development Strategy for Hong Kong* paper published by the Hong Kong SAR Government in 2005, building heights, building design, and green spaces are regarded as important planning factors contributing to a sustainable urban environment [7].

Based on the principle of sustainability promulgated by the Hong Kong SAR Government, in 2004, the Civil Engineering and Development Department (CEDD) developed and implemented a set of detailed Greening Master Plan (GMP) for urban areas [8]. The GMP initiative defines the overall greening framework for a specific urban area. This serves as a guide to all parties involved in the planning, design, and implementation of greening works. In view of the fact that most greenery is in the countryside, the GMP of an urban area is expected to improve urban greenery of built-up areas and seeks ways to bridge green linkages from the countryside into the urban areas. However, greening within Hong Kong's urban areas has many limitations, such as the narrow footpaths and the high pedestrian flow on them, the need to cater for the sightlines of pedestrians and drivers, and the need for areas to be set aside for loading/unloading. They all limit potential areas for planting. Furthermore, large overhanging signboards and high-rise buildings block the sunlight necessary for the healthy growth of plants [9]. Careful studies of the physical conditions and land use characteristics of the urban areas are needed, and this has not been an easy task. Since 2004, several GMPs for urban areas have been developed. Short-term greening works for several very-high-density districts have been implemented. For example, Fig. 2 shows the short-term, medium-term, and long-term GMPs for the district of Tsim Sha Tsui; and Figs. 3 and 4 show photos of completed short-term greening works as recommended by the GMPs in two major urban areas [8]. Further to the GMPs, the 2009 consultancy study on *Building Design that Supports Sustainable Urban Living Space in HK* prescribes the guideline that 20–30% of the building site areas should be provided with greenery [9]. Another study carried out by Hong Kong's Architectural Services Department (2007) recommends that green roofs can only be effective for mitigating UHI if large areas are covered [10].

Considering the aesthetic and recreational functions for urban inhabitants, greenery has been ranked as one of the top issues among inhabitants of Hong Kong. However, there are currently neither obligatory requirements nor effective incentives offered by

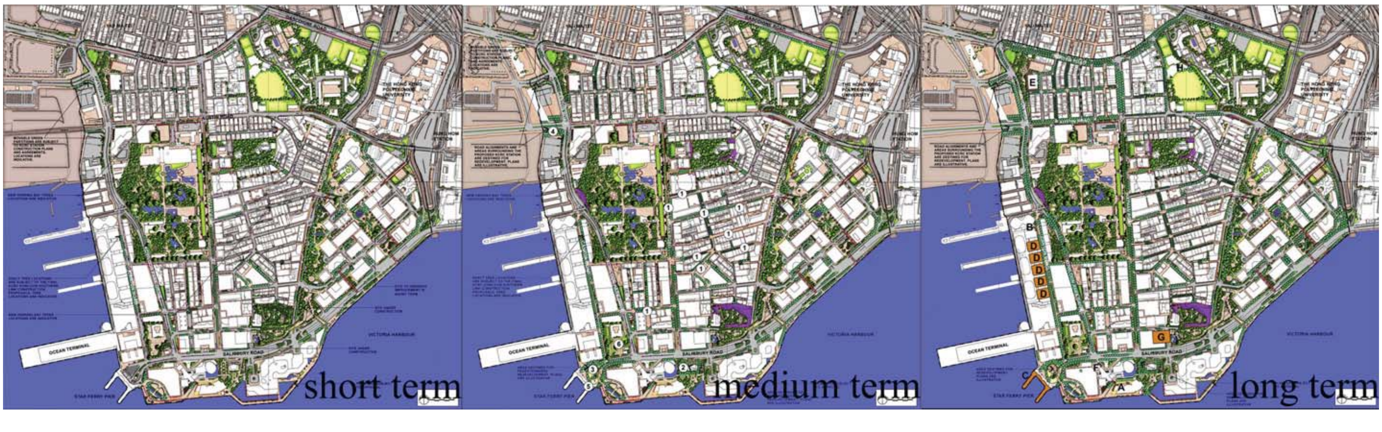

Fig. 2. Short-term, medium-term, and long-term greening master plans for Tsim Sha Tsui [pictures courtesy of CEDD (Civil Engineering and Development Department), HKSAR Government].

Fig. 3. Completed short-term greening works recommended by Greening Master Plans in Tsim Sha Tsui.

the regulative sector to promote greenery at the site level for private developments. No quantitative prescription within the major planning guideline document, the Hong Kong Planning Standards and Guidelines (2010), has been released [3]. No systematic research has been done on the environmental benefits of introducing more greenery within urban areas, and no quantitative guidelines can be derived. Although greenery has been suggested by researchers for hot and humid climates [11], research that quantifies the possible effects of different greenery schemes on the environment is lacking. Particularly for addressing some of the more important design parameters such as location (where?), types (what?), and amounts (how much?) of greenery to be used. This is unfortunate, as planning decisions on greening can directly affect the city's urban climate [12,13]. All in all, although policy efforts exist and the desires of stakeholders lead towards greening, further research efforts are necessary.

2. Urban vegetation and urban microclimate in tropical areas

Urbanization has caused many problems for city inhabitants. One of the more prominent problems, UHI of the Urban Canopy Layer (UCL), can increase energy consumption, increase ambient air temperature, and reduce human thermal comfort. Oke [14] identified two separate atmospheric layers. One is the UCL governed by the processes at the microscale. The climate here is dominated by the nature of its immediate surroundings, such as building orientation, albedo, emissivity, thermal properties, wetness, etc. The other layer is the urban boundary layer (UBL), where climate is affected by the presence of an urban area at its lower boundary (Fig. 5). Urban microclimate refers to the characteristics of climate in the UCL between the buildings' rooftops and ground surfaces [15,16]. Sources of urban heating in the UCL include: higher storage by urban structures compared with their counterpart in rural areas; and anthropogenic heat released by substantial urban activities [17]. Especially in low, middle, and high latitude cities, urban air temperatures are generally higher than their corresponding rural values. This is commonly referred to as the UHI phenomenon, which could occur at a scale range of a single building surrounding to a large portion of a city. Generally, heat islands in Hong Kong are undesirable because they add to cooling loads, thermal discomfort, and air pollution.

Urban greenery can bring beneficial microclimatic effects, including air temperature reduction, which eases the UHI effect [18]. The microclimatic beneficial effect of trees is obtained through several physical processes: (1) Solar heat gains on windows, walls, roofs, and urban surfaces, including human bodies, are lowered through shading; (2) the buildings' long-wave exchanges are reduced at lower surface temperatures through shading; (3) the dry-bulb temperatures are lowered through evapotranspiration processes; and (4) latent cooling is increased due to the addition of moisture to the air through evapotranspiration [18]. Estimating the decrease in ambient air temperature below the urban canopy is useful for human thermal comfort, especially at the pedestrian level, with different planting schemes.

Methods to study the microclimate within the urban setting include both numerical modeling and empirical analysis, such as

Fig. 4. Completed short-term greening works recommended by Greening Master Plans in Sheung Wan.

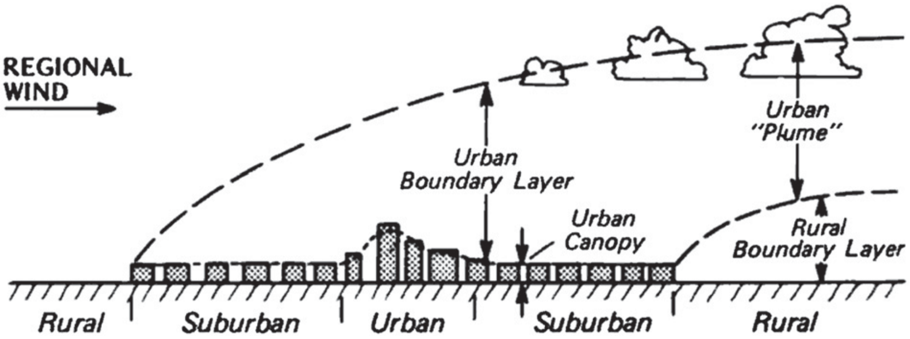

Fig. 5. Schematic representation of the urban atmosphere illustrating a two-layer classification of thermal modification (Source: [14]).

on-site measurement using mobile instruments, weather station data, and satellite data [19]. These investigation methods have been employed to study urban vegetation and urban climate in other research [20]. With empirical field data, investigations can be more specific but are limited in time and space. Thus, deriving a thorough understanding of the interaction between urban design parameters and urban climate for better planning and decision-making is difficult to achieve. Numerical modeling (mesoscale and microscale) together with verification using on-site observations may provide theoretical understanding.

Normally, vegetation can lower both the air temperature and wind speed on the surrounding microclimate. This helps reduce the cooling load. However, this is also still a generalization. Detailed studies on the interaction of local climates and urban development are needed for each city. The city-climate-specific interactions between urban vegetation, urban structures, and urban climates have been investigated in research on various climates: in Brazil [21,22], Mexico [23], Cairo [24], Israel [25–27], Singapore [28–30], Japan [31–40], China [41–43], Hong Kong [44,45], Sri Lanka [46], Botswana [47], USA [48], England [17], Germany [49], and so on. Research findings include the effects of a single park area to its neighborhood, and the average effects of distributed greenery areas within an urban setting. In general, researchers have agreed that greening is important for cities.

2.1. Numerical modeling

Both mesoscale and microclimate numerical models have been developed to study the basic pattern of urban effects, including air temperature rise and humidity decrease [34,50]. Among them, the mesoscale model of Colorado State University (CSU) Regional Atmospheric Modeling System (RAMS) has been employed to

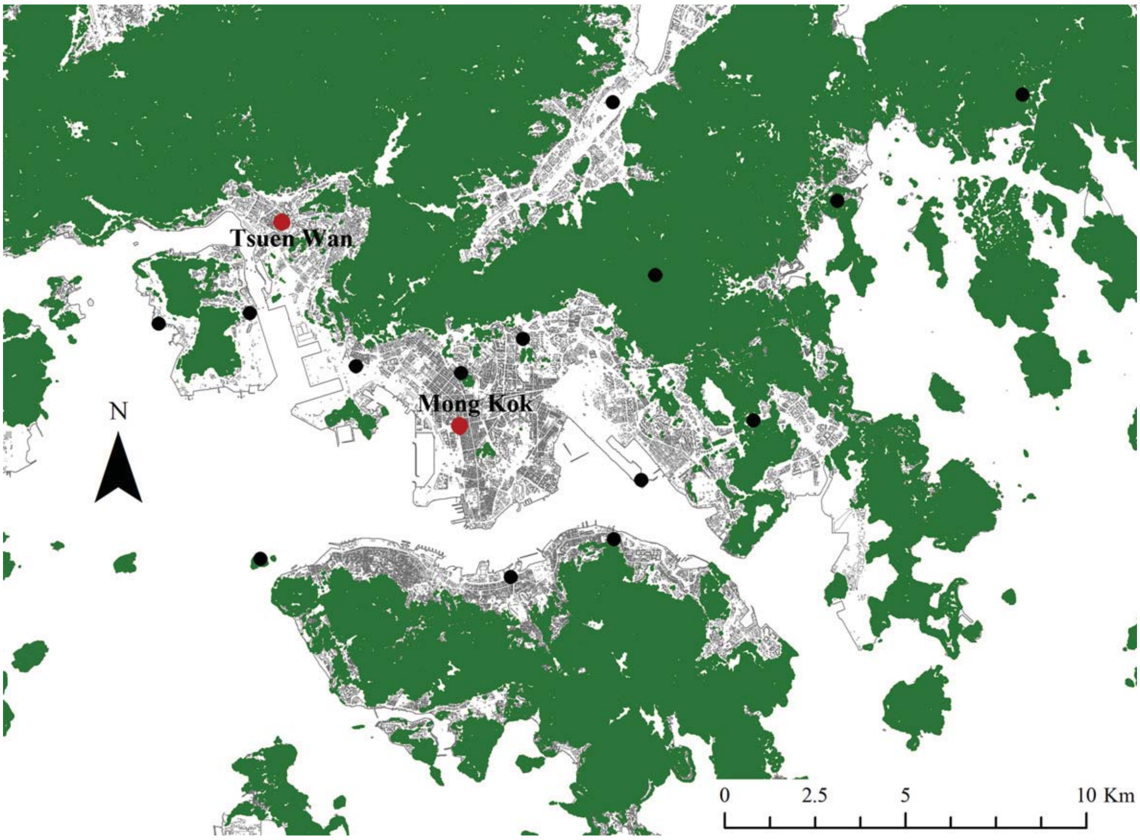

Fig. 6. The map showing the locations of the two study areas: Tsuen Wan & Mong Kok. The black dots are observatory stations. The green color areas are landscaped areas.

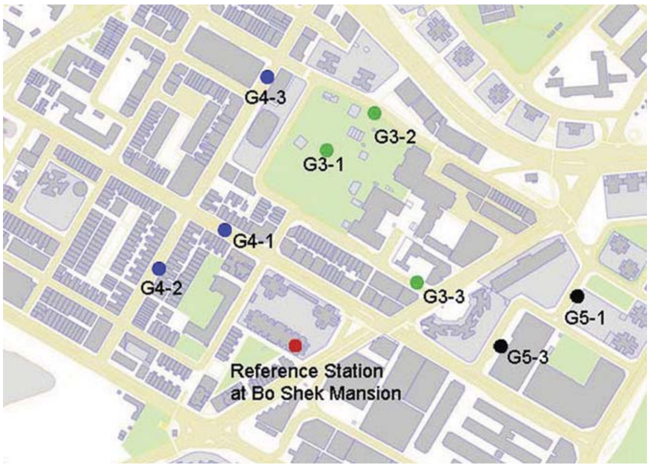

Fig. 7. Field measurement points conducted in Tsuen Wan on 9th May 2008.

Table 1
Meteorological data recorded by Hong Kong Observatory's station on 9 May, 2008, including air temperature (T), global solar radiation (Radiation), relative humidity (RH), wind speed (V) and duration of sunshine (Sunshine).

Date	Measurement period	T (°C)	Radiation (W/m^2)	RH (%)	V (m/s)	Sunshine (h)
9 May 2008	15:00–16:00	29.9–31.0	580–830	65–75	0.9–1.7	10.5

Table 2
Field measurement results of air temperature (T), relative humidity (RH), and wind speed (V).

Point index	Measurement time	T (°C)	RH (%)	V (m/s)
G31	15:00–15:10	30.6	68.6	1.2
G32	15:15–15:25	30.9	68.0	1.8
G33	15:30–15:45	33.1	61.3	1.2
G41	15:00–15:10	34.0	60.7	1.3
G42	15:15–15:25	33.0	64.1	1.8
G43	15:30–15:45	32.9	64.6	1.4

simulate the potential impact of vegetation on the urban thermal environment during the mid summer day of a mid-latitude city [50]. The simulated domain was 300 km wide, had a 5 km resolution, and up to 10 km height, with a first atmospheric level 2 m above ground surface. Simulations were differentiated by the parameter of their percentage of vegetation coverage in the urban areas, specifically 0, 33%, 67%, and 100%, which are common in reality. Simulation results of the study with hot and dry climate show that for no wind situation, up to 5 K reduction in air temperature at 3 pm can be observed for 33% vegetation and up to 10 K reduction for 67% vegetation. These results are also similar with mesoscale simulation studies by Taha [51]. However, the mesoscale modeling approach, with its very large computation domain and grid sizes (more than 10 m in the horizontal resolution), overlooks the influence of vegetation to its immediate proximity and mixes it with the accumulation of thermally modified air from upwind areas [18]. Besides, within a compact urban context, large-scale urban forestation, although very effective in reducing air temperature, is itself not applicable.

Aside from using mesoscale modeling, some researchers developed numerical and CFD models at larger scales, and determined the local effects of the urban structure (including building and vegetation) on the urban micro environment [32,37,52,53]. Some researchers compared two cases of “with” and “without” a certain area of greenery, which is usually a big park, to investigate the thermal effects of the particular park [37,52]. In the model used by Gao [32], buildings green spaces and roads are linearly arranged and a typical summer weather condition is used. Simulation results show that two urban choices are equivalent to maintaining the same daily average air temperature of about 30.5 °C; one uses a bulk ratio of 200% with a relatively lower green area, and the other uses a bulk ratio of 700% with a large green open space. For the 600% bulk ratio case with a road ratio of 20%, a 30% green area can reduce air temperature by nearly 1 °C and a 50% green area can reduce it by nearly 2 °C. Parametric studies were conducted by Dimoudi and Nikolopoulou [18] using CFD, with various densities of urban structures and sky view factors, green area sizes, distances from green areas, climatic conditions, and vegetation species.

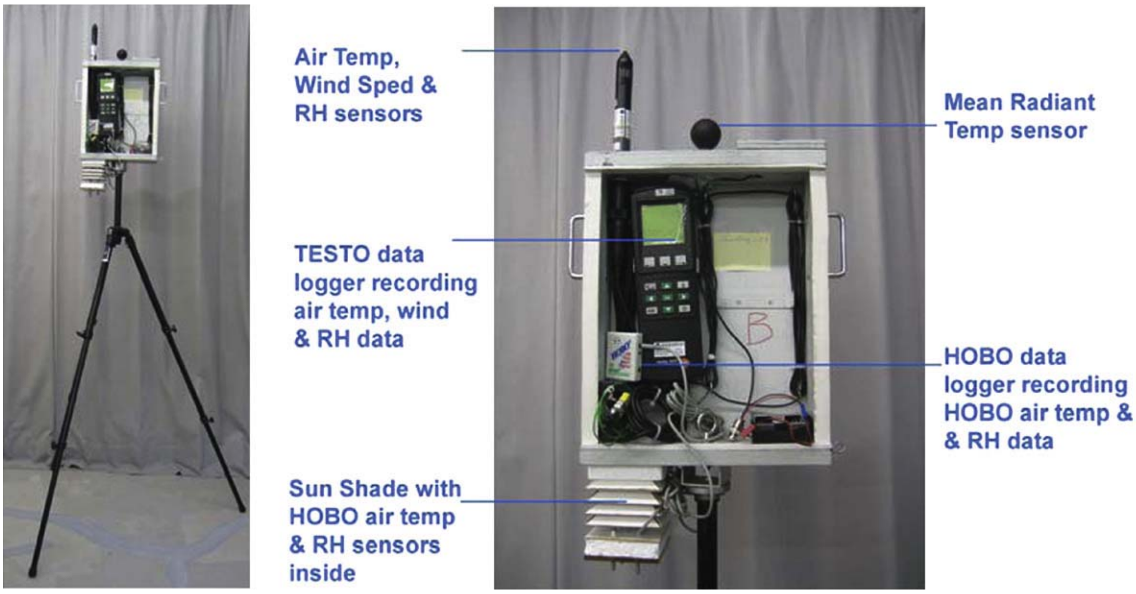

Fig. 8. Mobile meteorological station.

Table 3
Weather conditions of the selected days for verification with long-term monitoring.

Date	Air temperature			Mean relative humidity (%)	Mean wind speed (m/s)	Daily global solar radiation (MJ/m^2)	Total sun hour (h)
	Max (°C)	Mean (°C)	Min (°C)				
9 May 2008	31.0	27.8	25.9	84	5.1	25.14	10.5
16 May 2008	29.2	25.2	23.3	67	4.8	24.79	10.7
24 May 2008	29.5	27.6	26.3	83	4.3	18.34	6.5
20 June 2008	32.6	28.7	26.5	79	4.1	23.75	9.6
21 June 2008	32.9	28.7	26.4	78	2.4	26.34	10.9
22 June 2008	32.4	28.7	26.1	77	3.5	26.50	11.7
04 July 2008	32.7	29.0	27.1	79	2.1	25.44	10.2
17 July 2008	31.7	29.1	26.9	78	4.6	27.10	12.1
24 July 2008	32.5	29.6	27.6	72	4.8	27.73	11.5
02 Aug. 2008	32.4	29.1	27.3	77	4.2	20.48	10.3
13 Aug. 2008	31.8	29.0	27.0	75	3.4	26.50	10.4
26 Aug. 2008	31.6	28.5	26.6	78	3.1	26.03	10.8

Source: http://www.weather.gov.hk/wxinfo/pastwx/extract.htm.

Increasing the size of the park (the same as a single building in the layout plan) to double its original area leads to a reduction of air temperature by 1 K, and increasing the size of the park to more than three times its original area leads to further reduction of air temperature by 1.5–3 K. Moreover, as the building-height-to-street-width ratio increases, the wake effect increases. Therefore, mixing of air is reduced. This keeps the effect of the park relatively local. In another parametric study by a team lead by Moriyama [39,40], introduction of a greenery coverage of 30% was found to reduce urban air temperature by 1 °C. With the study result, Moriyama suggested that for the study area in the Osaka central district, the greenery ratio should be more than 30%.

2.2. On-site survey and remote sensing

Besides numerical simulation, another traditional and widely used approach is to conduct on-site observations by fixed stations or mobile equipment. This can be employed to study the environment on a standalone basis [18,23,29,30,35,49]. With the wider application of computers, the trend is to use both on-site survey and model simulations to cross-check [27,28,47]. The review conducted by Chen and Wong [28] found that when greening is arranged throughout a city in the form of natural reserves, urban parks, neighborhood parks, rooftop gardens, and so forth, the energy balance of the whole city can be modified through the added evaporating surfaces. Urban temperature can thus be reduced.

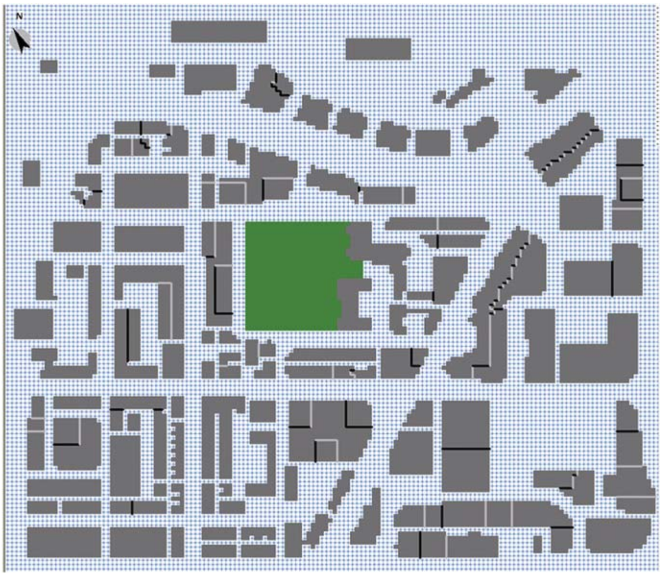

Fig. 9. Site plan for ENVI-met simulation.

According to the field measurements in Kumamoto, Japan [35], high temperature regions were found in densely built environment: the higher the ratio of green area, the lower the air temperature. Even for a small green area (60 m × 40 m), the cooling effect can be beneficial. The maximum difference between inside and outside the small green area was found to be 3 °C. Memon et al. [16] found that the maximum temperature reduction under the proposed combined mitigating measures of vegetation, lighter color of paving, no air-conditioning, and roof spray cooling was around 1–1.5 °C. Field measurements by Gao [32] reported that in Tokyo, vegetated zones during summer are on the average 1.6 °C cooler than non-vegetated zones; and in Montreal, urban parks can be 2.5 °C cooler than surrounding built areas. Jonsson reported that the measured summer daytime temperature of oases can be 2 °C cooler than the surrounding open fields of bare soil [47]. Field measurements in a city in the west of Tokyo [31] showed that a park size of 0.6 km^2 can reduce air temperature by up to 1.5 °C at noon time in a leeward commercial area at a distance of 1 km.

Nonetheless, most of the available studies on vegetation influence have been done for temperate and desert climates, focusing on medium and low-density environments with a building-height-to-street-width ratio of not higher than 2. In Hong Kong, local researchers [44] surveyed 216 sites of residential buildings, suggesting that in areas with 30% tree cover or more, the UHI will decrease. More specifically, it has been suggested by the study that increasing tree cover from 25% to 40% in pocket parks near a coastal residential development of Hong Kong can reduce the daytime UHI by a further 0.5 °C. Furthermore, for both daytime and night time during PSCS-days, the "tree cover dominated" locations are cooler by 0.5–1 °C compared with the "shrub cover dominated" locations.

In Hong Kong, studies using remote sensing techniques to derive relevant information on urban land cover and surface temperatures have been conducted [45]. Using the Geographic Information System (GIS) platform, satellite-derived land use/cover maps displaying the vegetation distribution were analyzed against land surface temperature maps to assess the influence brought about by vegetation. On-site measurements have been carried out [47], and statistical methods, such as the regression model and correlation analysis, have been used to analyze the data [48].

3. Parametric studies using ENVI-MET

ENVI-met is a three-dimensional numerical model with a typical resolution of 0.5–10 m in space and 10 s in time. The

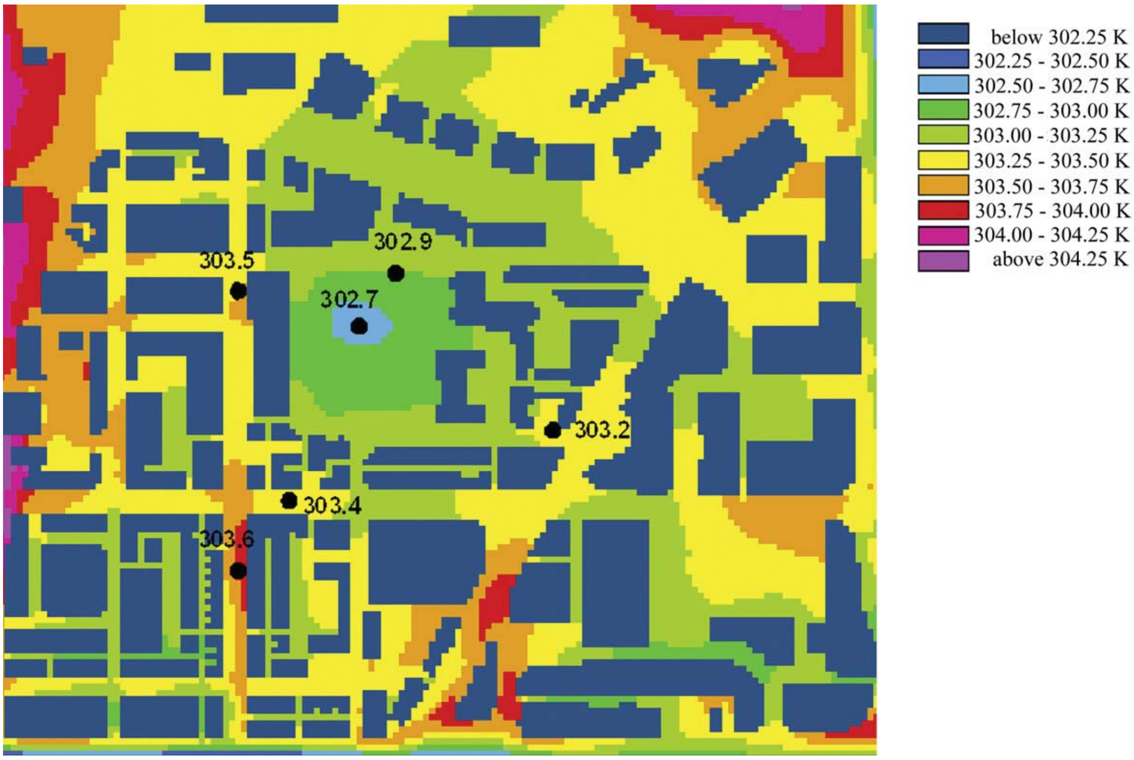

Fig. 10. Air temperature (K) at 2 m above ground at 3 pm from ENVI-met simulations.

model is a tool for studying the surface–plant–air interactions in the urban environment at the microclimate scale [20]. Although it is not an open source software, ENVI-met is a freeware program based on different scientific research projects. Some recent studies have used ENVI-met to simulate the effect of urban vegetation on microclimate [20,21,24,28,54]. Spangenberg et al. [21] conducted studies in São Paulo, Brazil, which has climate conditions similar to Hong Kong. Their study results show that among the three simulated cases, canyons covered with less dense (LAI = 1) and dense tree (LAI = 5) canopies respectively have on average 0.5 and 1.1 °C lower air temperatures than the case without trees. The cooling effect was also found to be less than that reported by Ali-Toudert and Mayer [20], which was up to 1.5 °C for a hot-dry city – which can be explained by the higher cooling effect of evapotranspiration due to the dryer air in the study. The São Paulo study further

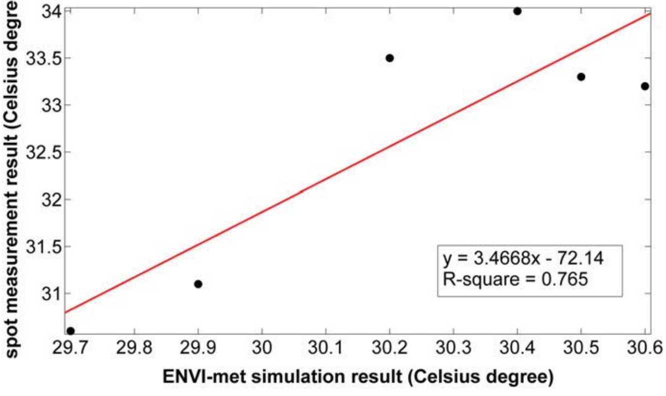

Fig. 11. The relationship between ENVI-met simulation temperature and measurement temperature (3 pm on 9th May 2008).

Fig. 12. The reference station installed on the roof of Bo Shek Mansion.

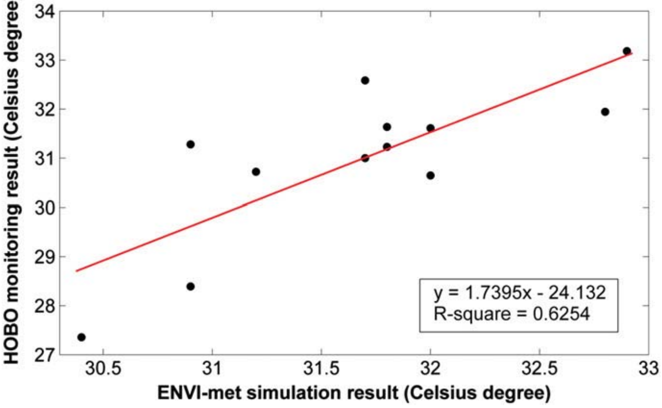

Fig. 13. The relationship between ENVI-met simulation temperature and HOBO meteorological monitoring records, from May to August, 2008.

concluded that creation of a greener city and mitigation of UHI are possible only through the implementation of city-wide changes from groups of trees to large-scale green space interventions as encouraged by modified building codes and citizen's initiatives.

3.1. *Verification with field measurements*

For the present study, ENVI-met is first verified using field measurements. An urban area in Tsuen Wan, Hong Kong was selected for the verification. The location is shown in the map (Fig. 6). The chosen study area has a dense building morphology and congested road patterns (Fig. 7) commonly found in Hong Kong. Tsuen Wan is a bay and approaches a mountain to the north 1–2 km away. A few scattered parks are located in this area. Overall the road patterns are regular and arranged in the direction of northwest–southeast.

Two types of field measurements are used for the verification. The first one is an on-site spot measurement covering spatially distributed locations considering the spatial variation of the microclimatic condition of the site. The second one is a long-term meteorological monitoring of a reference station (Fig. 7).

3.1.1. *Verification with spot measurement*

An on-site spot field measurement was carried out between 15:00 and 16:00 on 9th May 2008. The observation site consists of mixed commercial and residential buildings arranged in a compact form where a park of about 100 m^2 area lay in the center, rendering it a suitable candidate for observing the different microclimatic responses due to the varied land covers. On the measurement day, the prevailing wind came from the east according to the rooftop reference wind mast station set up nearby. Meteorological data from a station of Hong Kong Observatory near the site is presented in Table 1.

A number of identical set of mobile meteorological stations were used (Fig. 8). The TESTO 400 3-function sensor probe was used in this study for simultaneous measurement of air temperature, relative humidity and wind speed. These were DIN EN ISO 9001:2000 certified and calibrated in the laboratory prior to the field studies. The data was sampled every 10 s and logged manually every 10 min. As shown in Fig. 8, the mobile meteorological stations were positioned at a height of 2 m for the measurement [55] at the measurement points. Table 2 shows the measurement results.

An ENVI-met model was constructed according to the actual geometry of the site; with the highest building being 100 m. Settings as in Table 3 were used. The model was simulated for 24 h (Fig. 9) starting 6 am and ending 6 am the day after. This is because the best time to start is at sunrise and the total running hour should be longer than 6 h to overcome the influence of the initialization. The simulation results were observed (Fig. 10), and the specific air temperatures of the measurement points were extracted, plotted, and compared with the field measurements. Notably the field measurement results were normalized with Hong Kong Observatory data assuming temperature changes at different spots at the same pace. Fig. 10 shows that there can be a significant reduction in air temperature of 0.8–1.3 K in the park area compared with nearby built-up urban areas. The relationship of both results was found to be correlated with an *R*-squared value equal to 0.765 (Fig. 11). The verification process further rationalizes the use of ENVI-met to study the microclimate issues involving greening in a dense urban environment of Hong Kong with sub-tropical hot and humid summer climatic conditions.

3.1.2. *Verification with long-term meteorological station monitoring*

A HOBO meteorological station was installed at the top of Bo Shek Mansion (as shown in Fig. 7) as reference station to monitor the long-term meteorological condition of the study site (Fig. 12). The meteorological station is at 90 m above ground level, and keeps record of temporal variation of the local climatic condition, including air temperature, relative humidity, wind speed, radiation, etc. Whole-year monitoring was carried out and the 10 m average value was recorded. For the objective of this study, 12 days from May to August, 2008 were selected for the verification. Weather conditions of the selected days are shown in Table 3.

ENVI-met simulations were carried out for each of the selected day, and the simulated air temperatures at 15:00 were extracted and compared with the HOBO records. Fig. 13 shows the correlation result. The result shows reasonable agreement between ENVI-met simulation and measured results, with *R*-square in the order of 0.625. Judging from the verification result using on-site spot measurement and also long-term monitoring, the usefulness of

Table 4
Verified ENVI-met simulation settings.

Applicable period	Initial temperature	Start time	Relative humidity at 2 m (%)	Wind direction	Wind speed at 10 m (m/s)	Albedo of roofs	Albedo of walls
May-August	Daily min	6am	70–90	East	0.5–1.5	0.3	0.2

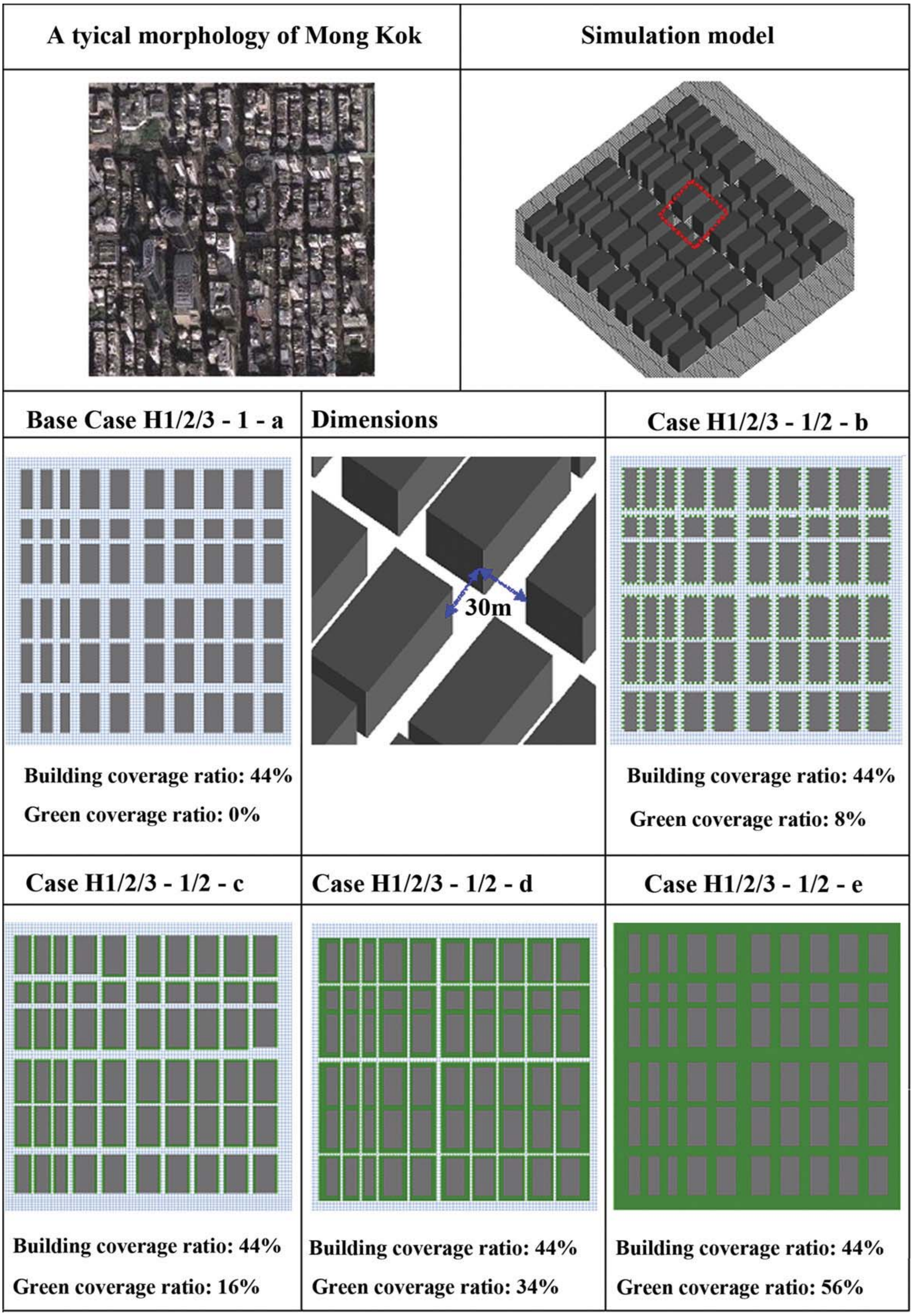

Fig. 14. Greening extent of the study cases.

Table 5
A summary of the study cases.

	No green	Greenery coverage 8%	Greenery coverage 16%	Greenery coverage 34%	Greenery coverage 56%	Green on rooftop
BH 60 m	Case H1 – 1 – a	Case H1 – 1 – b (tree)	Case H1 – 1 – c (tree)	Case H1 – 1 – d (tree)	Case H1 – 1 – e (tree)	Case H1 – 1 – f (tree)
		Case H1 – 2 – b (grass)	Case H1 – 2 – c (grass)	Case H1 – 2 – d (grass)	Case H1 – 2 – e (grass)	Case H1 – 2 – f (grass)
BH 40 m	Case H2 – 1 – a	Case H2 – 1 – b (tree)	Case H2 – 1 – c (tree)	Case H2 – 1 – d (tree)	Case H2 – 1 – e (tree)	Case H2 – 1 – f (tree)
		Case H2 – 2 – b (grass)	Case H2 – 2 – c (grass)	Case H2 – 2 – d (grass)	Case H2 – 2 – e (grass)	Case H2 – 2 – f (grass)
BH 20 m	Case H3 – 1 – a	Case H3 – 1 – b (tree)	Case H3 – 1 – c (tree)	Case H3 – 1 – d (tree)	Case H3 – 1 – e (tree)	Case H3 – 1 – f (tree)
		Case H3 – 2 – b (grass)	Case H3 – 2 – c (grass)	Case H3 – 2 – d (grass)	Case H3 – 2 – e (grass)	Case H3 – 2 – f (grass)

ENVI-met in modeling the intra-urban air temperature variation in Hong Kong's urban environment for summer courses is therefore confirmed. The verified simulation settings are given in Table 4. Admittedly, ENVI-met does not separately account for the effect of anthropogenic heat on air temperature. It is assumed that since the building forms of the verification study and the parametric study (refer to next section) are both high-density cases with similar building mass, the potential anthropogenic heat contribution, if any, can be considered as background contributions in both cases, which are inherent in the simulation. This also agrees with the wide applications of ENVI-met in modeling outdoor air temperature in urban climatology studies [20,28,46,56].

3.2. Input data

Once the ENVI-met and a set of particular model settings had been verified for use, research proceeded to parametric case studies. These studies were based on a typical Hong Kong urban morphology, in the Mong Kok district (as shown in Fig. 6 in the map). The corresponding layout plan and meteorological data were inputted.

For the parametric study, a generic layout plan based on the urban morphology of an urban area, Mong Kok, was used for the parametric study. Mong Kok lies in an urban area and has the highest population density in the world of 130,000 inhabitants per km^2 (Fig. 14). Mong Kok has a regular street layout with dense building blocks. For the parametric study, the real condition was simplified and a generic layout plan was created. Building sizes in the layout were taken as amalgamated blocks, ranging in size from 20×40 m^2, 20×80 m^2, and 80×80 m^2. The widths of the streets between buildings were 10, 15, 20, and 30 m. The building heights were first set to be homogenous at 60 m, which represents the average building height of the area (Case H1). Study cases of "Case H1" had building-height-to-street-width ratios from 2 to 6, which is a characteristic of the urban morphology in Hong Kong. In addition, models with other building heights of 40 and 20 m, study cases "Case H2" & "Case H3" respectively, were also constructed and simulated to include the influence of building heights on the cooling potentials of greening around buildings. The model used a horizontal grid size of 5×5 m^2, has a starting vertical telescoping grid width of 0.9 m and extends with the factor by 20%. The overall domain of the model was $700 \times 700 \times 300$ m. The layout plans of the 5 different greenery coverage ratios are illustrated in Fig. 14. Building materials defined in ENVI-met were the same in all 11 cases so that the study could focus on only the urban form based comparison. A total of 33 study cases were tested by varying the type of greening, the greening coverage ratio, and the building heights; this is summarized in Table 5. The study cases were designed to determine the (A) location (where?), (B) types (what?), and (C) amounts (how much?) of greening necessary for efficient cooling.

The simulation date selected was 23rd June which represents a typical hot summer day in Hong Kong. The meteorological entries are summarized in Table 6.

Both tree and grass types referred to in the simulation included: mature 20 m dense distinct crown trees, as in Fig. 15, and 50 cm average dense grass. The default leaf area density (LAD) setting in ENVI-met is used, where the height of the tree is divided into 10 equivalent segments, and LADs for each height segment from bottom-up are 0.075, 0.075, 0.075, 0.075, 0.250, 1.150, 1.060, 1.050, 0.920, and 0 m^2/m^3, respectively. In the generic model, greening (including evergreen trees and grass surfaces) was arranged along both sides of the streets. Trees therefore may provide shading from direct solar radiation. This may reduce heat gain and minimize pedestrians' solar exposure when walking on the streets [54].

4. Results and discussions

4.1. Cooling effects for building height 60 m

Since 60 m represents the average building height for the urban canopy layer, this group of simulation results is first reported in detail and discussed. Afterwards, the simulation results of cases with building heights of 20 and 40 m are reported. The cooling affects are reported by comparing the simulation results from 2 m above ground at 3 pm, as in Figs. 16a, 17a, 18a. Sectional temperature profiles are also presented in Figs. 16b, 17b, 18b. Fig. 16a and b reports the results of the effects of rooftop greening; Fig. 17a and b reports the results of the effects of tree planting; and Fig. 18a and b reports the results of the effects of grass surfaces.

For roof greening, the comparative results of Case H1 – 1 – f and Case H1 – 2 – f against the Base Case H1 – 1 – a, from both the cross section (Fig. 16a) and vertical section presentations (Fig. 16b), indicate that neither trees nor grass surfaces on the rooftop could yield useful cooling effects at the pedestrian level. Although Wong et al. reported that roof greening can be effective when the building height is less than 10 m [29], this was not observed in the parametric study, where the building height is 60 m. Instead, the parametric study results are in agreement with research in Japan [38], which showed that even with the introduction of 100% roof greening, benefits to the pedestrian-level air temperature are negligible when buildings are tall. Further analysis will follow later with building heights of 20 and 40 m. At this juncture, it may be

Table 6
The main meteorological data input for the parametric study.

Simulation day	Initial temperature	Start time	Relative humidity at 2 m (%)	Wind direction	Wind speed at 10 m (m/s)	Albedo of roofs	Albedo of walls
23 June	28 °C	6 am	70	East	1	0.3	0.2

Fig. 15. An example of 20 m dense distinct crown trees: Yamin Large evergreen tree, native to tropical East Asia.

initially speculated that ground level greening may be a more useful greening strategy to adopt.

For tree greening, as presented in Fig. 17a, Case H1 − 1 − c, with tree coverage of 16%, began to contribute to a maximum air temperature reduction of about 0.4 K. By increasing the tree coverage to 34% in Case H1 − 1 − d, the maximum air temperature reduction can reach 0.8 K. In Case H1 − 1 − e, with trees planted along roads that cover 56% of total area, the maximum air temperature reduction could be up to 1.8 K when compared with the base case with no vegetation. When the tree coverage is greater than 34%, the overall temperature across the area fluctuated less, which is another thermal benefit in addition to the absolute temperature reduction. The even distribution pattern of lower air temperatures in the ambient is more obvious as shown in vertical temperature profiles in Fig. 17b.

For grass surfacing, as shown in Fig. 18a, ranging from 8% (Case H1 − 2 − b), 16% (Case H1 − 2 − c), 34% (Case H1 − 2 − d), up to 56% (Case H1 − 2 − e) coverage, the cooling effects compared with those of the base case are observed. With the increase of grass coverage, ambient air temperatures are lower and more evenly distributed, as shown in vertical temperature profiles in Fig. 18b. However, they are considerably less effective in urban cooling than tree planting. This difference in the two vegetation types is less obvious when the coverage ratio is less or equal to 16%. However, when the coverage ratio increases to 34% and above, planting trees at the ground level can reduce pedestrian-level air temperatures more notably than grass surfaces. This is because trees can provide shading to surfaces, which is more effective in reducing the radiant temperature.

4.2. Effects of building heights on cooling

The cooling potential of the different greening strategies is related to the building morphology. The Hong Kong SAR Government's initiative *A First Sustainable Development Strategy for Hong Kong* (2005) includes the consideration of building height [7], aside from green space, as an important planning factor contributing to

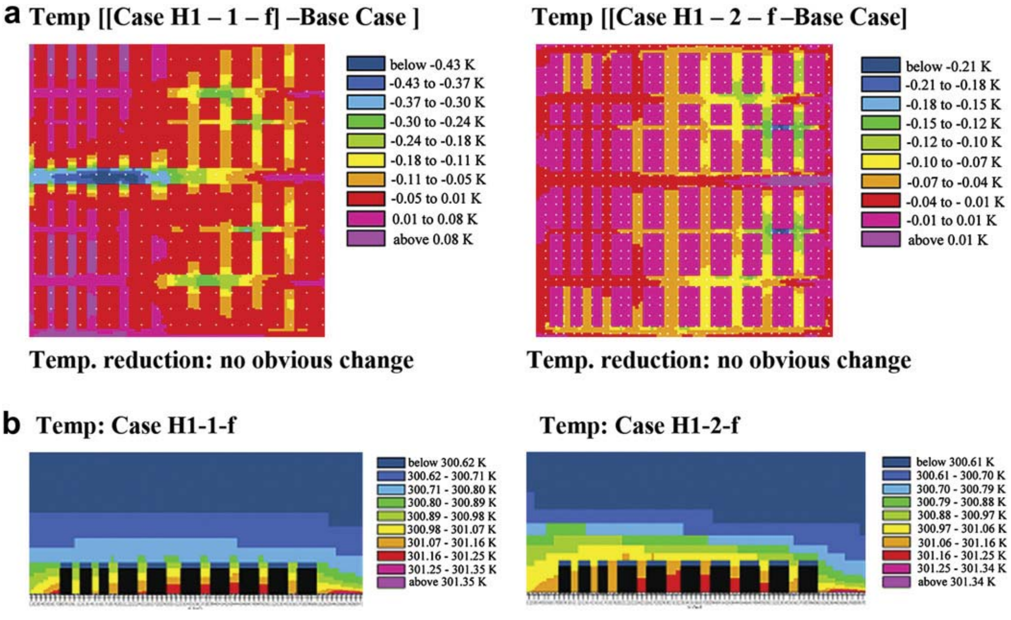

Fig. 16. a: Pedestrian-level temperature reduction of rooftop greening for Case H1 − 1 − f (planting trees on the rooftop) and Case H1 − 2 − f (planting grass on the rooftop). b: Sectional temperature profiles of section for Case H1 − 1 − f (trees on the rooftop) and Case H1 − 2 − f (grass on the rooftop).

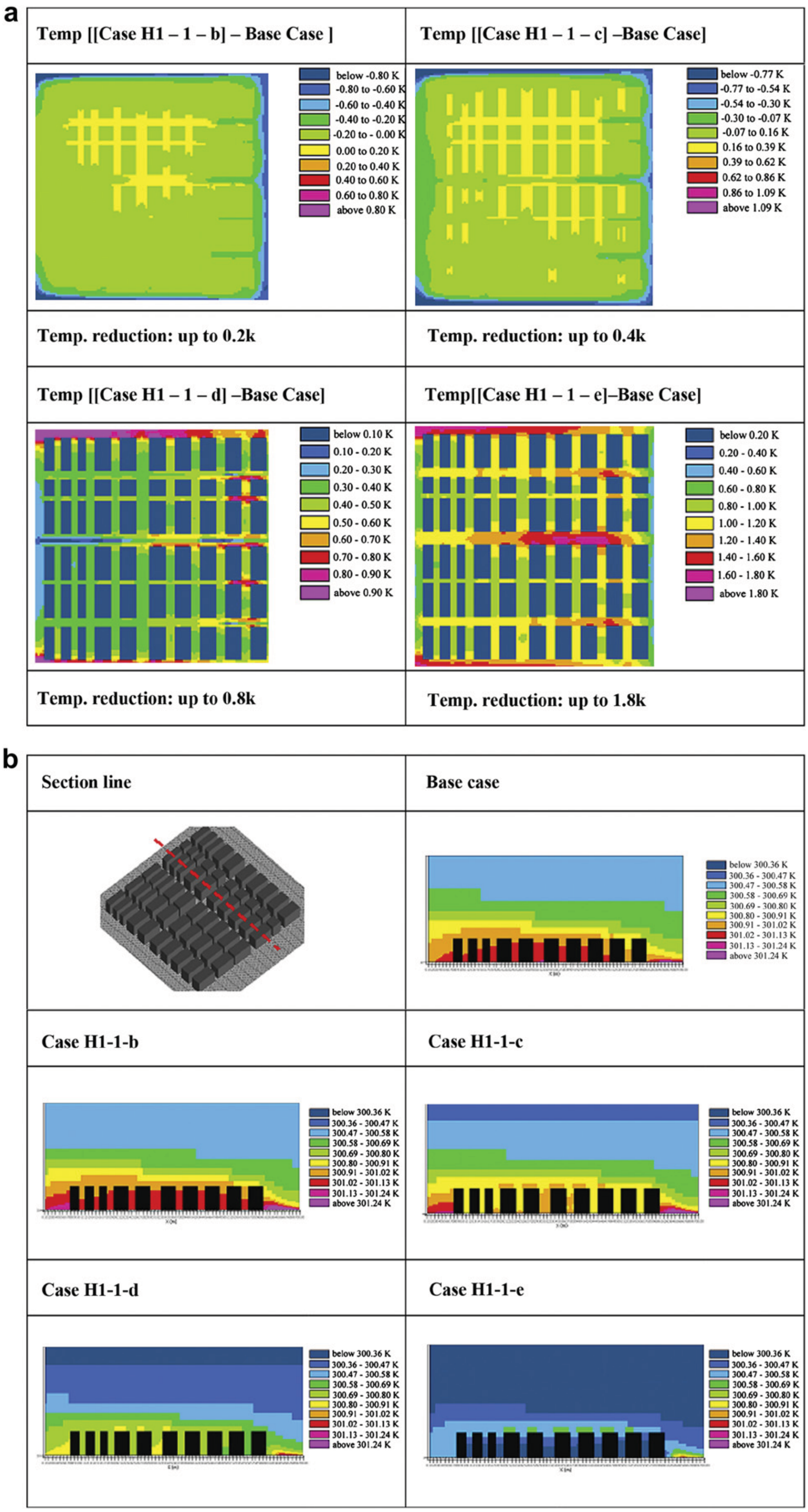

Fig. 17. a: Pedestrian-level temperature reduction for Case H1 − 1 − b, Case H1 − 1 − c, Case H1 − 1 − d, & Case H1 − 1 − e (planting trees on ground). b: Sectional temperature profiles for Base Case, Case H1 − 1 − b, Case H1 − 1 − c, Case H1 − 1 − d, & Case H1 − 1 − e (planting trees on ground).

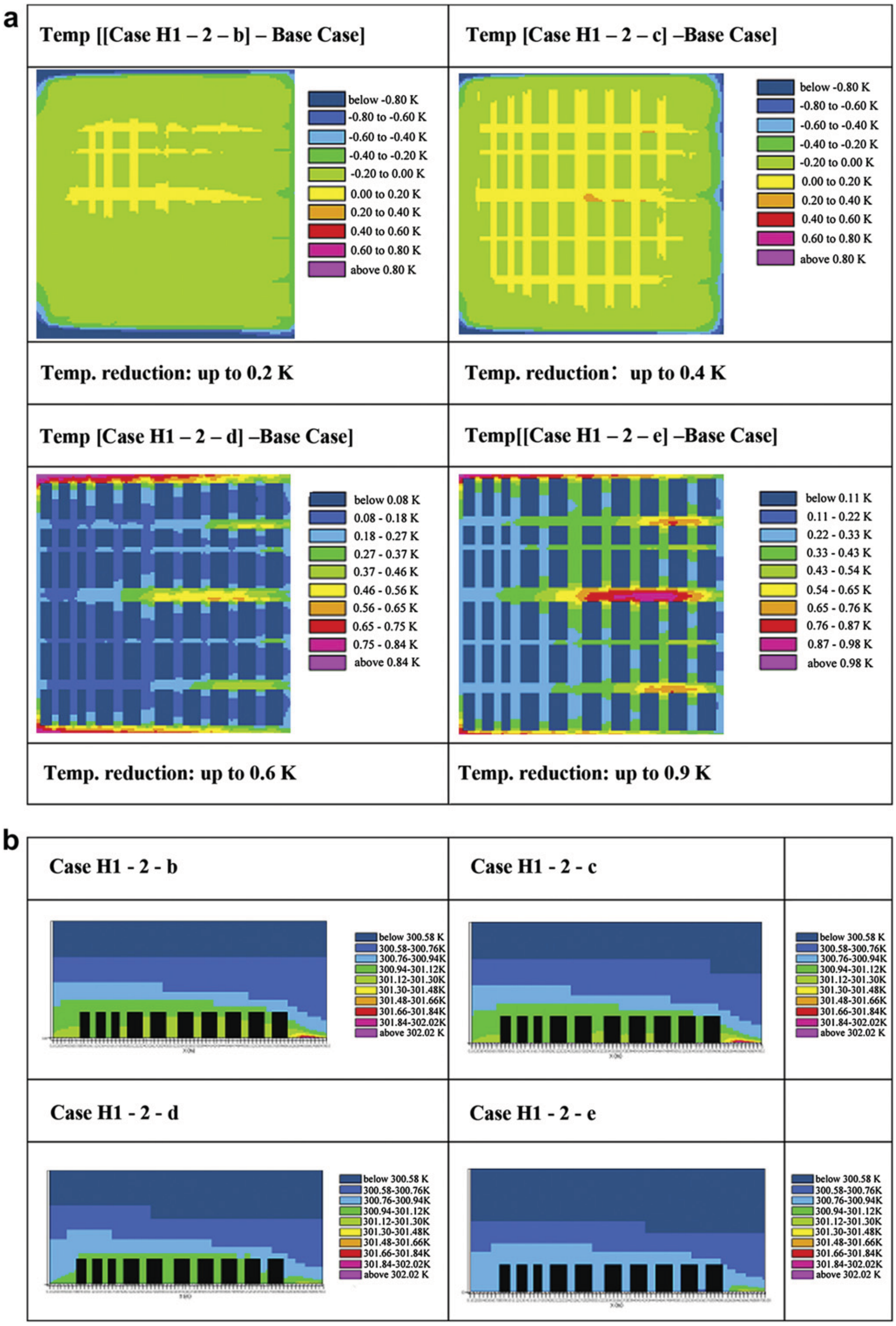

Fig. 18. a: Pedestrian-level temperature reduction for Case H1 – 2– b, Case H1 – 2 – c, Case H1 – 2 – d, & Case H1 – 2 – e (planting grass on ground). b: Sectional temperature profiles for Case H1 – 2 – b, Case H1 – 2 – c, Case H1 – 2 – d, & Case H1 – 2 – e (planting grass on ground).

a sustainable urban environment. Relevant investigations are therefore necessary to understand whether the basic building morphology can increase or decrease the cooling potentials brought about by greening, taking into account Hong Kong's overall densely built urban areas.

In line with the study cases discussed above and using 60 m as the average building height, simulations were also carried out for 2 building heights using ENVI-met, specifically, 20 and 40 m (Cases H2 and H3 in Table 5). For each of the 10 study cases of greening schemes, pedestrian-level air temperatures of 16 evenly distributed points (Fig. 19) were extracted at 3 pm and plotted together with results from the study cases of 60 m building height (Figs. 20–22).

Several observations on the effects of building heights and greening on the urban cooling potentials were revealed by comparative results. First, despite various building heights, tree planting was in general more beneficial than grass surfacing.

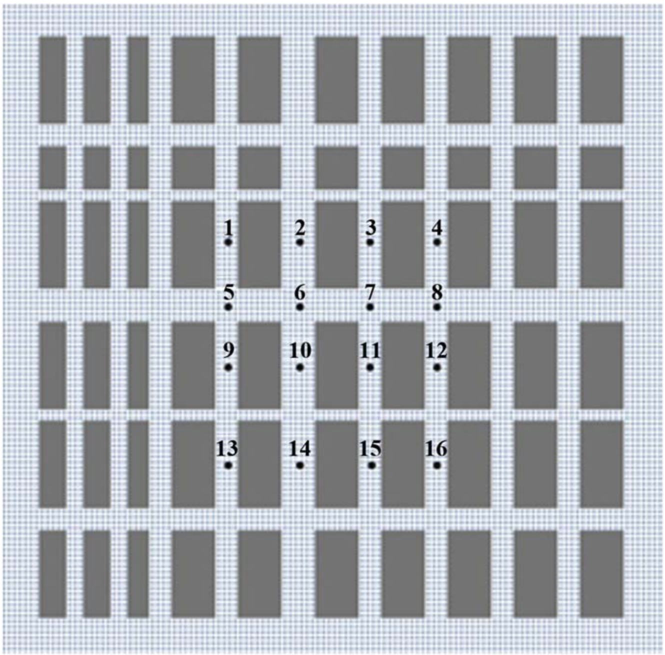

Fig. 19. 16 Points where air temperatures are extracted.

Second, as in Figs. 20–22, the cooling benefits of greening when building heights are lower (at 20 m) are higher than the cooling benefits when buildings are taller (at 40 m or 60 m). That being said, the differences between results of the study cases with 40 m and 60 m are small. The observation is valid for both tree planting and grass surfacing (Figs. 20 and 21).

5. Planning understanding

Based on the parametric study understanding, the following key observations useful for planners can be reported. First, greening is beneficial in cooling the urban environment and creating better urban microclimatic conditions for human activities at the ground level, especially during the hot and humid summer months in Hong Kong. Second, tree planting is more beneficial than grass surfacing. Third, ground level greening is a lot more useful than rooftop greening given the tall building urban morphology of Hong Kong. Finally, the amount of tree planting should be approximately 30% of the urban area.

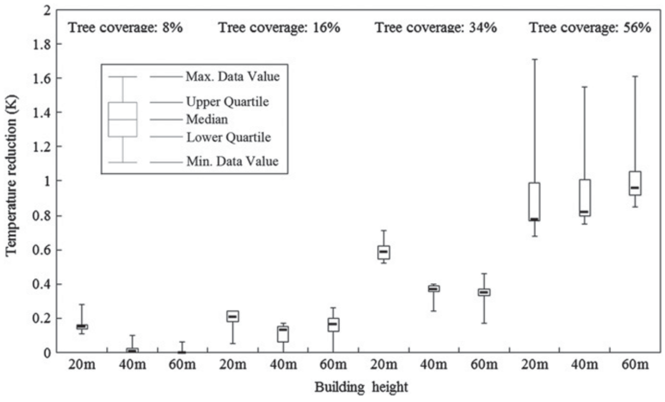

Fig. 20. Temperature reduction at pedestrian level due to varying coverage of trees on ground and building heights.

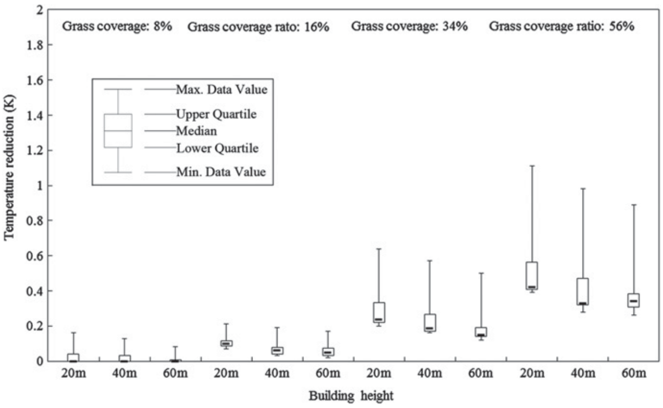

Fig. 21. Temperature reduction at pedestrian level due to varying coverage of grass on ground and building heights.

In general, the more greening, the better, however, from an urban planning perspective, implementation of vegetation schemes of say 50% coverage within the high-density urban context is either difficult or impractical. Based on the study results of the parametric tests, greening coverage of around 30% may be feasible and can be recommended. This percentage is in line with the *Consultancy Study on Building Design that Supports Sustainable Urban Living Space* in Hong Kong, which was completed in 2009 and suggested a guideline of 20–30% green coverage in individual development sites. The Consultancy Study of 2009 also reported that the ratio is comparable with the practices and recommendations elsewhere in the world, e.g., in China.

The parametric study offers some observations to the drafting of the Greening Master Plan currently being undertaken by the Hong Kong SAR Government. In general, the amount of greening suggested in many of the completed Plans is insufficient for environmental benefits. In addition to roadside greening, site greening is also an important consideration. The parametric study understanding is also useful information for the drafting of Hong Kong's Urban Climatic Map (UC-Map) and can support the classification scheme of the map [57]. Within the Urban Climatic Map of Hong Kong, the layer of Green Space is divided into two classes. Areas with greening coverage larger than 33% according to NDVI image are considered to reduce local thermal load by 1 UC-Map class.

A critical study of Greening Master Plan by the Hong Kong SAR Government was conducted to calculate the area-average greening coverage ratio within a grid size of 100 × 100 m, as shown in Fig. 23. The original plans are shown in Fig. 2. Even within the long-term

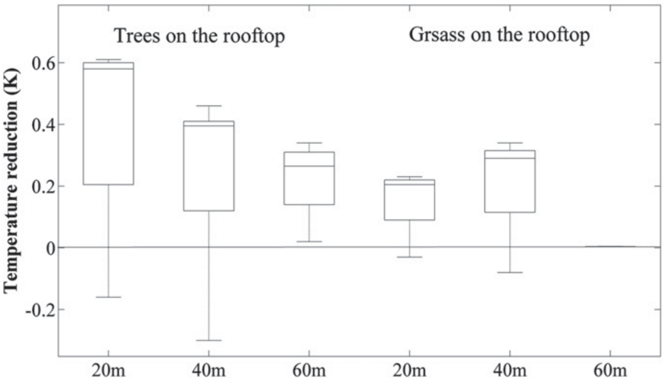

Fig. 22. Temperature reduction at pedestrian level due to planting trees or grass on the rooftop and varying building heights.

Fig. 23. Area-average greening coverage of short-term, medium-term and long-term greening master plans for Tsim Sha Tsui.

greening master plan, most grids did not reach the area-average coverage of 34%. Therefore, it can be recommended that more greening is necessary beyond that stipulated in the Greening Master Plan. To achieve that more effectively, regulations or guidelines on greening must be implemented at the building site level. Initiatives are encouraged by giving rewards to good practices of extensive greening.

6. Conclusions

This paper provides a brief history of urban planning in Hong Kong on greening issues. It emphasizes on the government efforts to promote urban vegetation since the introduction of the sustainable development principles in Hong Kong in 1999. A lack of systematic study towards effective greening policies from an environmental point of view can be noted.

This study investigates the thermal effects of greening on the urban microclimate. Parametric studies using ENVI-met have shown that proper greening may greatly improve the urban microclimate and lower the summer urban air temperatures at grade. For planners and policy makers, it may be stated that “the cooling effect of about 1 K is possible when tree coverage is larger than 1/3 of the total land area” – when the building coverage ratio is set to 44%, which is the average value in Hong Kong. On the other hand, it should be noted that neither planting trees or grass on rooftops nor planting grass on the ground is effective in cooling the pedestrian environment in high-rise, high-density urban Hong Kong. At best they may serve to benefit by not further warming up the hot urban environment as compare to artificial materials.

Building heights have an implication on the cooling benefits of planting on building tops. When the building-height-to-street-width ratio exceeds 1, the benefit of the cooling effects at grade is low. It is important therefore that greening and more importantly tree planting be positioned nearer to the level where human activities are concentrated.

The study focuses on the thermal environment; further work includes investigation of cooling benefits using a thermal comfort index such as PET under different greening schemes. In light of the typical morphology used in the simulation, a study on the thermal interaction of other buildings and urban morphologies with vegetation, such as variation of the building-height-to-street-width ratio and use of different road patterns, may be needed. Different tree species available locally, as well as soil conditions for vegetation, may also need to be further investigated [58]. The usefulness of vertical greening needs to be further studied. For urban areas that aiming for 1/3 greening is practically difficult, micro-neighborhood level detail studies may be conducted to investigate how positioning and grouping of tree planting at the strategic locations may produce the greatest benefits to human activities. Last but not the least, for practice, given that some of the Greening Master Plan for various districts in Hong Kong for short-term, medium-term, and long-term have been developed, studying and monitoring their potential benefits more methodologically may be useful.

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