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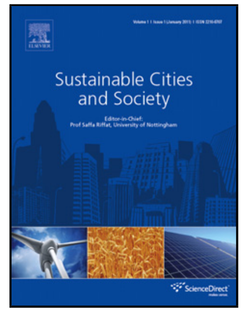

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Regulation of Outdoor Thermal Comfort by Trees in Hong Kong

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Highlights

1. Trees planted in high density urban contexts are more effective in improving thermal comfort than those in open spaces.
2. Urban trees with a large crown, short trunk and dense canopy are more effective in reducing average daytime T_{mrt} at pedestrian level during summer sunny day, with values up to 5.1°C in open space.
3. Five specific ways are proposed to facilitate the integration of tree planting into urban design.

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Abstract

Urbanization is transforming human society in many ways. Besides all the obvious benefits, it also brings negative impacts such as the well-documented urban heat island (UHI) effect and the magnified human heat stress. One way to reduce human heat stress is to increase vegetation density in urban areas, because they can provide evatranspiration and shading benefits. However, given the diversity of tree species and their morphological properties, it is important to understand rationally how different trees regulate thermal comfort. In this study, we investigated the impact of various trees on urban micrometeorological conditions in both open space and high density settings, and how they regulate outdoor thermal comfort. The study shows that trees planted in high density settings are more effective in improving pedestrians' thermal comfort than those in open spaces. The study further shows that trees with a large crown, short trunk, and dense canopy are the most efficient in reducing mean radiant temperature (T_{mrt}). Therefore we recommend five specific ways to facilitate the integration of tree planting into urban design. In a broader sense, our studies suggest that urban trees should be planted strategically to improve human thermal comfort as an integral part of all modern urban developments.

Key words: micrometeorological conditions, urban trees, human thermal comfort, mean radiant temperature (T_{mrt}), physiological equivalent temperature (PET)

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1. Introduction

Urbanization quickens around the world with various effects on urban living (Emmanuel, 2005; Cohen, 2006). One of the most documented effects associated with urbanization is the urban heat island (UHI), which is characterized by a higher air and surface temperature in urban centers than in their surrounding, especially at night (Grimm et al., 2008; Salmond et al., 2016). Furthermore, UHI also worsen human heat stress in urban areas (Oleson et al., 2015). One way to mitigate UHI thereby reduce human heat stress is to increase vegetation cover in urban areas as vegetation can provide evatranspiration cooling and shading benefits as well as other ecosystem services (Salmond et al., 2016). Recent studies have advanced our understanding of urban ecosystem services in general and tree planting in particular. As such, urban trees have attracted considerable interest because they have been shown to generate a wide range of ecosystem service (Salmond et al., 2016).

Trees and open green spaces can make various contributions to high quality urban living, i.e. improving the physical urban environment (Ng, et al., 2012b; Hagler, et al., 2012), enhancing the psychological health of urban dwellers (Thompson, et al., 2014), and promoting urban biodiversity (Sodhi, et al., 2010). In this study, we focus on the effect of trees on the physical urban environment. Planting trees has been one of the most efficient strategies to mitigate the UHI effect in daytime and create thermally comfortable habitats for local residents, especially in tropical and sub-tropical cities (Abreu-Harbich et al., 2015; Bowler et al., 2010; Gómez-Baggethun and Barton, 2013). The unique structure and function of trees provides shading and

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evaporative cooling benefits (Lin and Lin, 2010; Lee et al., 2013; Georgescu et al., 2014), so that trees can remove a large amount of short-wave radiation by reflection and transmission through their leaves to decrease the surrounding ambient air temperature (Brown and Gillespie, 1995). Abreu-Harbich et al (2015) found that individual trees can reduce the surrounding ambient air temperature by between 1.1 and 2.8 ^{o}C during summer. In addition, the shading effect of tree canopies was evaluated (Lee et al., 2013) and it could reduce mean radiant temperature (T_{mrt}) up to 30 ^{o}C during typical Central European summer day.

Due to the benefits of trees and open green spaces for the urban environment, greenery has been widely included in urban areas. The average per capita green space provision within the metropolitan cities in Asia, i.e. Singapore, Tokyo, Shanghai, and Hong Kong, are respectively 10 m^2 (Singapore National Parks Board, 2014), 7 m^2 (Tokyo Metropolitan Government, 2007), 12.5 m^2 (Bureau of Shanghai World Expo Coordination, 2005), and 2 m^2 with 40% of land as the green nature reserve (Hong Kong Planning Department, 2010). The Hong Kong SAR Government promotes sustainable development strategies in which green space is one of the important planning factors. Furthermore, the Hong Kong Civil Engineering and Development Department (HKCEDD) has published the detailed Greening Master Plan (GMP) which is specifically for tree planting in urban areas (HKCEDD, 2012). As shown in Figure 1, several GMPs have been implemented since 2004, such as GMPs for Tsim Sha Tsui, a high density district in Hong Kong.

Figure 1. Long term GMP in Tsim Sha Tsui and the street canyon after the GMP work at Tsim Sha Tsui and Mong Kok (Ng, et al, 2012b).

However, as shown in Figure 1, it should also be noted that there are many limitations on greenery in urban areas, especially for tree planting in high density urban areas, such as the

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limited areas with the potential for planting due to the narrow footpaths and the large built areas. Therefore, to maximize the benefits of trees in the urban context, we performed a thorough literature review in this study, for better understanding of the effect of trees on air temperature (T_a), the mean radiant temperature (T_{mrt}), and wind speed (U) (Section 2), and to parameterize two major effects of trees, i.e., shading and wind resistance (Section 3) by using leaf area index (LAI: the ratio of leaf area to ground cover) and greenery ratio (λ_{ftree}: the ratio of green area to ground cover) respectively. This study provides a quantitative and more detailed understanding of the benefits of trees of different species within the urban context (Section 4) and addresses more specific landscape design issues (Section 5), i.e. the number and species of trees, and the best planting locations.

2. Review of trees as a regulator of the micrometeorological conditions and human thermal comfort within cities

As stated above, urban trees serve multiple purposes. Trees can provide regulatory functions, positively and negatively, in controlling the micrometeorological conditions and affecting human thermal comfort by: 1) the shading effect decreasing T_{mrt}; 2) transpiration cooling the ambient air, i.e. reducing T_a, and 3) wind resistance impeding the surrounding wind speed. The details of the studies are listed in Table 1, in which the effects of trees of different types on the micrometeorological and human thermal comfort conditions in different climatic zones have been investigated.

2.1 Shading by trees

Shading by trees can remove a large amount of incoming short wave radiation by reflection and transmission through their leaves, as shown in Figure 2 (Brown and Gillespie, 1995). T_{mrt} is the variable that is directly decreased by tree shading, given the dependency of T_{mrt} on radiation (Mayer et al., 2008; Tan et al, 2013; Lee et al., 2014). Therefore, the surface and air temperature can be lower in the shade of trees than in surrounding unshaded areas (Holst and Mayer, 2011; McPherson et al., 2011; Armson et al., 2012; Lee et al., 2016). The decrease in T_a in tree shade compared to unshaded areas has been widely investigated in previous studies (Lin and Lin, 2010; Armson et al., 2012 and 2013; Shahidan et al., 2012). A few studies have also monitored surface temperature to indicate the potential cooling effect of urban trees (Leuzinger et al., 2010; Lin and Lin, 2010), as tree canopy tends to reduce surface temperature in the shade and thus reduces storage and convection of heat (Armson et al., 2013).

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In general, leaves can reflect 10% of visible energy and 50% of solar infrared, and transmit 10% of visible energy and 30% of the solar infrared (Figure 2). Multiple layers of leaves can reduce transmission by more as indicated by Berry et al. (2013): a dense and tall tree canopy can lead to a significant reduction in surface temperature through shading during the hot summer period. Specifically, different tree species provide different amounts of radiation interception due to their varied structural characteristics, i.e. average height, tree height variability, and normalized tree volume (Brown and Gillespie, 1995).

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Table 1. Characteristics of studies that have investigated the micrometeorological and human thermal comfort effects of trees.

Climate	City	Types of Tree	LAI	ΔRad	ΔT_a (°C)	ΔRH	ΔT_{mrt} (°C)	ΔU	ΔPET (°C)	References
Tropical	Singapore	mature trees	5.3	--	0.9 -1.5	5%	3.0	80%	3.0	Wong and Jusuf (2010)
		young palms	2.2	--	0.5	0	5.1	80%	2.0	
	Serdang, Malaysia	*Mesua ferrea*	6.1	93%	--	--	--	--	--	Shahidan et al. (2010)
		H. crepitans L.	1.5	79%	--	--	--	--	--	
	Colombo, Sri Lanka	street trees	--	--	0.2	--	2.0-4.0	--	2.0	Emmanuel, et al., (2007)
	Campinas, Brazil	12 trees species	--	--	1.1 - 2.8	--		--	9.5 - 16	Abreu-Harbich et al. (2015)
	São Paulo, Brazil	street trees	5.0		1.1	NSD	24	45%	12	Spangenberg et al., (2008)
			1.0		0.5	NSD	11	7%	7.0	
Subtropical	Shanghai, China	street trees	2.1-6.4	--	1.5-2.0	--	11-47	--	5-20	Yang et al. (2011)
	Taipei, Taiwan	10 tree species and 2 species bamboo	1.5 - 6.1	--	0.6 - 2.5	--	--	--	--	Lin and Lin (2010)
	Osaka, Japan	street trees	2.5-4.8	--	1.0	NSD	--	15%	--	Yoshida et al. (2015)
	Tokyo, Japan	street trees	--	--	0.7	NSD	--	--	--	Narita et al. (2008)
	Saitama, Japan	Gold Crest Wilma	--	--	0.8-1.9	--	24	51%	--	Park et al. (2012)
	Thessaloniki, Greece	21 tree species	--	--	1.6 -7.5	6 - 31%	--	--	--	Georgi and Zafiriadis (2006)
	Hong Kong, China	street trees (higher SVF)	--	--	1.5	--	26	--	--	Tan et al. (2015)
		street trees (low SVF)	--	--	0.3	--	23	--	--	
Mediterranean	Tel Aviv, Israel	*Ficus Retusa*	--	--	1.5	--	--	--	--	Shashua-Bar et al. (2010)
		Tipuana Tipu	--	--	1.2	--	--	--	--	
		Date Palm	--	--	0.9	--	--	--	--	
Temperate	Freiburg, Germany	Chestnut	--	--	1.0	--	30	--	15	Matzarakis et al., 1999
		linden			1.7		32.8		15.7	Lee et al., (2013)
		Maple trees	--	--	2.7		39.1		17.4	Lee et al., (2016)
Temperate Oceanic climate	Manchester, UK	*C. laevigata,*	1-3	--	NSD	--	4.6	--	--	Armson et al. (2013)
		Prunus Umineko	1-2		NSD		3.8	--		
		Lime trees and Scots pine	--	--	--	--	5.0 – 7.0	--	--	Armson et al. (2012)
	Utrecht, Netherlands	street trees	--	--	NSD	--	1.0 - 4.8	--	--	Klemm et al. (2015)
Oceanic climate	Göteburg, Sweden	Chestnut	--	80%	--	--	16	--	--	Lindberg and Grimmond (2011)
			--	95%	--	--	22	--		
Arid-desert	Cairo, Egypt	*Figus elastic*	3	84%	--	--	--	--	--	Fahmy et al. (2010)
	Negev, Israel	*Prosopis juliflora*	--	--	1.1	--	--	--	--	Shashua-Bar et al. (2011)

LAI = leaf area index; ΔRad = solar radiation reduction; ΔT_a = air temperature reduction; ΔRH = relative humidity increase; ΔT_{mrt} = mean radiant temperature reduction; ΔU = wind speed reduction; ΔPET = physiological equivalent temperature reduction (-- denotes data not available; NSD for no significant difference)

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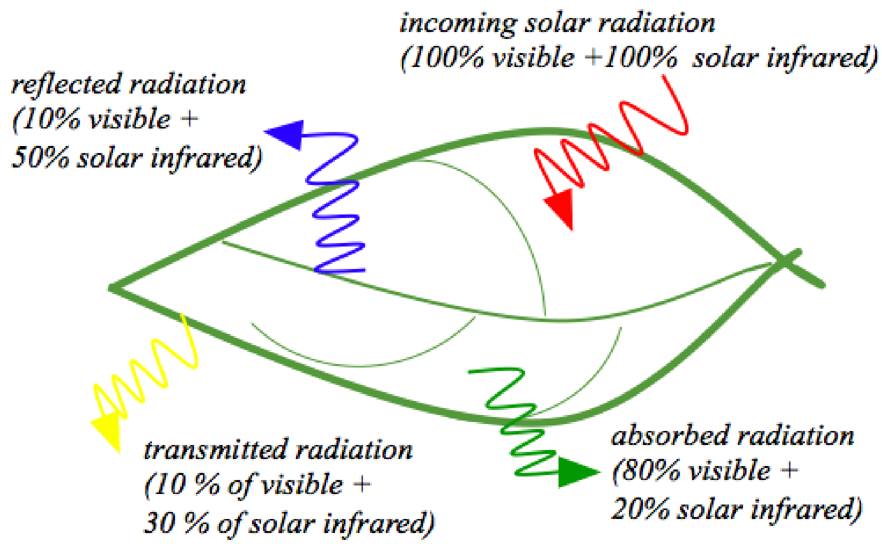

Figure 2. Solar radiation that is absorbed (green), reflected (blue) and transmitted (yellow) by plant leaves (modified from Brown and Gillespie, 1995).

2.2 Transpiration of trees

Trees release water vapour to the air from leaf stomata during photosynthesis, which is known as transpiration (Oke, 1987). Transpiration can mediate latent heat loss during the conversion of liquid water to vapour, thereby resulting in the cooling of the leaf and the surrounding environment. Hence, transpiration has been considered as one of the major means to dissipate the energy load on leaves (Oke, 1987) and one of the most important regulating ecosystem services (McPherson et al., 2011). The transpiration rate of trees depends on both local environmental factors such as the T_a, CO_2, and soil water (Oke, 1987; Fahmy, et al., 2010) and the characteristics of the trees, such as the height and the angle of leaves, the thickness and colour of leaves, and the architecture of tree trunk and branches (Heisler, 1986; Abreu-Harbich et al., 2015). Pataki et al. (2011) reported that whole-tree transpiration differs greatly among species for urban forests in the Los Angeles metropolitan area, due to different morphologies of tree species.

Combined with the shading effect, the transpiration of trees affects T_a. Georgi and Zafiriadis (2006) reported that T_a reduction in tree shade ranged from 1.6 to 7.5 ^{o}C in the early afternoon during the summer period. Similarly, Lin and Lin (2010) investigated the cooling

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effect of 10 species of shade trees and two species of bamboo in a subtropical urban park at midday in summer in Taipei. They observed that T_a reduction was between 0.6 and 2.5 ^oC under the tree canopy. Furthermore, Abreu-Harbich et al (2015) found that individual trees can reduce air temperature by between 1.1 and 2.8 ^oC during summer. It should be noticed that the decrease of T_a under the tree canopy is caused by both shading and transpiration, and that the transpiration can affect the ambient T_a more broadly, not only in the shaded area, and more directly than the shade provided by trees.

2.3 Wind resistance of trees

Trees in the street canyon impede the air flow and decrease wind speed (Park et al., 2012, Mochida, et al., 2008, Salim, et al., 2011), resulting in an impairment of the local air quality. Furthermore, these have a negative effect on thermal comfort in sub tropical and tropical areas (Brown and Gillespie, 1995; Ng et al., 2012b; Park et al., 2012).

In street canyons, trees can increase the turbulence intensity and reduce the average wind speed (Figure 3), and may thus affect human comfort, especially in cities with relatively low wind speed and hot summers such as Hong Kong. Tree cover was observed to have a strong correlation with the upwind direction and reductions in average wind speed in suburban neighborhoods (Heisler, 1990). Densely arranged trees may reduce the mean wind speed by up to 90% below the top of tree canopy compared to open areas (Heisler et al., 1994). Park et al. (2012) reported that in street canyons the presence of four sidewalk trees could reduce wind speed under the canopy by up to 51%. To mitigate this negative effect on thermal comfort, it is critical to select tree species with appropriate forms and size in landscape design.

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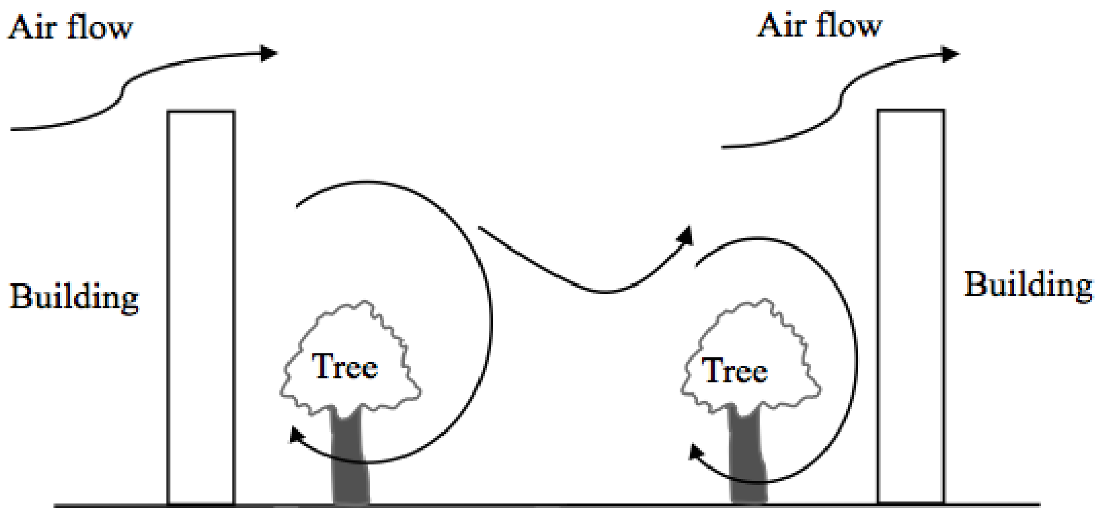

Figure 3. Wind flow in a street canyon with trees.

3. Methodology

3.1 Objectives

This study is to provide better understanding of trees as regulators of human thermal comfort in the urban context, in order to maximize the trees' cooling benefit on the urban environment. The challenge here is to select the right tree species and plant them appropriately. On the other hand, as discussed above, trees also provide shading benefits and transpiration cooling efficiency, resulting in changes in air and radiant temperature, which in turn affect the wind flow pattern and turbulence. Therefore, the findings detailed in section 2 need to be consolidated and collated to form a holistic understanding of human thermal comfort, as well as to provide a guide for planners as to what tree species to use, and, how and where they should be incorporated into landscape design to achieve the optimum scheme.

Given limited information on the geometric parameters for the placement of trees in a landscape to create a comfortable thermal environment, it would clearly require considerable effort to investigate parameters and then integrate them. The parameters involved include the breadth of each tree's canopy and the crown height of trees, in each case looking at the effects on the shading, transpiration and wind resistance of trees. Therefore, both the advantages and disadvantages of incorporating trees into a landscape should be taken into account to assess their integrated effect on thermal comfort.

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In this study, we employed T_{mrt} simulation and parameterization calculation of the wind speed in urban canyons by taking the effect of trees into account. We further performed correlation analysis and multiple regression analysis using SPSS 19.0 software to investigate the influence of tree characteristics on T_{mrt} reduction. Finally, we calculated PET with RayMan software package (Lee and Mayer, 2016). The detailed methodologies are described below.

3.2 Modelling shading effect

In order to model the shading effect of different tree species, the Solar and Long Wave Environmental Irradiance Geometry (SOLWEIG) model was used to examine the effect of different tree species on the reduction in T_{mrt}. It simulates the three-dimensional shortwave and longwave radiation fluxes as well as T_{mrt} at any particular point within the study area. The model has been shown to simulate successfully the spatial variation of T_{mrt} in complex urban settings in different climatic regions (Lindberg et al., 2008; Lindberg and Grimmond, 2011, Lau et al., 2014; Krayenhoff et al., 2014). Two types of input, namely spatial and meteorological data, are required. Spatial data are in the form of a digital surface model (DSM) at a spatial resolution of 1 m as well as a geographical location (i.e. latitude, longitude, and altitude). Hourly meteorological observations include T_a, relative humidity and three components of solar radiation (global, direct and diffuse radiation).

Two settings, 100 m × 500 m and 35 m × 500 m in size, are employed as the simulation domain (Figure 4) in the present study. The two street canyons are surrounded by two rows of buildings with a height of 60 m. The corresponding sky view factors (SVFs) are 0.8 and 0.2, which represent open and high density settings respectively. T_{mrt} is calculated for a standing person where the angular factors (proportion of radiation received by the human body in each direction) are set to 0.22 for radiation fluxes from the four cardinal points (east, west, north and south) and 0.06 for radiation fluxes from above and below (Höppe, 1992). Standard values of absorption coefficients for shortwave and longwave radiation are set to 0.7 and 0.97, respectively (Höppe, 1992). Values for albedo and emissivity for buildings and vegetation are set to 0.20 and 0.95 respectively in accordance with Oke (1989).

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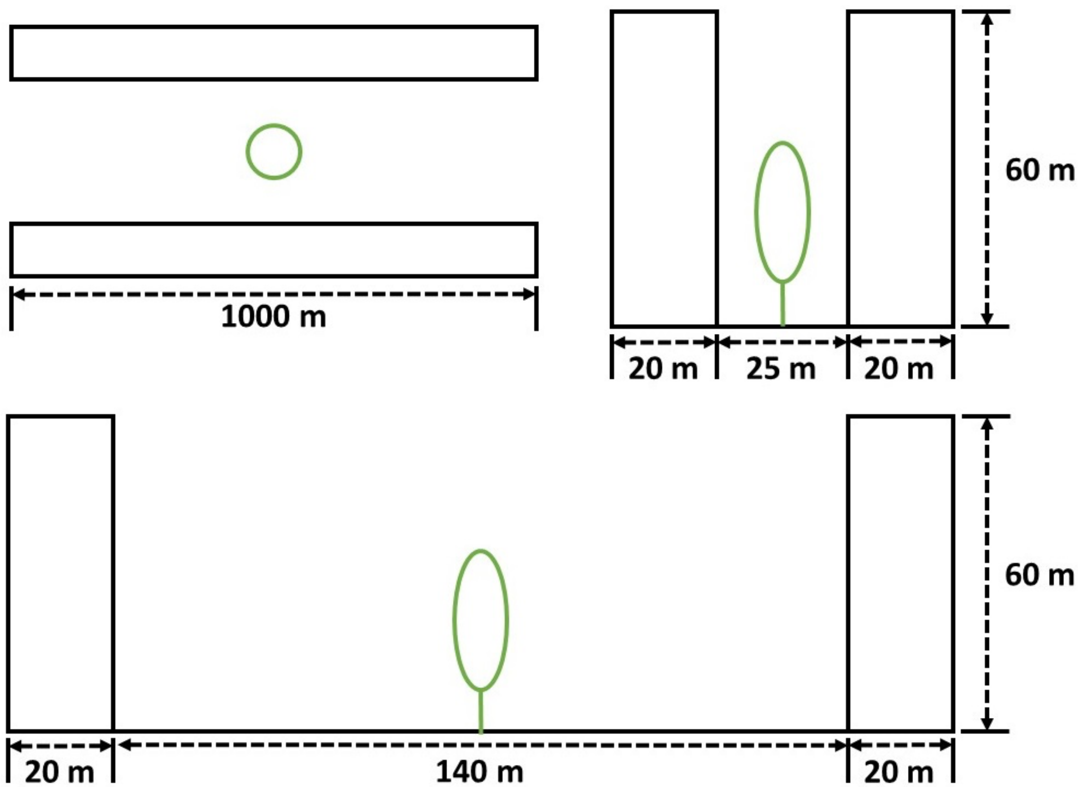

Figure 4. Simulation domain of open and high density settings.

A single tree is placed in the center of the simulation domain and T_{mrt} values under the tree canopy are recorded for subsequent analysis. The physical configuration of the tree is represented by three parameters, including tree height, trunk height and the diameter of tree crown. The transmissivity of solar radiation through tree crown and LAI were individually set for different species (Table 2). Among them, LAI is a central characteristic and has been widely used, because the cooling effects of trees, i.e. shading and transpiration, are primarily determined by the extent of leaves (Grimmond and Oke, 1991; Ong, 2003; Fahmy et al., 2010; Shahidan et al., 2010; Arx et al., 2013; Rahman et al., 2014). High LAI indicates high tree shading potential and thus high amount of solar radiation interception. The relationship between LAI and light interception of tree canopy can be expressed by the Beer-Lambert law (Holst et al., 2004; Deguchi et al., 2006):

$$LAI = \frac{-\ln\left(\frac{Q_i}{Q_0}\right)}{k} \qquad (1)$$

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where k is the light extinction coefficient, Q_i is the irradiance beneath the tree canopy and Q_0 irradiance above the tree canopy. Fahmy et al. (2010) showed that tree species *Figus elastic* with LAI at 3 could intercept almost 84% of direct radiation. In Malaysia, Shahidan et al. (2010) showed that tree species *Mesua ferrea* with LAI value at 6.1 and canopy transmissivity around 5%, could reduce incoming solar radiation by 93%, thus significantly contributing to the cooling benefits.

There are two types of method in determination of LAI values: direct and indirect (Ong, 2003). Direct measurement involves destructive harvest of leaves, and calculation of leaf area in relation to the crown area of the tree. Indirect measurement includes the measurements of light transmittance of plant canopy, and light absorption of canopy through remote sensing (Green and Clark, 2000). The values of LAI may vary with the different methods of measurement. In this study, we took hemispherical photographs for 12 tree species (Table 2 and Figure 5) in the campus of the Chinese University of Hong Kong on an overcast day with a Nikon Coolpix 800 and an FC-E8 fish eye lens. It is worth noting that, except for *Peltophorum pterocarpum* which is less common, the 12 tree species are common species for amenity planting in Hong Kong (Jim, 1990; Zhang and Jim, 2014). Then the images were used for calculating LAI and transmission of solar radiation using Software Hemisfer (Figure 5, Schleppi et al., 2007; Thimonier et al., 2010).

Table 2. Tree species in the present study.

	Species name	Leaf habit	H	TH	CH	CDL	CDW	DBH	LAI	TM
T1	*Acacia confusa*	Evergreen	10.0	1.8	8.2	18.0	16.0	60	2.40	16.5%
T2	*Aleurites moluccana*	Evergreen	9.0	2.6	6.4	7.0	7.0	20	2.77	18.6%
T3	*Bauhinia blakeana*	Evergreen	7.2	2.0	5.2	6.0	6.0	24	3.55	10.6%
T4	*Bombax malabaricum*	Deciduous	9.0	2.8	3.2	8.0	7.0	23	1.83	35.5%
T5	*Casuarina equisetifolia*	Evergreen	13.0	4.4	9.6	8.0	4.0	23	1.52	30.3%
T6	*Delonix regia*	Evergreen	4.4	2.0	2.4	14.0	12.0	35	1.91	23.5%
T7	*Ficus microcarpa*	Evergreen	7.8	1.8	6.0	23.0	18.0	78	2.81	9.7%
T8	*Livistona chinensis*	Evergreen	11.2	6.2	5.0	6.0	6.0	20	2.11	23.0%
T9	*Macaranga tanarius*	Evergreen	4.2	1.2	3.0	13.0	8.0	25	3.02	16.2%
T10	*Melaleuca leucadendron*	Evergreen	10.6	3.2	7.4	6.0	6.0	43	3.42	23.5%
T11	*Peltophorum pterocarpum*	Deciduous	11.4	2.0	9.4	15.0	15.0	42	3.15	10.6%
T12	*Roystonea regia*	Evergreen	12.6	9.0	3.6	6.0	6.0	37	1.10	51.6%

H: Height of the tree (m); TH: Trunk height (m); CH: Crown height (m); CDL: Crown diameter length (m); CDW: Crown diameter width (m); DBH: Diameter at breast height (cm); LAI: Leaf area index (m^2/m^2); TM: Transmissivity of downward radiation (%)

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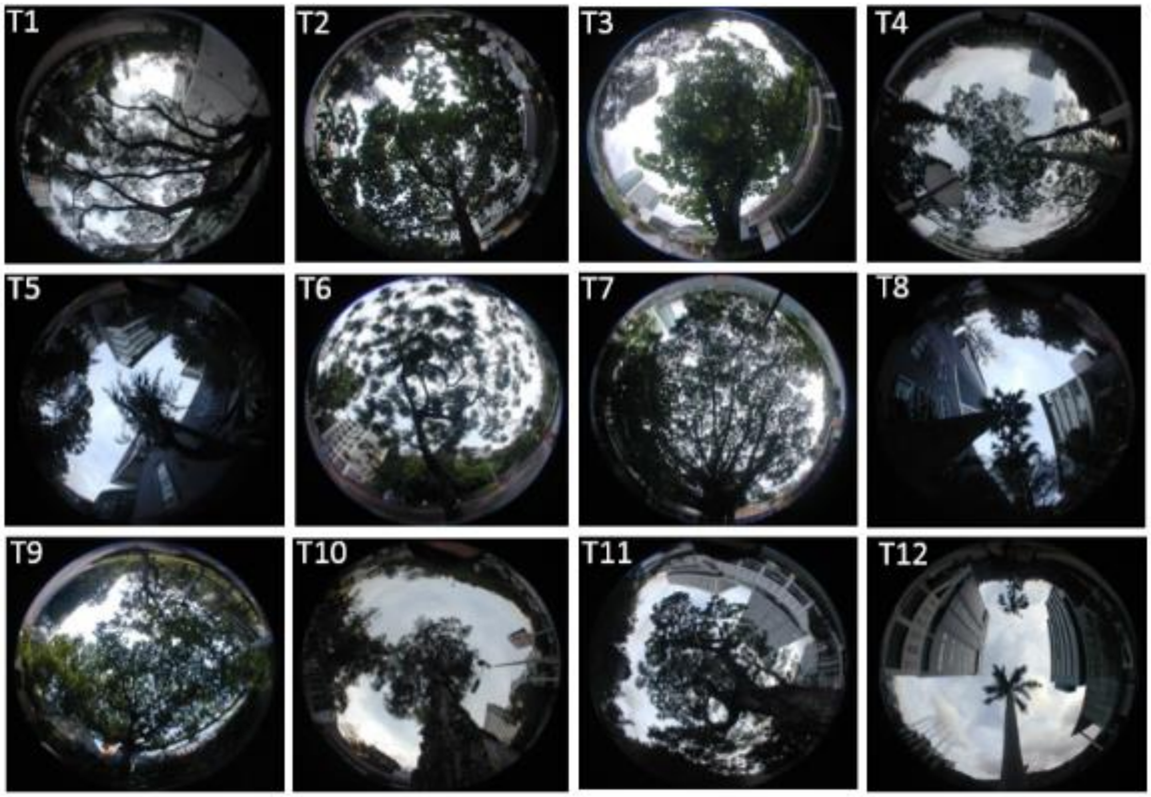

Figure 5. Hemisphere photographs of 12 studied trees

3.3 Modelling wind resistance effects

To investigate the wind speed in urban canyons with trees, we applied an semi-empirical model which is based on the balance between horizontal momentum flux and drag force on both buildings and trees (Bottema, 1996 and Macdonald, 2000):

$$\sum_{obstacle} (C_{D(building)} A_{front_{building}}) + \sum_{obstacle} (C_{D(tree)} A_{front_{tree}}) \quad) \qquad (2)$$

where λ_p is the site coverage ratio, A_{front} is the frontal area, A_{site} is the site area, C_D is the drag force coefficient, and τ_w is the vertical flux of horizontal momentum from the upper layer to the lower layer due to the turbulence mixing effect, which can be expressed as $\tau_w = \rho u_*^2$, in which u_* is the friction velocity and ρ is the air density. Therefore, the averaged wind speed in the street canyon U_c normalized by friction velocity u_* can be estimated by:

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$$\frac{U_c}{u_*} = \left[\left(\frac{2[(1-\lambda]_p)}{C_{D_{building}}\lambda_{f_{(building}}} + C_{D_{tree}\lambda_{f_{tree}}}\right)\right]^{0.5}, \text{ in which } \lambda_f = \frac{A_{front}}{A_{site}} \quad (3)$$

We chose the values of drag coefficient of trees $C_{D(tree)}$ and building $C_{D(building)}$ as 1.0 and 2.0 respectively (Cheng and Castro, 2002; Gromke and Ruck, 2008). $\lambda_{f_{building}}$ was calculated as a sectional frontal area density $\lambda_{f_{0-15m}}$ to solve U_c, since the sectional frontal area density can better estimate u_c than the conventional λ_f. We then need to parameterize friction velocity, u_*, and the frontal area density of tree, λ_{ftree}, to close the equation 3. Friction velocity (u_*) is estimated in this study by the log-law equation:

$$\frac{U_h}{u_*} = \frac{1}{\kappa}\ln\frac{z_h - d}{z_0} \quad (4)$$

where z_0 is the roughness length and z_d is the displacement height. Both of them are parameterized by the relations between **roughness length** (z_0), **displacement height** (z_d), **and frontal area density** (λ_f) (Grimmond and Oke, 1999), as tabulated in Table 3. It should be noticed that we assumed that the tree does not affect the log-law wind profile, since the buildings dominate the air flow.

Table 3. Indices, roughness length (z_0) and displacement height (z_d) to estimate u_*. Total 11 cases with λ_f from 0.05 to 1.0 are included. The reference height is 500m and the mean building height is 60m.

Cases	λ_f	$\frac{z_d}{z_H}$	z_d	$\frac{z_0}{z_H}$	z_0	$\frac{u_*}{U_{ref_{500m}}}$
1	0.05	0.1	6	0.03	1.8	0.071
2	0.1	0.55	33	0.1	6	0.092
3	0.2	0.76	45.6	0.11	6.6	0.095
4	0.3	0.81	48.6	0.07	4.2	0.086
5	0.4	0.87	52.2	0.04	2.4	0.076
6	0.5	0.92	55.2	0.038	2.28	0.076
7	0.6	0.94	56.4	0.036	2.16	0.075
8	0.7	0.96	57.6	0.035	2.1	0.075
9	0.8	0.98	58.8	0.03	1.8	0.073
10	0.9	0.99	59.4	0.03	1.8	0.073
11	1	1	60	0.03	1.8	0.073

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Consequently, the values of u_* normalized by $U_{ref_{500m}}$ can be estimated as shown in Figure 6. Similar to z_0 and z_d, u_* is only sensitive in the change of λ_f when λ_f is less than 0.3-0.4, and is almost constant when λ_f larger than 0.3 -0.4.

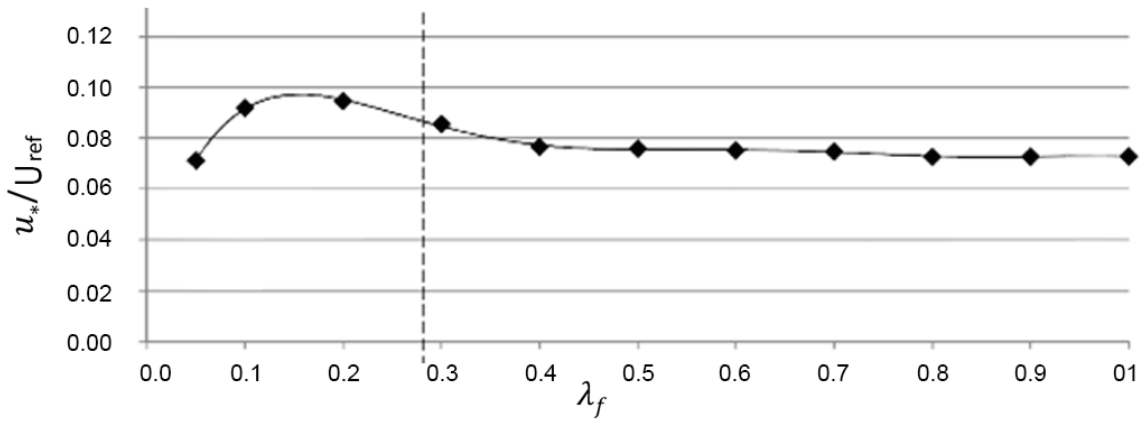

Figure 6. Relation between $\frac{u_*}{U_{ref_{500m}}}$ and λ_f.

Therefore, $\frac{u_*}{U_{ref}}$ is constant, 0.07, with $\lambda_f \geq 0.4$ and reference height wind speed measured at 500 m above the ground, as:

$$u_* = 0.07 \cdot U_{ref_{500m}}, \text{ when } \lambda_f \geq 0.4 \qquad (5)$$

Then we get:

$$Uc = 0.07\, U_{\downarrow}(ref_{\downarrow}500m)\ 〖(((2\ 〖(1-\lambda〗_{\downarrow}p))/(C_{\downarrow}(D_{\downarrow}building)\ \lambda_{\downarrow}(f_{\downarrow}(_{\downarrow}building)) + C_{\downarrow}(D_{\downarrow}tree\lambda_{\downarrow}(f_{\downarrow}tree))\ ))〗^{\uparrow} \qquad (6)$$

In which effects of both the tree and building on the vertically normalized wind speed within the street canyon are included.

4. Results and discussions

4.1 Impact of trees on T_{mrt}

4.1.1 Reduction in T_{mrt} of trees in open and high density settings

The presence of trees generally reduces downward shortwave radiation due to their shading effect. Table 4 shows that eight of the species are able to reduce average daytime downward shortwave radiation by over 50% in both open and high density settings, with the

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highest reduction observed for *Acacia confusa, Ficus microcarpa* and *Peltophorum pterocarpum,* due to their large tree crowns and relatively short trunks (Figure 7). The downward shortwave radiation is reduced by up to 234 Wm^{-2} (78 %) for *Peltophorum pterocarpum* under open settings. The lowest reduction is observed for *Livistona chinensis* and *Roystonea regia* (12.5% and 5.2% respectively). This is because these taller trees with smaller tree crowns only provide shading at noon and spaces under them are more exposed to downward shortwave radiation.

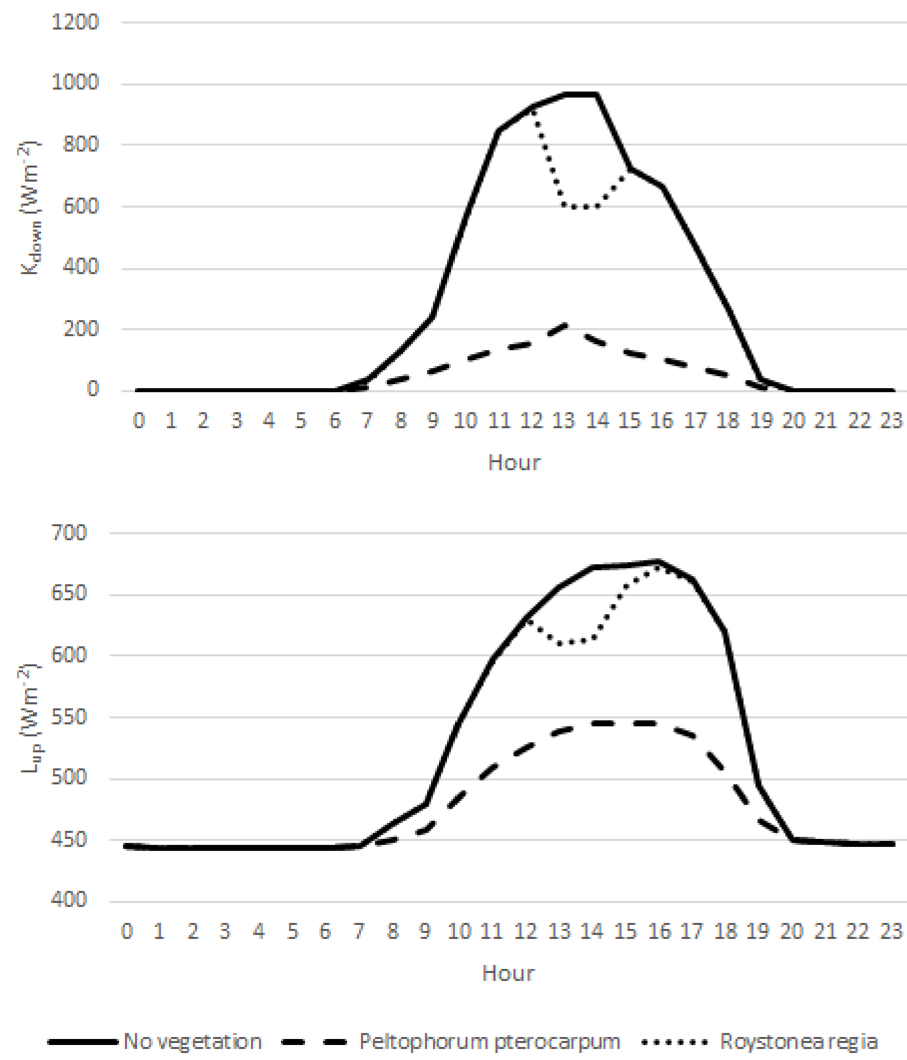

Figure 7. Diurnal variation of downward shortwave (upper) and upward longwave (lower) radiation of no-vegetation, *Peltophorum pterocarpum* (dense tree crown) and *Roystonea regia* (sparse tree crown) on 12 July 2009 in the open settings.

The reduction in upward longwave radiation is similar to that in incoming shortwave radiation, with the highest reduction of around 40 Wm^{-2} (8 %) observed in the three species with large tree crowns. The extensive shading lowers the temperature of the ground surface and results in the reduction of upward longwave radiation. The effect of the transmissivity of the tree crown is best observed in *Aleurites moluccana* and *Bombax malabaricum*. Both trees have the same height and crown size but the transmissivity of *Aleurites moluccana* is about half that of *Bombax malabaricum*, leading to a 13.2% difference in the reduction in downward shortwave radiation.

The effect of different tree species on the reduction in average daytime T_{mrt} ranges from 0.1 to 5.1°C, with the highest reduction observed in *Acacia confusa*, *Ficus microcarpa* and *Peltophorum pterocarpum* (Table 4). They are closely followed by *Aleurites moluccana*, *Bauhinia blakeana* and *Macaranga tanarius* with reductions in T_{mrt} ranging from 3.0 to 4.0°C. These species are generally characterized by shorter tree trunks, and with transmissivity ranging from 10-20%. This implies that the choice of species is important in order to improve thermal comfort at pedestrian level.

The differences between open and high density settings are quite small. The effect of trees on downward shortwave radiation is reduced by about 30 - 70 Wm^{-2} due to the exposure to incoming shortwave radiation in high density settings. The differences in average daytime T_{mrt} is also limited with about 1.0 °C difference observed in the species with a dense tree crown. This suggests that the density does not greatly affect the effect of vegetation.

Unlike the small effect on T_a, T_{mrt} was strongly affected by the shade of the tree crowns. A previous study has reported that T_{mrt} was 3.8 - 4.6 °C by average lower in tree shade than the open space (Armson et al. 2013). T_{mrt} was found with maximum values about 30 K lower within the tree-lined street canyon (Holst and Mayer, 2011; Lee et al., 2013, 2016). Similarly, Park et al. (2012) also observed that T_{mrt} was 24 °C lower inside the sidewalk tree canopy. Furthermore, previous studies have reported that shading of trees can significantly influence human thermal comfort in terms of PET (Abreu-Harbich et al. 2015; Holst and Mayer, 2011; Lee et al., 2013 and 2016). Specifically, PET could be reduced from 9.5 to 16 °C for different tree species under the tree shade than that in the sun during midday in summer in Campinas, Brazil (Abreu-Harbich et al. 2015), and the reduction in PET reached 15.7 °C by shading effect of tree canopies in Freiburg during typical Central European summer day (Lee et al., 2013).

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4.2 The impact of trees on wind speed in the street canyon

The sensitivity of Uc to the change of λ_{ftree} is tested by using equation 6. We set $U_{ref_{500m}}$ is equal to 4.5 m/s, averaged wind speed in summer, based on the MM5 modelling results at Hong Kong (Yim et al., 2007). The values of λ_p are equal to 0.1, 0.2, 0.3, 0.4, 0.5 and $\lambda_{f\ building}$ are equal to 0.1, 0.2, 0.3, 0.4 and 0.5.

Based on the result of the analytical study shown in Figure 8, the effect of trees on the wind speed in the street canyon within the high density context (λ_p or λ_p larger than 0.3) could be ignored, specifically when the wind speed is less than 1.0 m/s. It will be sensitive only when the background density is less than 0.3. The decrease in wind speed ranged from 0.5 m/s to 0.8 m/s, with λ_{ftree} increasing from 0.1 to 0.4 in an open setting when λ_p at 0.1. Furthermore, from the perspective of practical urban planning, if assuming the crown shape of the tree is a sphere, we can transfer λ_{ftree} to the greenery ratio $\lambda_{p\ tree}$. The normal range of $\lambda_{p\ tree}$ applied in urban planning practice is highlighted in Figure 8, and we can see the effects of such a greenery ratio on the wind speed in the street canyon within different background urban densities, i.e. λ_p or λ_p.

Previous studies have illustrated the close link between frontal area density of trees λ_{ftree} and leaf area index (LAI), for instance, Raupach et al. (1996) assumed $\lambda_{ftree} = {LAI}/{2}$, while Novak et al. (2000) observed $\lambda_{ftree} = {LAI}/{3}$ for spruce forests both in wind tunnel and field studies. Therefore, we evaluated wind speed reduction under trees with different LAI based on λ_{ftree} in Figure 8 for open and high density settings.

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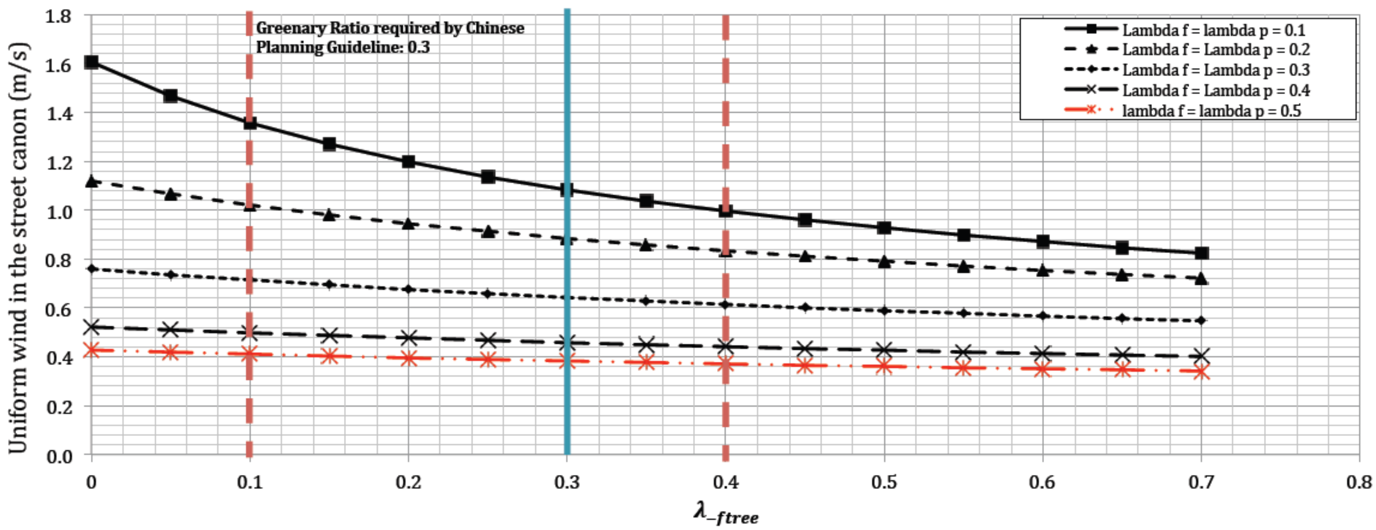

Figure 8. Sensitivity of U_C on the change of λ_{ftree}, with the different urban densities. The normal range of $\lambda_{p\ tree}$ applied in urban planning practice is highlighted in Figure 8.

4.3 PET calculation

Previous studies have investigated the influence of trees on air temperature and T_{mrt}. However, much less attention has been paid to the influence of trees on relative humidity and wind speed, which also contribute to human thermal comfort. Therefore, it is critical to investigate all these micrometeorological parameters to determine the effect of different trees on human thermal comfort in terms of PET.

We further categorized trees into three groups based on their canopy characteristics: dense canopy, sparse canopy and palms (Table 5). We then summarized the influence on T_a, T_{mrt} and wind speed of each group based on the previous studies and our simulation. The simulation period is June to August 2009 and the average values are obtained by averaging all the daytime T_{mrt} values. Finally we calculated the PET reduction values with the RayMan model.

As illustrated in Table 5, the decrease in air temperature under tree canopy varied between 1.6 - 2.5 ^{o}C for trees with dense canopy, and 0.6 -2.2 ^{o}C for sparse canopy, based on the study of Lin and Lin (2010). Wong and Jusuf (2010) reported that there is no significant cooling of the sidewalks planted with young palms, with cooling effects at 0.5 ^{o}C only at some points in their study, as palm trees could not provide enough shading due to their low canopy density. We further showed T_{mrt} reduction could be up to 5.1 and 2.2 ^{o}C, under dense and sparse canopy trees

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respectively, in opens settings. The corresponding values for high density settings were 3.9 and 1.8 °C. In addition, two palm trees in our study performed poorly in T_{mrt} reduction in both settings, with values at 0.2 and 0.1 °C only. Our results also indicated that wind speed reduction was around 0.8, 0.7 and 0.5 m/s in open settings under trees with dense canopy, sparse canopy and palms respectively, while wind speed reduction was lower than 0.1 m/s in a high density context.

Table 5. The influence of different urban trees on mirco-scale temperature modification, wind speed and PET for open and high density settings.

	Canopy type	ΔT_a (°C)*		ΔT_{mrt} (°C)		ΔU (m/s)	ΔPET (°C)	
		min	max	min	max		min	max
Open settings								
Trees	Dense canopy (2.4 < LAI < 3.6)	1.6	2.5	1.1	5.1	0.78	0.0	2.9
	Sparse canopy (1.5 < LAI < 1.9)	0.6	2.2	1.1	2.2	0.68	-0.5	1.5
Palms	1.1 < LAI < 2.1	0.5	0.5	0.1	0.2	0.52	-0.6	-0.7
High density								
Trees	Dense canopy (2.4 < LAI < 3.6)	1.6	2.5	1.0	3.9	0.09	1.2	3.4
	Sparse canopy (1.5 < LAI < 1.9)	0.6	2.2	1.6	1.8	0.07	1.0	2.2
Palms	1.1 < LAI < 2.1	0.5	0.5	0.0	0.1	0.04	0.2	0.2

ΔT_a = air temperature reduction, ΔT_{mrt} = mean radiant temperature reduction, ΔU = wind speed reduction, ΔPET = physiological equivalent temperature reduction (negative values indicate PET increase). * Values of ΔT_a of trees obtained from Lin and Lin (2010), and values of ΔT_a of palms obtained from Wong and Jusuf (2010)

In addition, our calculations of PET indicated that greenery in high density settings could lead to higher reductions in PET than those in the open spaces, and trees showed greater cooling benefits than palms (Table 5). Specifically, in high density settings, the maximum reduction in PET could reach to 3.4 °C and 2.2 °C under trees with dense and sparse canopy respectively; and 2.9 °C and 1.5 °C in open settings. Furthermore, we observed that palm trees planted in open spaces caused an increase in PET, mainly due to their reduction effect on wind speed. Therefore *Ficus microcarpa*, *Peltophorum pterocarpum* and *Acacia confusa* (related to Table 2), when

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fully grown, would yield the greatest benefit in terms of reducing the PET of the urban environment during the summer period in Hong Kong.

5. Application to local Greening Master Plans (GMPs)

Although the overall Hong Kong total greening ratio is about 66%, 40% belongs to country parks and nature reserves and the greenery coverage ratio actually in urban areas is quite limited. Since 2004, the Civil Engineering and Development Department (CEDD) of the Hong Kong SAR Government has initiated the framework of Green Master Plans (GMPs) to improve greening of high density downtown areas by identifying possible planting locations and providing suitable tree species (HKCEDD, 2012). According to the local culture and landscape context, and future development needs, different greening themes for each GMP have been formulated. For each selected urban area, three time scales of GMPs have been created i.e. short term plan (STP), medium-term plan (MTP), and long-term plan (LTP) (HKLEGCO, 2014).

Tsim Sha Tsui is one of the densest commercial and shopping areas in Hong Kong, located in the south of Kowloon Peninsula. Due to heavy traffic and the dense population of citizens and visitors of this area, the major traffic roads and popular shopping streets, like Natham Road, and Cantham Road South were selected and highlighted in the GMPs for improvement of pedestrian level comfort by increasing roadside greening (Figure 9a). In the GMPs for the Tsim Sha Tsui area, it can be found that most of the selected species have dense canopies, such as *Ficus benjamina* (Nathan Road), *Cinnamomum burmannii* (Nathan Road and Catham Road South), *Cinnamomum camphora* (Salisbury Road), *Spathodea campanulata*, (Canton Road). Palm trees such as *Wodyetia bifurcate* were also planted on Nathan Road and Salisbury Road (Figure 9b).

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Figure 9a. Locations of selected theme plants in Tsim Sha Tsui Area (modified from HKCEDD, 2012).

Figure 9b. Theme plants in the greening master plans for Tsim Sha Tsui area (modified from HKCEDD, 2012).

In the Tsim Sha Tsui area, the Short-term plan (STP) (Figure 10a) has been completed in 2007, while the Mid-Term Plan (MTP) (Figure 10b) and Long-Term Plan (LTP) (Figure 10c) are to be implemented in the near future (HKLEGCO, 2014). Based on the research findings from

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section 4, a thermal comfort evaluation on these three GMPs for the Tsim Sha Tsui area was conducted. Physiological equivalent temperature (PET) was employed as the thermal comfort index. Different grid sizes of 25 m × 25 m, 50 m × 50 m, and 100 m × 100 m have been tested to pursue the optimal resolution of PET results for illustrating and visualizing the roadside greenery's cooling effect after adopting the proposed three GMPs. Finally a grid size of 25 m × 25 m was chosen (Figure 11 and 12).

Figure 12a shows the base case after adopting the STP, with the possible cooling effect that can be achieved on major roads. If the MTP was implemented, then compared with the STP situation, the thermal comfort condition of the East Tsim Sha Tsui area can be further improved by 1 ^{o}C of PET, especially those pedestrian areas along Salisbury Road, Hankow Road, Mody Road, Humphreys Avenue and Cameron Road. Once the LTP is completed, then compared with the STP situation, the pedestrian level thermal comfort condition of most streets in Tsim Sha Tsui area can be further reduced by 1 ^{o}C of PET. In addition, a few spots in the busiest roads like Nathan Road and, Chatham Road South can achieve a 2 to 3 ^{o}C drop in PET. Given climate change and further urban development in Tsim Sha Tsui area, a hot future is expected. Although more roadside trees will be planted, the overall area average greenery coverage ratio of the LTP is less than 15% and its cooling effect at district level is limited (Ng et al., 2012b). The lessons we learnt on the vegetation species with dense canopies from this study can be further referred to CEDD in order for them to refine their GMPs. As such, given the high density high-rise urban morphology of Hong Kong, more greenery in urban areas, especially tree species with dense-canopies, is recommended, not only along the streets to form greenery networks to mitigate the heat island effect, but also on the top of building podiums or at lower building levels to improve the pedestrian level thermal comfort condition (Figure 13, Ng et al., 2012a; HKPSG, 2005). Georgescu et al. (2015) suggested that interdisciplinary cooperation in the field of urban climatology, urban planner and landscape architecture should work together to advance sustainability solutions to urban problems. Here we also argue that academics must be proactive in terms of urban planning and environmental protection. It is possible to bring in expertise from diverse fields together and solve any issues in a quickened pace. The skills in architecture, environmental monitoring, health care, financial and commercial services, and modern biological sciences can be all brought into this research enterprise.

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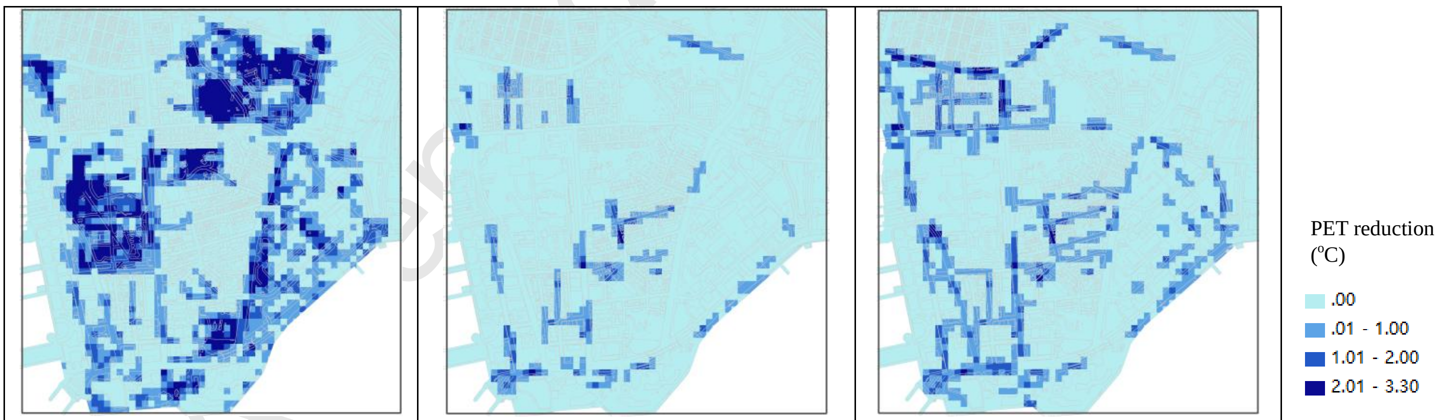
a	b	c

Figure 10. Three time-scale greening master plans for Tsim Sha Tsui area (from HKLEGCO, 2005).

a	b	c

Figure 11. Vegetation coverage of short-term, mid-term and long-term greening master plans for Tsim Sha Tsui area (resolution 25 m × 25 m).



a. ΔPET after adopting STP	b. ΔPET (MTP-STP)	c. ΔPET (LTP-STP)

Figure 12. Cooling effect on thermal comfort based on the comparison between different time-scale GMPs for the Tsim Sha Tsui area (resolution 25 m × 25 m).

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Figure 13. The recommended greenery design strategies to improve the pedestrian level comfort condition.

In addition, Georgescu (2015) demonstrated results on near-surface temperature benefits resulting from cool, green, and hybrid roof deployment, and observed that maximum near-surface cooling is greater for cool roofs than green roofs. Therefore, in future urban planning, additional modifications related to longwave radiation loss during nighttime hours through employing high emissivity materials and a preferred landscape configuration could also be considered to tackle the effects of the UHI. Given that urban heat island in Hong Kong is greater during nighttime hours than daytime hours (Wang et al., 2016). Besides increasing vegetation coverage, good natural ventilation during city planning needs to be implemented as suggested by Wang et al. (2016).

6. Recommendations for urban design strategies

Street trees are most effective in reducing radiant heat load and mitigating heat stress when placed in sunlit areas (Bowler et al., 2010; Lee et al., 2013, 2016; Klemm et al., 2015), and trees with higher LAI can reflect incoming shortwave radiation and provide extensive shading at pedestrian level. Such effects are most prominent in open spaces like urban parks, due to the frequent visits by urban dwellers. Based on the analysis in the section 4 and 5, the following recommendations are proposed for urban design strategies in order to maximize the benefits of trees in the dense urban environment:

- Trees with larger crowns, such as, *Ficus microcarpa*, *Macaranga tanarius*, and *Acacia confusa*, are preferred over those with smaller ones, such as *Livistona chinensis* and *Melaleuca leucadendron*, since the former can provide extensive shading to the canyon surface and a closer spacing offers continuous shading in the street environment.

- From a practical point of view, the size and spacing of tree crowns can be optimized according to the actual circumstances at local level. For example, it may require fewer trees with larger crowns to provide similar levels of thermal comfort than those with smaller crowns.

- Reducing radiant heat load is important in order to improve pedestrian-level thermal comfort and reduce heat stress in the dense urban environment. Therefore, extensive shading should be provided by trees with large tree crowns. It is also important to ensure continuous shading in order to avoid excessive exposure to direct sunlight.

- In addition, spaces under the canopy of street trees should be accessible by pedestrians, i.e. pedestrians should be able to walk under the canopy, so that they can benefit from the shading. Therefore, parallel rows of trees should be used in wider streets. In open spaces, sitting areas under tree canopy are also important to maximize the benefits.

- Since the impact of trees on wind speed is minimal in the dense urban context, tree species with a shorter trunk base may be preferred within narrow street canyons to ensure sufficient shading at ground level. Previous studies suggesting that street trees reduce wind speed in street canyons may not be applicable to the high density urban environment (Park et al., 2012). A short trunk base can also compensate for the limited shading provided by trees with small crowns which are commonly used in narrow street canyons.

Beyond the scientific findings, a combination of various strategies should be adopted in designing pedestrian streetscapes. For example, colonnades and projections and architectural features are possible measures to supplement shading in sub-tropical or tropical regions where sun altitude is extremely high in summer. Fountains can also be considered in open spaces in order to provide additional evaporative cooling. All mitigation measures should be collectively considered to reduce the thermal load of the urban environment.

7. Conclusions and future studies

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There is no doubt that urban trees can provide many benefits to cities and therefore should be incorporated throughout the planning and implementation phases during urban development. In this study, we have analyzed trees in terms of their potential role in regulating the urban microclimate, particularly in the tropical environment. Specifically, we have considered the influences of trees on thermal comfort for local residents. While we have investigated the biological and physical properties of trees in regulating thermal comfort, we also realize that our current understanding of trees to provide those services is rather limited. Thus we propose to employ LAI as the leading indicator to evaluate the thermal benefits of urban trees, and PET to assess thermal comfort. Furthermore, we observed that the wind environment in high density areas of Hong Kong (λ_p higher than 0.4) is too poor to achieve any thermal comfort level and the impact of trees on wind speed is very limited in these high density urban contexts. We further hypothesize that faster growing trees may provide better thermal benefits due to their rapid increase in LAI and therefore larger capacity for transpiration cooling. Together, we suggest that tree species with large crowns, short trunks, and dense canopies, such as *Ficus microcarpa*, *Macaranga tanarius* and *Acacia confusa*, should be employed for urban greening to achieve optimal thermal benefits. On the other hand, we also suggest that more studies are warranted to ensure careful consideration can be given to both the environmental benefits and the costs for the candidate trees to be used in urban greenery. In addition, some of the less common species such as *Peltophorum pterocarpum* which have great thermal benefits, therefore deserve more attention.

Due to the limited information on the long-term and local transpiration of different urban tree species, we must try to find new methods to evaluate their transpiration in future studies. It is of interest that previous studies over the past decades have already investigated the total landscape water consumption by estimating the total evapotranspiration based on meteorological measurements or modelling (Grimmond and Oke, 1991; Mitchell et al. 2008). By re-evaluating the above mentioned investigations, it is possible to assess the local transpiration of different tree species more accurately, as water consumption is much easier to measure than the local water vapour emission from the leaf.

Lastly, we also propose to integrate growth rates of trees into our considerations. Fast growing species have been widely adopted to achieve more rapid greening effects. But growth

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rate may conflict with other cooling benefits. For instance, when both the growth rate and dimensions are considered, the majestic species such as *Ficus microcarpa*, *Delonix regia* and *Acacia confusa* have been avoided for roadside greening, and yet both have the best cooling effect as this study indicates.

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Table 4. Reduction in downward shortwave radiation (K_{down}), upward longwave radiation (L_{up}) and T_{mrt}.

Tree species	*Open settings*						*High density*					
	Kdown (Wm^{-2})	Reduction (%)	Lup (Wm^{-2})	Reduction (%)	Tmrt (°C)	Reduction (%)	Kdown (Wm^{-2})	Reduction (%)	Lup (Wm^{-2})	Reduction (%)	Tmrt (°C)	Reduction (%)
T1	216	72	36	7	4.3	10	153	68	28	6	3.3	8
T2	194	64	27	5	2.7	7	146	65	23	5	2.7	7
T3	174	58	26	5	2.8	7	132	58	20	4	2.3	6
T4	154	51	23	4	1.1	3	118	52	19	4	1.7	4
T5	135	45	19	4	1.3	3	113	50	19	4	1.6	4
T6	164	54	26	5	2.2	5	112	50	20	4	1.8	5
T7	230	76	41	8	5.1	12	162	72	32	6	3.9	10
T8	38	13	5	1	0.2	1	31	14	5	1	0.1	0
T9	181	60	30	6	3	7	124	55	22	4	2.3	6
T10	107	35	15	3	1.1	3	83	37	14	3	1	2
T11	234	78	37	7	4.9	12	167	74	29	6	3.8	10
T12	16	5	2	1	0.1	0	15	7	2	1	0	0

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