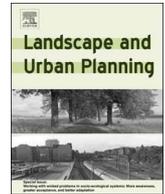




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Research paper

A semi-empirical model for the effect of trees on the urban wind environment

Chao Yuan^{a,*}, Leslie Norford^b, Edward Ng^{c,d,e}^a Department of Architecture, School of Design and Environment, National University of Singapore, Singapore^b Department of Architecture, Massachusetts Institute of Technology, USA^c School of Architecture, Chinese University of Hong Kong, Hong Kong, China^d Institute of Environment, Energy and Sustainability, Chinese University of Hong Kong, Hong Kong, China^e Institute of Future Cities, Chinese University of Hong Kong, Hong Kong, China

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ABSTRACT

High-density urban areas are often associated with limited outdoor natural ventilation. Given the growing call for more vegetation in cities, it is important to study the wind resistant of urban trees in order to address outdoor natural ventilation problem in the landscape planning. Currently, Computational Fluid Dynamics (CFD) simulation and wind tunnel experiment can only model the simplified street canyon with roadside trees, at the expense of intensive technical support and high computational cost. Thus, they are mostly for the research purpose only, and the impact of research outputs on the landscape planning remains low. In this study, we developed a practical semi-empirical model to provide scientific understandings for the landscape planning practice. The new model was developed based on the balance between momentum flux and the drag force of both buildings and trees on air flow. Friction velocity (u_*) was modeled and validated by existing CFD and wind tunnel data, and effective frontal area density ($\lambda_{f,tree}$) was estimated by the measured leaf area index. Effects of urban context density and trees (i.e. plant canopy density and typology) on wind environment were clarified. This research correlated the urban density and tree geometry indices with wind speed, thereby enabling planners to calculate trees' effects on airflow using their in-house data. With such new practical tool and understandings, the knowledge-based landscape planning can be conducted to introduce more trees into urban areas, while avoiding negative effects of trees on the outdoor wind environment at cities at the same time.

1. Introduction

In the context of rapid urbanization and depletion of natural resources, high-density urban living for better allocation of natural resources is an inevitable growing trend. However, such high-density living also has negative impacts on urban living, such as stacked housing and crowded living with poor air quality and thermal discomfort. As one of the essential elements at urban areas, urban vegetation can improve thermal comfort (Dimoudi & Nikolopoulou, 2003; Ng et al., 2012), enhance psychological health of urban dwellers (Thompson, Aspinall, & Roe, 2014), and promote urban biodiversity (Kowarik, 2011; Savard, Clergeau, & Mennechez, 2000). Consequently, landscape planning is critical in the entire urban planning system, especially in (sub) tropical cities. Urban vegetation has been widely introduced into the metropolitan cities. For example, the average per capita green space provision is 10 m² in Singapore (Singapore National Parks Board, 2015), 7 m² in Tokyo (Tokyo Metropolitan Government,

2007), 2 m² in built areas in Hong Kong with 40% of land designated as the green nature reserve (Hong Kong Planning Department, 2011), and 12.5 m² in Shanghai (Bureau of Shanghai World Expo Coordination, 2009).

Trees have three major functions in urban microclimate: they 1) provide shading effect to reduce heat gain on buildings and ground (Shahidan, Shariff, Jones, Salleh, & Abdullah, 2010); 2) transpire water to the atmosphere to decrease heat storage in the urban canopy layer (Loughner et al., 2012), and 3) resist wind (Cullen, 2005; Gromke & Ruck, 2008). Among them, the shading and evaporation aspects of trees have been well documented, and are considered positive impacts to the urban environment, because they either improve the outdoor thermal comfort by directly blocking solar radiation or mitigate urban heat island intensity by removing the heat from the urban canopy layer. However, the wind resistance aspect of trees is still not fully understood. Conventional studies have mainly focused on pedestrian safety and tree risk, e.g., breakage of large roadside trees as a

* Corresponding author.

E-mail addresses: akiyuan@nus.edu.sg, yuanc04@gmail.com (C. Yuan), lnorford@mit.edu (L. Norford), edwardng@cuhk.edu.hk (E. Ng).

result of strong gusts (Cullen, 2005). In high-density urban areas, wind speed tends to be slow, and outdoor natural ventilation becomes an environmental issue. For example the mean wind speed at 20 m above the ground level in urban areas of Hong Kong has decreased by about 40%, from 2.5 m/s to 1.5 m/s over the last 10 years (Hong Kong Planning Department, 2005). Consequently, when there is limited outdoor natural ventilation and a strong desire to introduce more vegetation into urban areas, it is not only important to focus on the drag force of buildings on airflow, but is also critical to study the additional drag force of trees, in order to address the outdoor natural ventilation issue in urban landscape planning.

CFD simulation and wind tunnel experiment are two major methods to investigate the effect of trees on airflow (Aubrun, Koppmann, Leitl, Mollmann, & Schaub, 2005; Gross, 1987). However, it might be more difficult to reproduce aerodynamic properties of trees due to porosity and flexibility than buildings in CFD and wind tunnel experiment. In the city scale, Li and Norford (2016) conducted a WRF modelling (300 m × 300 m resolution) to investigate the cooling effect of vegetation at urban areas, but no aerodynamic effects of trees in the urban canopy layer were included. In the neighborhood and building scales, several studies have included both individual or group of trees in the CFD simulation and wind tunnel experiment (Gromke & Ruck, 2008; Hiraoka, 1993; Mochida et al., 2008). While these studies provide important knowledge on the aerodynamic properties of trees, they did not include buildings in the modelling in most cases. Even though sharp-edged buildings dominate airflow in the urban boundary layer, it is still needed to clarify the aerodynamic effects of trees within the urban context. Gromke (2011) did just that by conducting the wind tunnel experiment to investigate the effect of roadside trees on the air pollutant dispersion in the typical street canyon, by measuring the pressure loss coefficient. This experiment was later reproduced by Jeanjean, Hinchliffe, McMullan, Monks and Leigh (2015) using CFD simulation, and then applied in the real urban scenario (East Midlands region of the UK). However, all of these studies require intensive technical support and high computational capability. They are mostly for research purposes and the impact of research outputs on landscape planning practice is still low. Therefore, a more practical modelling method is needed for the design and planning practice.

Morphological method has been considered as a practical tool (Grimmond & Oke, 1999; Ng, Yuan, Chen, Ren, & Fung, 2011; Wong, Nichol, To, & Wang, 2010). This method correlates the geometric indices, such as frontal area density (λ_f) and site coverage ratio (λ_p), with experimental wind data by statistical distribution fitting. The experimental wind data could be either wind speed directly or aerodynamic indices, such as roughness length (z_0) and displacement height (z_d). It has been shown that these wind data are strongly related to the geometric indices. Therefore, the aerodynamic effect of buildings on air flow can be parameterized and modelled, and complicated calculations of fluid mechanics can be avoided, significantly lowering the computational costs. Calculated by pixels in Geographic Information System (GIS), these geometric indices have been used to evaluate the wind environment in spatially heterogeneity urban areas (Gál and Unger, 2009; Ng et al., 2011; Wong et al., 2010; Yim et al., 2009; Yuan, Ren, & Ng, 2014; Yuan, Norford, & Ng, 2016). Nonetheless, there are currently no existing morphological models suitable for general use given that the development of these models is mainly based on the statistical fitting (Grimmond, King, Roth, & Oke, 1998), and most existing models do not include trees in the street canyon.

Compared with the morphological method, semi-empirical urban canopy models, algorithms that incorporate urban geometric indices, are derived from physical understanding, such as the balance between momentum flux and drag force, rather than the statistical fitting (Coceal & Belcher, 2004; Lettau, 1969; MacDonald et al., 1998). On the other hand, the model coefficients (e.g., drag coefficient (C_D)) are deduced from the experiment or field measurement data. Therefore, urban canopy models are semi-empirical. Bentham and Britter (2003)

developed a practical and comprehensive urban canopy model to estimate the average wind speed at the urban canopy layer (U_c), and MacDonald et al., 1998 conducted a urban canopy model to estimate the vertical wind profile. Despite that, most of the existing urban canopy models only include buildings, but no urban trees, given that buildings dominate the micro environment in the urban boundary layer as mentioned before.

This study develops a new urban canopy model to correlate the urban density and tree species indices with wind speed in the urban canopy layer, to enable more efficient decision-making in landscape planning. By coordinating the information on the momentum flux and porosity of trees from the literature review, a new urban canopy model is derived from the balance between the vertical momentum flux from the upper layer and drag force of both buildings and urban trees on airflow in Section 2.1. The momentum flux and porosity of tropical urban trees are parametrized in Sections 2.2 and 2.3 respectively. A parametric study is conducted in Section 3. Both urban density and tree species indices are inputted into the new semi-empirical model to calculate the average wind speed in the urban canopy layer U_c . In doing so, we identify the key ways to decrease the undesirable aerodynamic impact of urban trees on the wind environment, and provide the corresponding design strategies in Section 4. A case study, as the implementation, is provided in Section 5.

2. Development of modelling method

2.1. Balance between momentum flux and drag force

The development of the new modelling method is derived from the balance between momentum flux and the drag force of both buildings and trees on airflow. It is assumed that the momentum flux above the urban canopy layer and the surface shear stress only depend on buildings because buildings dominate airflow in the urban boundary layer, since they have much larger drag force than trees (Krayenhoff, Santiago, Martilli, Christen, & Oke, 2015). Given the steady and uniform airflow, the balance in the urban canopy layer between momentum flux (left side of Eq. (1)) and drag force of both buildings and trees on airflow (right side of Eq. (1)) can be stated as:

$$\tau_w A_{site} = \frac{1}{2} \rho U_c^2 / (1 - \lambda_p) \left(\sum (C_{D,building} A_{front,building}) + \sum (C_{D,tree} A_{front,tree}) \right) \quad (1)$$

where τ_w is the vertical flux of horizontal momentum from the upper layer to the lower layer due to the turbulence mixing effect, and can be expressed as $\tau_w = \rho u_*^2$, in which u_* is the friction velocity. U_c is the average wind speed in the urban canopy layer, λ_p is the site coverage ratio, A_{front} is the frontal area, A_{site} is the site area, and ρ is the air density. The first and second items on the right side of equation are the drag force of buildings and trees, respectively. Some research (Gromke & Ruck, 2008; Kitagawa et al., 2015) has indicated that the horizontal wind force on a tree varies linearly rather than quadratically with increasing wind speed due to the decrease of trees' frontal area. But it can only be applied if there is very strong wind, and for the tree risk management. Even though there is no clear threshold value of wind speed suggested by existing research, the conventional drag equation with velocity squared is still considered to be appropriate in this study, as the average wind speed in the urban canopy layer (U_c) is rarely large enough to reshape the plant crown. Therefore, U_c normalized by the friction velocity, u_* , can be expressed as:

$$\frac{U_c}{u_*} = \left(\frac{2(1 - \lambda_p)}{C_{D,building} \lambda_f + C_{D,tree} \lambda_{f,tree}} \right)^{0.5}, \text{ in which } \lambda_f = A_{front} / A_{site} \quad (2)$$

To close Eq. (2) and solve U_c , we need to identify: 1) friction velocity (u_*); 2) drag coefficient of trees ($C_{D,tree}$) and buildings ($C_{D,building}$); and 3) frontal area density of buildings ($\lambda_{f,building}$) and trees ($\lambda_{f,tree}$). Based

on the literature, we chose $C_{D,building}$ as 2.0 (Coceal & Belcher, 2004) and $C_{D,tree}$ as 0.8 that is appropriate for the low wind velocities (< 10 m/s) (Gromke & Ruck, 2008). $\lambda_{f,building}$ was calculated as the sectional frontal area density (Ng et al., 2011; Yuan et al., 2016), which can better represent the effect of building on the airflow due to the skimming flow associated with high-density urban areas. Therefore, in following sections, we need to parameterize friction velocity (u_*) and frontal area density of trees ($\lambda_{f,tree}$), as the unknown variables.

2.2. Parametrization of friction velocity (u_*)

Friction velocity (u_*) is directly related to surface shear stress, and defined as $\sqrt{\tau_w/\rho}$ in the fluid mechanics literature (Schlichting & Gersten, 2000). It is one of the basic variables to describe the near-surface flow (Britter & Hanna, 2003). Compared with mean velocity (U_{ref}) at the reference height (z_{ref}), u_* does not depend on the boundary layer height (Schlichting & Gersten, 2000), and thus u_* is frequently used to non-dimensionalize other velocity variables, such as the use of u_* in the logarithmic law equation (Eq. (3)). Except for the well-controlled wind tunnel experiments that can directly measure surface shear stress (τ_w) (Cheng & Castro, 2002), u_* can be estimated by turbulence fluctuation, using ultrasonic anemometer in the field (Walker, 2005). But similar to wind speed measurement at urban areas (Oke, 2006), the representative observation of turbulence fluctuation at urban areas is difficult. While commercial LIDAR technology (airplane/satellite based) and Doppler Weather Radar (ground-based) have been used to detect the wind shear, for example at airports and wind farms (Bot, 2014; Kumer et al., 2016), they are rarely applied in urban areas with stagnant airflow.

$$\frac{U_{ref}}{u_*} = \frac{1}{\kappa} \ln \frac{z_{ref} - z_d}{z_0} \tag{3}$$

In what follows in this section, we estimated u_* in urban areas using the logarithmic law as shown in Eq. (3). This method is not as straightforward as the wind tunnel experiment and field measurement, since it is necessary to model the roughness length z_0 and the displacement height z_d . But, with the existing methods to estimate z_0 and z_d , this curve-fitting method is more practical than the wind tunnel experiment and field measurement. More important, this method makes it possible to clarify the relationship between u_* and the geometry of surface roughness elements. Grimmond and Oke (1999) conducted a broad and critical review of the existing morphological methods to model z_0 and z_d , and provided a general understanding of the relationship between z_0 , z_d , λ_f , and λ_p as shown in Fig. 1. In this study, we directly used these fitted curves, the solid lines in Fig. 1, to associate

values of z_0 and z_d with corresponding values of λ_f . Because z_0 and z_d were normalized by z_h , we used the height of roughness sub-layer z_* as the reference height, and take z_* as $2z_h$ for compact building canopies, as Roth (2007) and Raupach (1992) suggested. As shown in Table 1, total 11 cases are included with λ_f from 0.05 to 1.0 to clarify the relationship among λ_f , z_0 , and z_d , since values of λ_f could be larger than 0.45 (maximum value in Fig. 1) at high-density cities.

Consequently, u_* normalized by the mean wind speed at the top of roughness sub-layer z_* (U_{ref}) can be estimated by λ_f as shown in Fig. 2. Similar to z_0 , the sensitivity of u_* to increasing λ_f significantly decreases when λ_f is larger than 0.4, i.e. u_* is almost constant when λ_f is larger than 0.4. It is reasonable, since surface shear stress decreases when more roughness elements are included and start to interfere with each other, i.e. the skimming flow (Oke, 1987). Quantatively, u_*/U_{ref} is constant, 0.12 with $\lambda_f \geq 0.4$, and u_* can be expressed as:

$$u_* = 0.12 \cdot U_{ref}, \text{ when } \lambda_{f,building} \geq 0.4 \tag{4}$$

We validated the modelling results of u_* by comparison with the wind data from wind tunnel experiment and CFD simulations. The wind tunnel experiment was conducted by Hong Kong University of Science and Technology for the Air Ventilation Assessment (AVA) project (Hong Kong Planning Department, 2008), and CFD simulation data is from Architectural Institute of Japan (AIJ) for the cases of city blocks (Tominaga, Mochida, Yoshie, Kataoka, Nozu and Yoshikawa (2008). With the values of u_*/U_{ref} in Fig. 2 as the input data, we used the Bentham and Britter model (2003) to calculate U_c/U_{ref} , shown as a solid line in Fig. 3. The observed data, i.e. AVA and AIJ data (Hong Kong Planning Department, 2008; Tominaga et al., 2008), were plotted together with modelling results for cross comparison. The P value of 0.9559 in the hypothesis test was also obtained, which indicates that there is no significant difference between modelling results and measurement data at confidence level of 0.95. Thus, this shows that the modelling method in this study can accurately estimate u_* , so that average wind speed in the urban canopy layer U_c can be easily calculated by λ_f as Eq. (5) (non-tree scenario) (Bentham & Britter, 2003). For the scenario with both buildings and trees, Eq. (2) can be expressed as Eq. (6) where both building and tree drag force are included by parameterizing friction velocity u_* .

$$\frac{U_c}{U_{ref}} = 0.12 \left(\frac{\lambda_f}{2}\right)^{-0.5}, \text{ when } \lambda_{f,building} \geq 0.4 \tag{5}$$

$$\frac{U_c}{U_{ref}} = 0.12 \left(\frac{2(1 - \lambda_p)}{C_{D,building}\lambda_{f,building} + C_{D,tree}\lambda_{f,tree}} \right)^{0.5}, \text{ when } \lambda_{f,building} \geq 0.4 \tag{6}$$

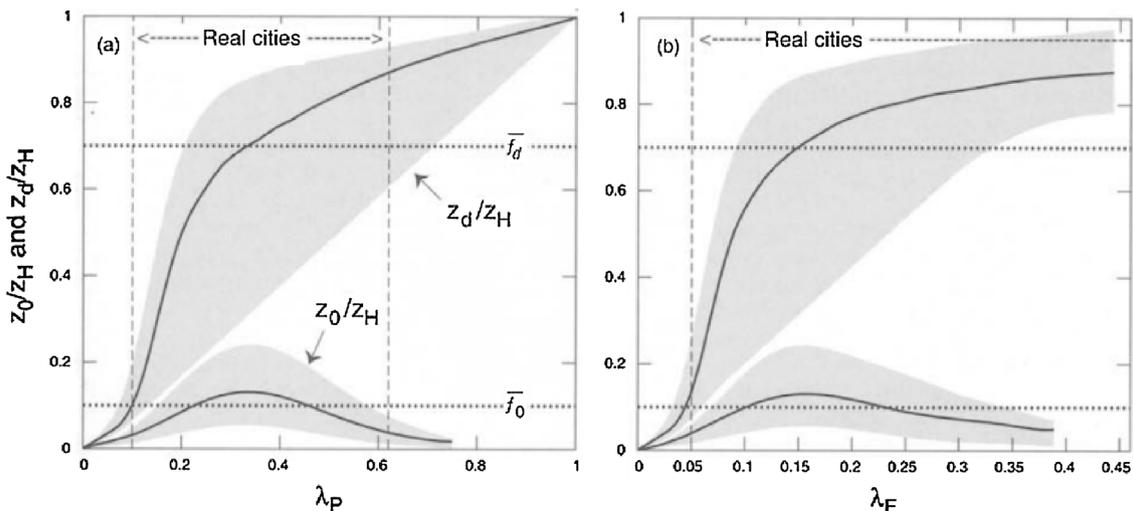


Fig. 1. Determination of z_0 , z_d using λ_f and λ_p (Grimmond & Oke, 1999).

Table 1
Variation of z_0 and z_d with λ_f from 0.05 to 1.0 to estimate u_c .

	1	2	3	4	5	6	7	8	9	10	11
λ_f	0.05	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
z_d/z_h	0.10	0.55	0.76	0.81	0.87	0.92	0.94	0.96	0.98	0.99	1.00
z_0/z_h	0.03	0.10	0.11	0.07	0.04	0.038	0.036	0.035	0.03	0.03	0.03

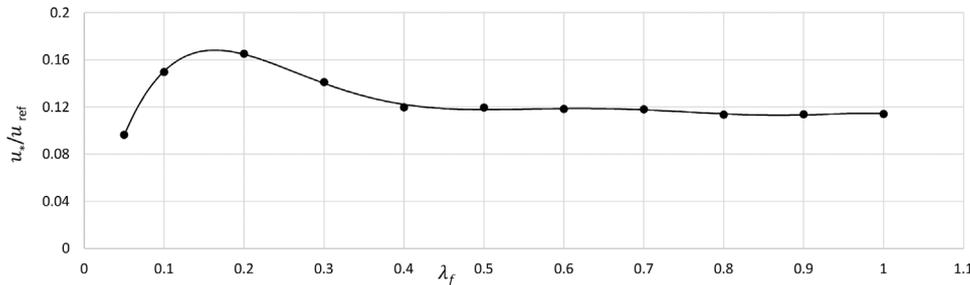


Fig. 2. Relationship between u_c/U_{ref} and λ_f . u_c is constant, 0.12, when λ_f is larger than 0.4.

2.3. Parametrization of tree porosity

In this section, we parameterized the effective frontal area density of trees ($\lambda_{f,tree}$), which is the area-weighted plant frontal area index of a site, and depends on the porosity (leaf area index (LAI)), typology (typology ratio (R) between vertical and horizontal area of canopy), and population size (N). Leaf area index (LAI) is defined as the total single-side leaf area normalized by projected tree canyon area, which is essential for evaporation, radiation extinction, and water and carbon gas exchange (Breda, 2003). We applied the leaf area index (LAI) provided by Tan and Sia (2009) to estimate the porosity of plant canopies, in which the indirect measurement using the LiCor LAI 2000 plant canopy analyzer was conducted for the most commonly used landscape trees in tropical areas. According to the LAI values measured in the field, the density of tree canopies has been categorized as dense (close arrangement and multiple stacking of foliage within the canopy), intermediate (intermediate between ‘dense’ and ‘open’), and open canopy (sparse foliage arrangement), as tabulated in Tables 2 and 3 (Tan & Sia, 2009). Because Tan and Sia (2009) conducted an indirect (radiation) measurement, all canopy elements, such as plant stems and leaves, were included in the measurement. Consequently, the measured index represents the entire plant, not only leaves. Since all canopy elements contribute to the drag force, this LAI measurement fits the objective of this study.

We defined the effective frontal area density of trees ($\lambda_{f,tree}$) as the effective aerodynamic surface area ($A_{f,tree}$) normalized by the site area (A_{site}), as shown in Eq. (7). In this definition, it is assumed that leaves would not interfere with each other for airflow, i.e. ideally uniform in behavior (Cionco, 1965; Nepf, 2012). Due to the plant flexibility and porosity, trees have a smaller interference area than cubic solid roughness elements, such as buildings (Shao & Yang, 2005). To calculate $A_{f,tree}$, we used the horizontally measured LAI, as an indirect measurement (Tan & Sia, 2009). By assuming that the orientation of

each leaf is random in the whole tree, i.e. ideally uniform in distribution and geometry (Cionco, 1965; Nepf, 2012), the horizontally measured index can be converted to the vertical index. $A_{f,tree}$ can be calculated as Eq. (8), where A is the vertical canopy area and can be calculated by Eq. (9), where R is the plant canopy typology ratio between A and A_c (horizontal canopy area). R can be classified into spreading canopy ($R < 1$), spherical canopy ($R \approx 1$) and Columnar Canopy ($R > 1$), as shown in Table 4. Therefore, based on the definition of LAI, and assuming the random leaf distribution and no interference between leaves, the effective frontal area density of trees ($\lambda_{f,tree}$) can be calculated by Eqs. (7)–(9) and the calculation schematic is presented in Fig. 4.

$$\lambda_{f,tree} = \frac{nA_{f,tree}}{A_{site}} \quad (n: \text{tree population}) \quad (7)$$

$$A_{f,tree} = LAI \cdot A \quad (8)$$

$$A = R \cdot A_c \quad (9)$$

At last, substituting Eqs. (4) and (7) into Eq. (2), i.e. parametrizing momentum flux and trees’ drag force, we can estimate U_c in the urban canopy layer that includes both trees and buildings as:

$$U_c = 0.12 \cdot U_{ref} \left(\frac{2(1 - \lambda_p)}{C_{D,building} \lambda_{f,building} + C_{D,tree} n LAI R A_c / A_{site}} \right)^{0.5} \quad (10)$$

Furthermore, we non-dimensionalized U_c using wind velocity ratio (VR) as:

$$VR = \frac{U_c}{U_{ref}} = 0.12 \cdot \left(\frac{2(1 - \lambda_p)}{C_{D,building} \lambda_{f,building} + C_{D,tree} LAI R \lambda} \right)^{0.5} \quad (11)$$

in which λ is green coverage ratio as:

$$\lambda = \frac{nA_c}{A_{site}} \quad (12)$$

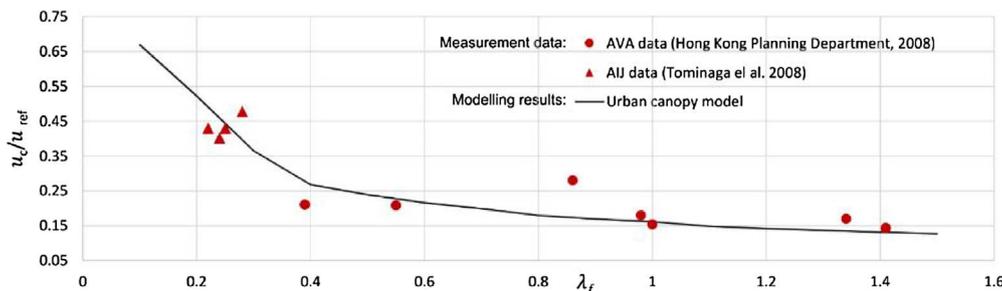


Fig. 3. Validation. Modelling results by new urban canopy model matches well with the experimental measurement data (Confidence level: 95%).

Table 2
Values of LAI and canopy area of trees in categories (Tan & Sia, 2009).

Category	Sample of tree	LAI	Canopy area (A_c) according to tree girth (G) (m^2)			
			G1 (< 0.5 m)	G2 (0.5–1.0 m)	G3 (1.0–1.5 m)	G4 (> 1.5 m)
Dense Canopy	Filicium decipiens	4.0	12	36	80	150
Intermediate Canopy	Tabebuia rosea	3.0	12	36	80	150
Open Canopy	Peltophorum	2.0	12	36	80	150

Table 3
Examples of tree species with different LAI values (Tan & Sia, 2009).

Dense Canopy	Intermediate Canopy	Open Canopy
Filicium decipiens 	Tabebuia rosea 	Peltophorum pterocarpum 

Table 4
Category of trees with different typologies: Spreading, Spherical, and Columnar canopies.

Spreading Canopy	Spherical Canopy	Columnar Canopy
Samanea saman 	Filicium decipiens 	Swietenia macrophylla 

According to Eq. (11), aerodynamic impact of trees on the average wind speed in the urban canopy layer depends on urban density (i.e. λ_p and $\lambda_{f_building}$), plant population density (i.e. λ), and trees species (i.e. R and LAI).

3. Parametric study – effects of urban density, trees species and population

A parametric study at Hong Kong was conducted using the new urban canopy model (Eq. (11)) to clarify the effects of trees on the urban wind environment. As shown in Fig. 5, the normalized difference vegetation index (NDVI) distribution at Hong Kong indicates that most vegetation is located at country parks, and greenery (e.g., trees) is very limited in the urban areas. However, urban trees benefit urban living by directly affecting the microclimate in the street canyon (Ng et al., 2012). Thus, Hong Kong Civil Engineering and Development Department (2010) conducted the detailed Greening Master Plan (GMP), and implemented several GMPs in the highest density districts to introduce more vegetation into urban areas.

In this study, two representative urban areas with high and low densities were chosen. The average wind speed in the urban canopy layer (U_c) with various urban densities, trees species and population sizes were calculated. In Fig. 6, Sheung Wan was chosen as the high-density urban area ($\lambda_{f0-15m} = 0.45$; $\lambda_p = 0.45$), and Sha Tin was

chosen as the low-density urban area ($\lambda_{f0-15m} = 0.18$; $\lambda_p = 0.13$). λ_{f0-15m} and λ_p were calculated using the methods developed by Ng et al. (2011). It should be noted that λ_{f0-15m} represents $\lambda_{f_building}$ of buildings in this study, due to the skimming flow in urban areas (Ng et al., 2011; Yuan et al., 2016). According to NDVI data in Figs. 5 and 6, we assumed that there were no trees, but only grass within the test area. Then, two parametric scenarios were modeled with two urban tree parameters: leaf area index (LAI) in Scenario I and urban tree plant typology ratio (R) in Scenario II. In both scenarios, the green coverage ratio (λ) was increased from 0 to 0.55 and 0.87 in high and low-density urban areas respectively, to indicate tree canopies covering all unbuilt areas. The input data (i.e. urban density and urban tree geometry indices) for the parametric study are summarized in Table 5. The modelling results, i.e. wind velocity ratio (VR), are shown in Fig. 7.

4. Discussion

Fig. 7 summarizes the effects of urban trees on the wind environment (i.e. U_c) at low- and high-density urban areas. As shown in Fig. 7, the wind velocity ratio (VR) decreases with increasing green coverage ratio, i.e. planting more trees in urban areas could slow down air flow at the urban canopy layer. Specifically, effects of trees on the urban wind environment greatly depend on the density of the urban context, as well as the density and typology of the plant canopy.

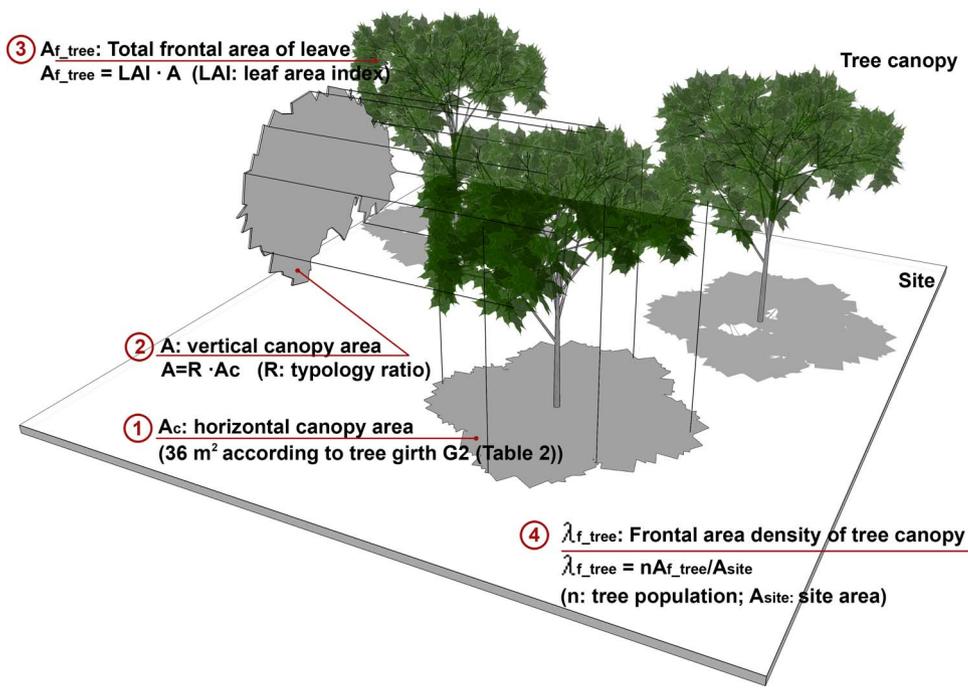


Fig. 4. Calculation schematic of effective frontal area density of tree canopy.

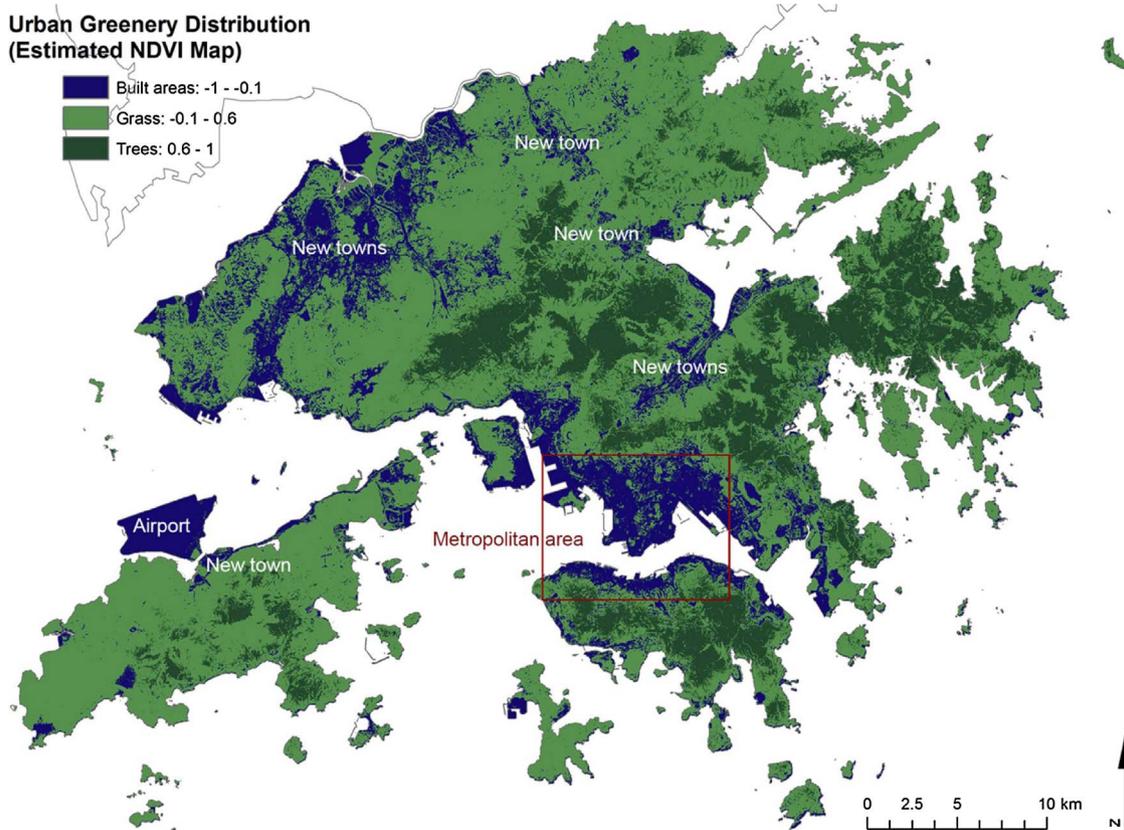


Fig. 5. NDVI Distribution at Hong Kong. Most of urban vegetation is located at country parks, and limited greenery is located at urban areas.

The impact of any particular tree population is different in urban areas with different densities. As shown in Fig. 7, each line type refers to a different tree species, and each line color refers to different urban context densities. The values of VR decrease more rapidly at low-density urban areas (black lines) than high-density urban areas (red lines), even though tree species and population are the same. It is reasonable that the impact of trees on the wind speed is decreased as the urban

area becomes denser, since drag forces of both buildings and trees are in the denominator in Eq. (11) and buildings have a much larger drag force coefficient. Physically, a high-density urban area induces a weak wind environment, so that planting more trees will minimally decrease the already-slow wind speed.

The above observation shows that, rather than investigating trees alone, it is necessary to investigate trees' effects within the urban

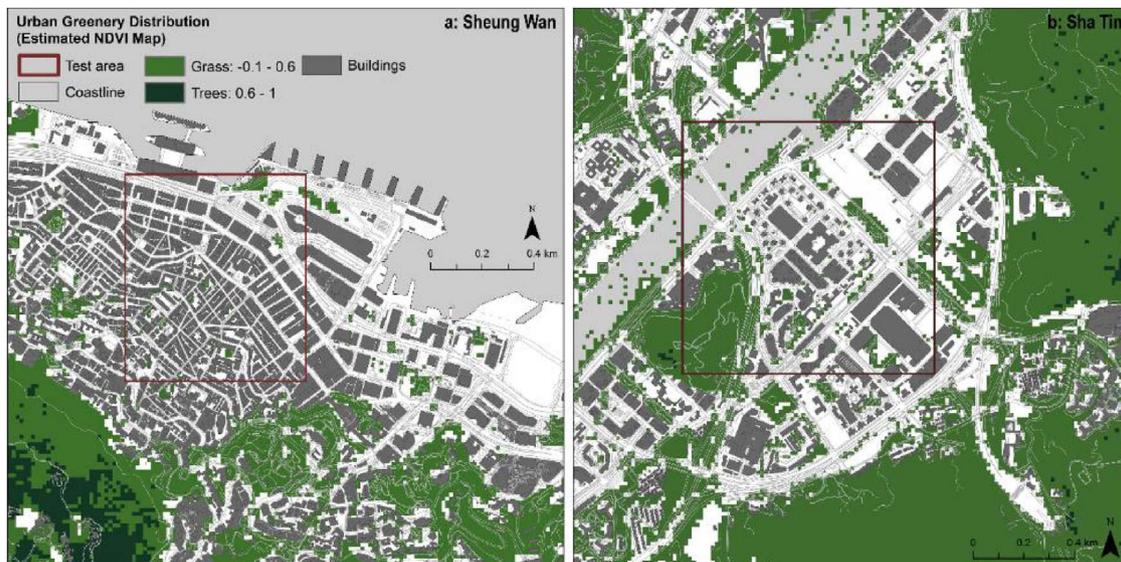


Fig. 6. Urban contexts with different densities; a: Sheung Wan: $\lambda_{f0-15m} = 0.45$; $\lambda_p = 0.45$; b: Sha Tin: $\lambda_{f0-15m} = 0.18$; $\lambda_p = 0.13$.

Table 5

Input data: urban density and urban tree geometry indices. Two tree geometry parameters in two scenarios are highlighted, i.e. LAI in Scenario I and R in Scenario II.

Scenario I	Site	Urban Density		Urban tree geometry				
		λ_{f0-15m}	λ_p	A_c	R	LAI (Dense Canopy)	LAI (Intermediate Canopy)	LAI (Open Canopy)
High-density case	Sheung Wan	0.45	0.45	36	1.0	4.0	3.0	2.0
Low-density case	Sha Tin	0.18	0.13	36	1.0	4.0	3.0	2.0
Scenario II	Site	Urban Density		Urban tree geometry				
		λ_{f0-15m}	λ_p	A_c	LAI	R (Spreading Canopy)	R (Spherical Canopy)	R (Columnar Canopy)
High-density case	Sheung Wan	0.45	0.45	36	4.0	0.5	1.0	2.0
Low-density case	Sha Tin	0.18	0.13	36	4.0	0.5	1.0	2.0

Note: 1) λ_{f0-15m} : Frontal area density from 0 to 15 m; λ_p : Site coverage ratio; A_c : Plant canopy area (36 m²) according to tree girth (G2 in Table 2); R: Plant typology ratio between vertical and horizontal crown projected areas; LAI: Leaf area index. 2) Maximum green coverage ratio (λ) in high and low-density cases are 0.55 and 0.87 respectively, which means that the sites are totally covered by both buildings and trees.

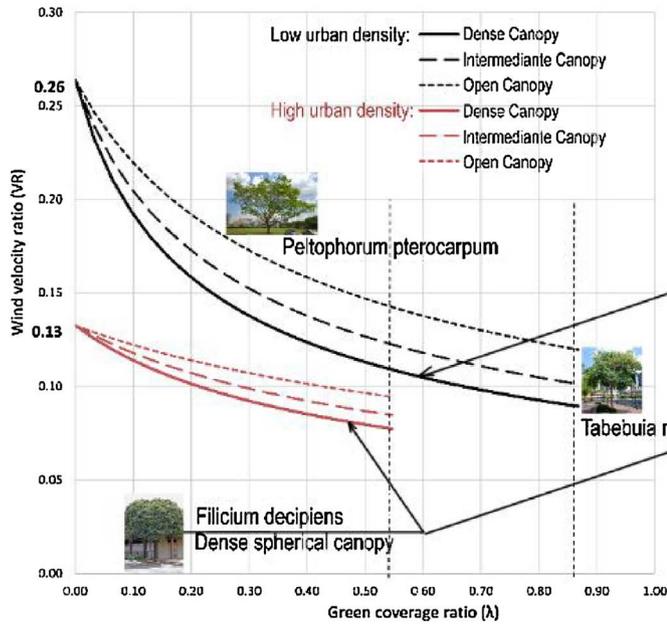
context with various urban densities. For example, if green coverage ratio rises to 40% in low-density urban areas by planting *Filicium decipiens* (Tables 3 and 4) that has a dense spherical canopy (LAI: 4.0; R: 1.0), the wind velocity ratio could decrease from 0.26 to 0.13, as shown in Fig. 7. Such wind environment in the low-density urban area could be similar with the one at the high-density urban areas without trees. Given the wind speed at the reference height is 6.7 m/s, the wind speed could decrease about 0.9 m/s, which can pose significant impact to outdoor thermal comfort. In other words, if we plant the same tree population in low-density urban areas, the impact of urban trees is two times larger than the one in high-density urban areas, where wind speed could only decrease 0.5 m/s. Urban density of Hong Kong, represented by λ_{f0-15m} , was classified by the impact of trees on urban wind environment, as shown in Fig. 8. Class A ‘High impact’ means that effect of trees is equal or more significant than the black lines in Fig. 7; and Class C ‘Low impact’ means that effect of trees is equal or lower than the red lines in Fig. 7. Class B is between Class A and Class C. Furthermore, considering the impact of trees with the existing understanding of urban air path (Ng et al., 2011), it is important to note that only the areas with low-density have been identified as the potential air paths, and thus the impact of urban trees on the performance of these potential air paths is significant.

Moreover, the effect of trees on urban wind environment depends on the tree species, i.e. plant canopy density and typology. As shown in Fig. 7 (Scenario I), open canopy trees (short dash lines) have the

smallest impact on wind velocity ratio, followed by intermediate canopy (long dash lines). Wind velocity ratio decreases most rapidly with the dense canopy (solid lines). It is reasonable since a denser canopy means larger effective frontal area that causes larger drag force of trees on airflow. In the Scenario II, the densities of the plant canopy are the same, but the typologies are different. The tree species with spreading canopy (solid lines) has the smallest impact on the wind velocity ratio. With the same green coverage ratio (i.e. same horizontal canopy area), the tree with the spreading canopy has the smallest vertical canopy area, and thus the smallest effective frontal area and drag force.

Such observation indicates that it is still possible to mitigate this impact by choosing the appropriate tree species, even though the impact of trees on the wind environment at low-density urban areas is significant as mentioned before. For example, as shown in Fig. 7, we could increase the wind velocity ratio to 0.16 (wind speed: 1.0 m/s) by choosing either *Peltophorum pterocarpum* (open canopy) or *Samanea saman* (rain tree: spreading canopy), rather than *Filicium decipiens* (dense and spherical canopy). On the other hand, the wind environment could be even worse (short dashed line in Scenario II), if we choose the wrong tree species, e.g. *Swietenia macrophylla* (dense, columnar canopy). In that case, the wind velocity ratio will be lower than 0.1, and thus wind speed less than 0.6 m/s that could cause outdoor thermal discomfort. Suggestions of tree species to address the natural ventilation issue at the urban areas are shown in Fig. 9.

Scenario I: Plant canopy density



Scenario II: Plant canopy typology

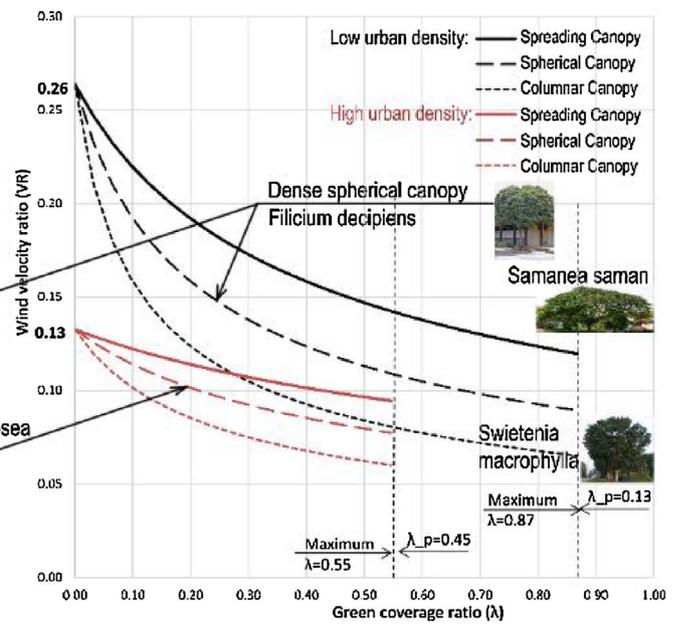


Fig. 7. Effects of urban trees on the wind environment at low and high-density urban areas. Plant canopy densities (Table 2) and typologies (Table 4) were tested in Scenarios I and II, respectively. Maximum green coverage ratios (λ) are 0.55 and 0.87 in high and low-density cases, respectively. (For interpretation of the references to colour in the text, the reader is referred to the web version of this article.)

Urban Density Map

represented by λ_f 0-15m; classified by the impact of trees

- Non Urban area (λ_f 0-15m: 0.00)
- A: High impact (λ_f 0-15m: 0.01-0.18)
- B: Intermediate (λ_f 0-15m: 0.19-0.45)
- C: Low impact (λ_f 0-15m: 0.46-0.80)

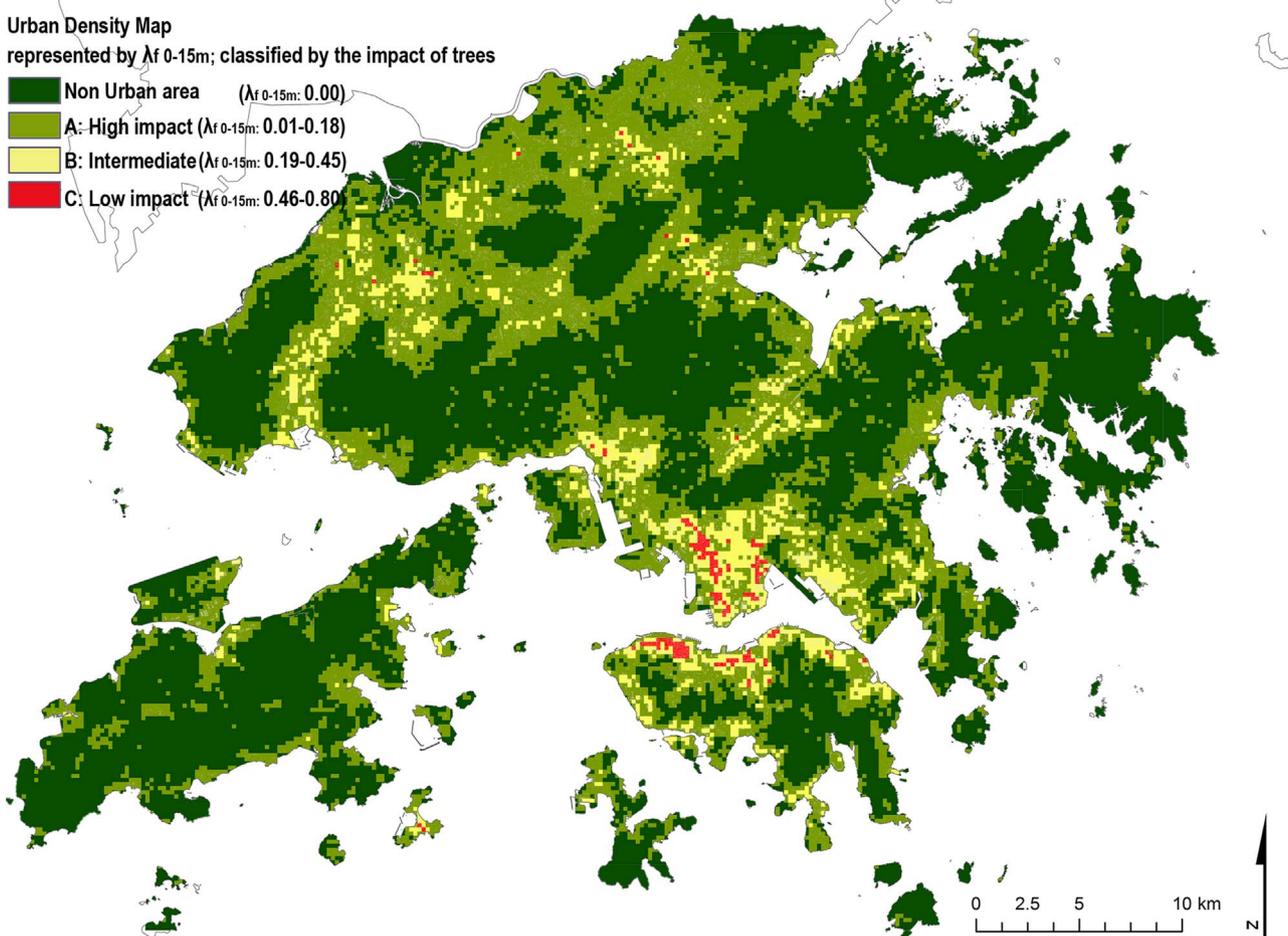


Fig. 8. Urban density map classified by impact of urban trees on wind environment at urban areas with various urban densities (Resolution: 100 m × 100 m).



Fig. 9. Suggestions of tree species to address natural ventilation issues at urban areas.



Fig. 10. Map of trees' impact on urban wind environment and landscape planning strategies.

5. Implementation

We conducted a case study at Tsim Sha Tsui, one of the metropolitan areas with limited urban vegetation at Hong Kong (Fig. 5) to illustrate how to apply the understandings in this study into landscape design practice. First, the local urban density (i.e. λ_{r0-15m}) was calculated in the resolution of 100 m × 100 m, using the method developed by Ng et al. (2011). Second, according to the discussion in Section 4, the impact of trees on local urban wind environment was evaluated and mapped based on various urban densities, as shown in Fig. 10. With this map, landscape design strategies can be established as following:

- Trees' impact on urban wind environment (Class A: high impact) is high at waterfront areas, i.e. low-density areas. Since the waterfront area is important to the leeward wind environment, it is recommended to restrict tree population at waterfront areas, i.e. increasing green coverage ratio by planting grass or shrub, rather than trees. The tree species chosen for waterfront areas must be with porous and spreading canopy.
- It is recommended to plant trees with porous and spreading canopy at the areas with medium density (Class B: immediate impact) to increase the green coverage ratio. By doing so, landscape designer can mitigate the negative aerodynamic impact of trees, and increase the shading and evapotranspiration benefits at the same time. Furthermore, compared with high-density areas (Class C), it is easier to plant trees with spreading canopy at medium-density areas (Class B), given the larger unbuilt areas and wider street canyon.
- The green coverage ratio at most high-density areas is low (less than 5% (Fig. 5)). Since the impact of trees on wind environment is low at high-density urban areas (Class C), it is recommended to plant trees for more shading and evapotranspiration benefits, rather than grass

or shrub. Tree species with dense and columnar canopy, even with large drag force, may still be acceptable, because the average wind speed is not sensitive to the change of tree species at high-density urban areas.

6. Conclusions and future work

While urban vegetation can mitigate the negative impacts of high-density living (e.g., promote urban biodiversity), it can also slow down airflow or trap air pollutant and anthropogenic heat. In this study, we focused on the drag force of trees on the airflow in the urban canopy layer. In this study, we developed a new semi-empirical urban canopy model that correlates the urban density and tree geometry indices (Table 5) with urban wind environment (Fig. 7). A parametric study clarified the effects of urban context density, trees population and species (i.e. plant canopy density and typologies) on the wind environment at urban areas. The new modelling method gives planners and designers both scientific understanding and a practical modelling tool, so that they are able to conduct knowledge-based landscape planning to introduce more trees into urban areas while avoiding the negative effects on the outdoor wind environment.

This semi-empirical modelling method was derived from the balance between momentum flux and drag force of buildings and trees, in which friction velocity and drag force of trees were parametrized. Consistent with our prior research (Ng et al., 2011; Yuan et al., 2016), the new semi-empirical model calculates indices of urban density and tree geometry, instead of an expensive fluid mechanics calculation. Therefore, compared with CFD simulation and wind tunnel experiments, this new model is more practical, and it can provide more direct modelling results to guide the planning and design.

Future studies are warranted to integrate the understandings of

trees' effect, such as shading and evaporation, on the urban environment. In addition, urban or neighborhood scale CFD simulation or wind tunnel experiments with urban trees are needed to further validate and modify the semi-empirical model.

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