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Right tree, right place (urban canyon): Tree species selection approach for optimum urban heat mitigation - development and evaluation

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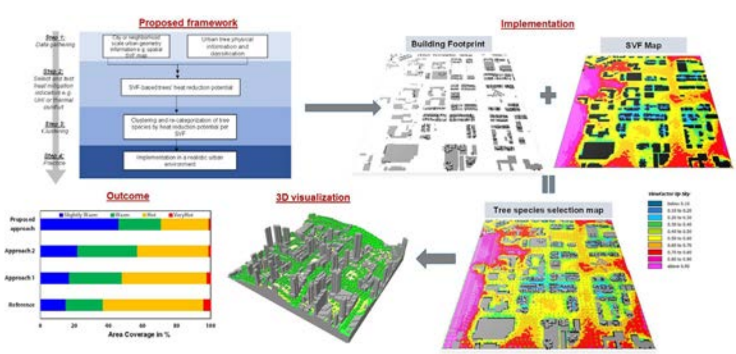
HIGHLIGHTS

- A "Right tree, right place" approach for optimum urban heat mitigation was proposed.
- The approach was developed and evaluated through a parametric case study under hot-humid prevailing climate.
- Proposed approach was found significantly more efficient compared to two others in a realistic urban neighborhood.
- Heat reduction potential of trees was location-dependent and species-specific.

GRAPHICAL ABSTRACT



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ABSTRACT

The re-integration of trees into the urban landscape is a veritable strategy for urban climate mitigation and adaptation. However, dysfunctional trees in terms of urban heat mitigation are dominant in many sub-tropical cities' landscapes due to the lack of scientific basis of tree selection. Therefore, this study proposes and evaluates a methodological framework as an approach for "right tree, right place" for urban heat mitigation through parametric ENVI-met simulations that involve the combination of 54 generic tree forms and 10 characteristic urban morphology – Sky-View Factor (SVF). Results show variable temperature regulation by tree forms (species) with varying magnitude in different urban morphology. Daytime and nighttime temperature regulation effects were between 0.3 °C – 1.0 °C and 0.0 °C – 2.0 °C, respectively depending on tree forms and SVF value. Furthermore, the Heat Reduction Potential (HRP) of trees forms were determined in terms of their human thermal comfort improvement. In general, we found a range of +5% and − 20% depending on SVF, negative and positive values imply heat reduction and increment, respectively. With the competing shading effect of buildings, the HRP of trees reduces from high to low SVF area with variable magnitude among tree forms (species). Hence, the proposed morphology-based tree selection approach was evaluated by comparison with two uninformed selection approaches in a realistic urban neighborhood in Hong Kong. Results clearly indicate the proposed approach's capability in improving human thermal comfort by up two times more than either of the other approaches. Finally, evidence-based recommendations were given for the reference of policy-makers when they make urban green development plan.

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1. Introduction

1.1. Background of study

Cities are amalgam of "grey" (such as residential and industrial buildings, roads, utilities and parking lots); "blue" (such as waterbodies; lakes, rivers, ponds and water channels); and "green" (such as trees, shrubs and grasses in green spaces and streets) infrastructures which all interact with the prevailing weather conditions to determine the local micro-climate and thermal comfort perception of urban dwellers. Most densely populated cities have now become concrete jungles deficient of the natural ecosystem due to the rapid increases in the global urban population resulting in unprecedented growth in the "grey" at the detriment of the "blue" and "green" infrastructures, especially, trees which is the focus of this study.

Consequently, a huge amount of energy is absorbed by the abundant paved surfaces during the daytime which results in the warming of the immediate atmosphere. At nighttime, the absorbed energy during solar hours is released, warming up the cities to a higher degree than surrounding rural areas, a phenomenon often referred to as Urban Heat Island (UHI) effect (Oke, 1988). This effect is intensified by the increasing global mean surface and air temperature projected to further increase by 2.6–4.8 °C and 2–4 °C, respectively by the end of this century especially in urban areas (Brysse et al., 2013; Chairs et al., 2014). Thus, higher frequency and intensity of summer temperature extremes, urban heat stress or thermal discomfort, and heatwaves have been observed in most tropical countries and has led to heat-related mortality and morbidity as reported around the world (Zittis et al., 2014; Lhotka and Kyselý, 2015; Wang et al., 2019). Also, cooling energy consumption is highly correlated with urban overheating as increases in urban temperature is a precursor to energy consumption in many cities by increasing the demand for refrigeration and air conditioning; and reducing space heating demand (Morakinyo et al., 2019; Santamouris et al., 2017).

One of the sustainable methods of dealing with this problem is the implementation of urban climate mitigation and adaptation strategies such as the innovative choice and combination of urban fabrics, morphology, and re-integration of green infrastructures into the city planning and design (Morakinyo et al., 2017a; Lobaccaro and Acero, 2015). In particular, increasing the coverage of green infrastructures (especially trees) within our cities cannot be overemphasized due to their shading and transpirational cooling capacities. Knowing this, several cities have developed tree planting policies which have resulted in an increase in the coverage of green spaces especially within their heat island hotspots (Müller et al., 2013; Klemm et al., 2015). However, recent studies have shown that trees cooling capacity is not the same but varies from species to species due to their different physical or structural characteristics and their location of placement in an urban environment (Morakinyo et al., 2017b; de Abreu-Harbich et al., 2015; Tan et al., 2017; Kong et al., 2017). Hence, an improved cooling benefit can be realized if the right tree species are selected for the right location. Meanwhile, there is scant documentation of tree species selection strategies for urban heat mitigation for many cities. Thus, the study aims to develop, evaluate, and implement a generalized methodology that enables urban planners, foresters and landscaper architects to select the right tree species, in the right place (local environment) for optimum urban heat mitigation. The proposed methodology is founded on investigations of the relationship between tree forms (species), thermal performances and urban morphology.

1.2. Urban morphology and cooling potential of trees

As stated earlier, some previous studies (Morakinyo et al., 2017b; Tan et al., 2017; Kong et al., 2017; Tan et al., 2015) have revealed a relationship between urban morphology and trees' performance for urban heat mitigation. Such a relationship is expatiated in this section. Urban morphology characterized by the canyon's sky-view factor (SVF) which is the degree of sky visibility within street canyons (Gong et al., 2018) when trees and other elements view factors are not considered, is one of the primary determinants of the thermal environment of an area. This is because it determines the daily solar exposure and exposed human heat balance (Oke, 1988; Oke, 1973). Several studies have shown a linear relationship between urban morphology (i.e. SVF or aspect ratio) and urban microclimate, nocturnal urban heat island (UHI) effect and human thermal comfort (Morakinyo et al., 2017b; Tan et al., 2017; Tan et al., 2015; Johansson, 2006). Specifically, Johansson (Johansson, 2006) found daytime air and surface temperature are lower in deeper than shallow canyons (i.e. low SVF) because of solar blocking and shadowing effect of taller buildings when anthropogenic heating was not considered. Also, daytime relative humidity was found to be higher in such deep canyons whereas wind speed was also found to be lower and more stable than in shallow canyons. Furthermore, urban heat island intensity is higher in deep than shallow canyons which are caused by the trapping for longwave radiation in such canyon while the reverse is true for shallow canyons (Oke, 1988; Johansson and Emmanuel, 2006). Giridharan et al. (Giridharan et al., 2004) further reported that a 1% reduction in SVF would reduce the daytime UHI intensity by 1–4% under subtropical climatic conditions. Thus, in terms of thermal comfort typified by mean radiant temperature (MRT)or Physiological Equivalent Temperature (PET), the deep street canyons are often more thermally comfortable (i.e. lower MRT and PET) than their shallow or open counterparts (Morakinyo et al., 2017b; Morakinyo and Lam, 2016).

Another shading element aside buildings' shadow are trees, they help in urban heat mitigation and improvement of the thermal environment through their shading and evaporative cooling capacities. Therefore, the shadow-cast effect of buildings which could either complement or outweigh the tree shading potential especially in deep canyons and vice-versa for open and shallow street canyon (Morakinyo et al., 2017b; Morakinyo et al., 2018). Understanding the relationship between these two shading factors could further inform a morphology-based urban planning guidelines and strategies. For instance, a profound difference was found between air temperature reduction of a tree-shaded and unshaded area in high SVF domain even though the differences with medium-low SVF is not significant (Tan et al., 2015; Morakinyo and Lam, 2016; Ali-Toudert and Mayer, 2006). However, in terms of radiation shading, a substantial reduction under trees was found in medium-low SVFs than their high SVF counterparts mainly because of the additional shading by shadow-cast effects (Morakinyo et al., 2017b; Tan et al., 2015; Morakinyo and Lam, 2016).

However, the tree-shading effect on mean radiant temperature was more sensitive to the building morphology of the site(Ali-Toudert and Mayer, 2006) and more evident under cloudy conditions than under sunny conditions(Tan et al., 2017). Norton et.al (Norton et al., 2015) developed an urban tree planting prioritization scheme based on this understanding which accorded low priority in a highly dense urban setting and vice-versa for open-low density areas. While their framework is efficient at identifying suitable planting locations for heat mitigation, it is void of tree species selection technique or approach for optimum urban heat mitigation. Meanwhile, recent studies have shown variable cooling effects and heat mitigation outcomes (i.e. solar attenuation, air cooling, and thermal comfort improvement with different tree-species. Such variability in the cooling effects have been found to be related to the differences in their morphological or structural characteristics such as height, foliage density, crown diameter, shape, trunk height, leaves' thickness and colour, and tree trunk and branches' architecture (Morakinyo et al., 2017b; de Abreu-Harbich et al., 2015; Kong et al., 2017; Lin and Lin, 2010). Thus, as an assumption in this paper, tree

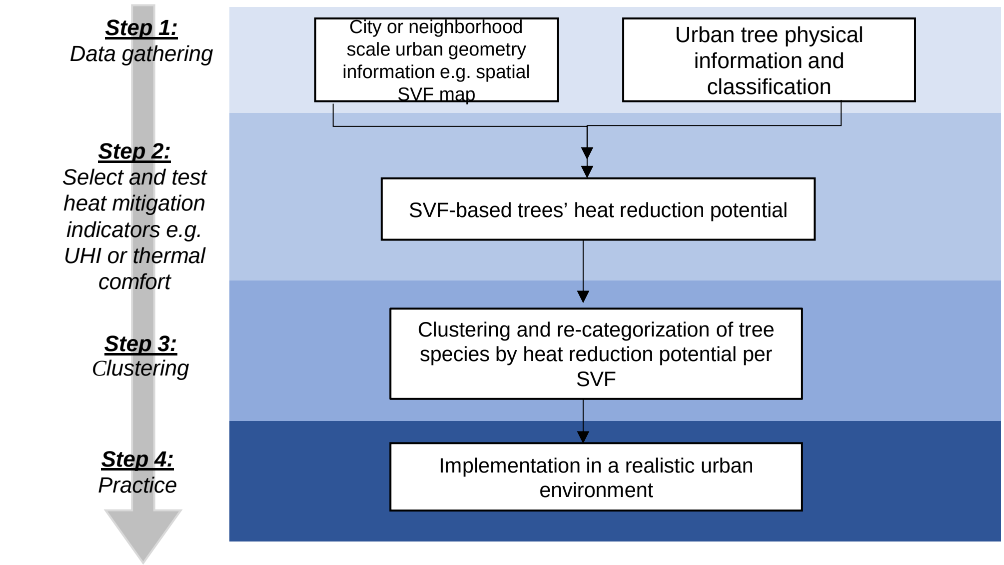


Fig. 1. Proposed right tree species, right place selection methodological framework for urban heat mitigation.

species are equated to tree form, hence, parameterized using four morphological characteristics i.e. height, trunk height, foliage density and crown diameter".

The aim of the present study is to introduce, implement and evaluate a generalized methodological framework for right tree-species selection for urban heat mitigation through the relationship between **urban morphology** characterized by SVF and **tree morphology** which in this study is assumed to be a proxy to tree species Unlike previous studies, the full range (i.e. 0 to 1) of SVF is considered together with 54 forms of trees developed based on a generic tree classification scheme parameterized by foliage density, tree height, trunk height, and crown diameter. The goal is to propose urban morphology (i.e. SVF) as a tool to select appropriate trees form (or tree species) capable of mitigating urban heat in a certain street or urban domain. This method has two main advantages: 1) detection and prioritization of locations or hotspots for greening interventions; 2) assist in planting the right trees at the right place. With the right description of the form or morphology of trees that could meet the thermal needs of an urban environment, corresponding tree species can be easily selected for planting thus reducing dysfunctional, inefficient and under-utilized trees in the urban domain. In addition to the optimal thermal benefits, this method can aid the realization of high diversity of species and genera has been suggested as a key requirement to have and maintain a healthy and sustainable urban tree population (Giridharan et al., 2004; Morakinyo and Lam, 2016). Results provide planning recommendations for professionals and policy/decision-makers on cities' tree planting plans and the maintenance of an urban microclimate.

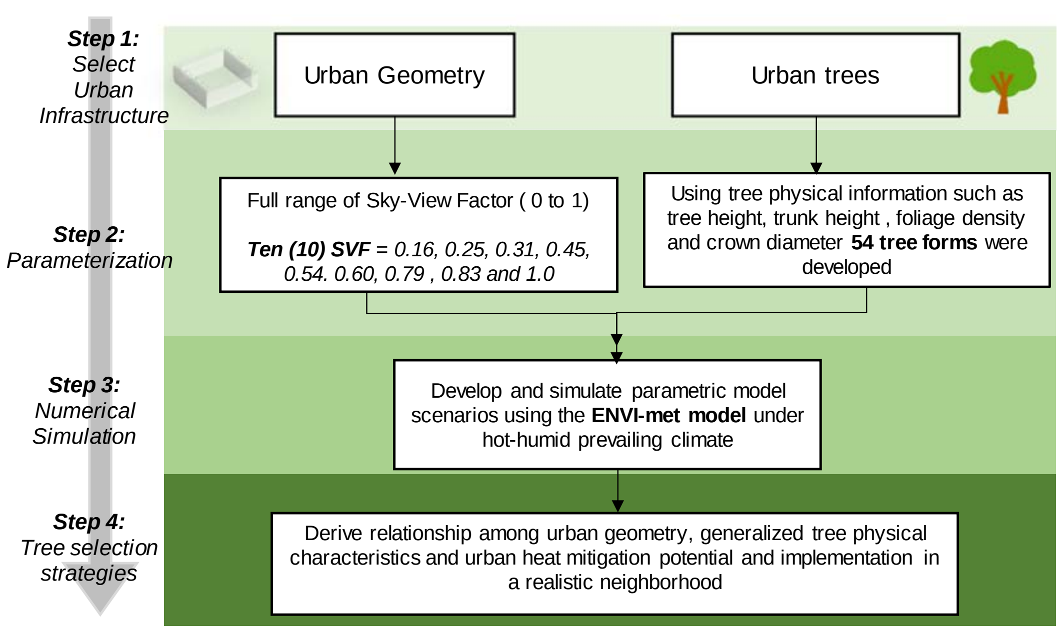


Fig. 2. A methodological framework for right tree species, right place for urban heat mitigation in Hong Kong.

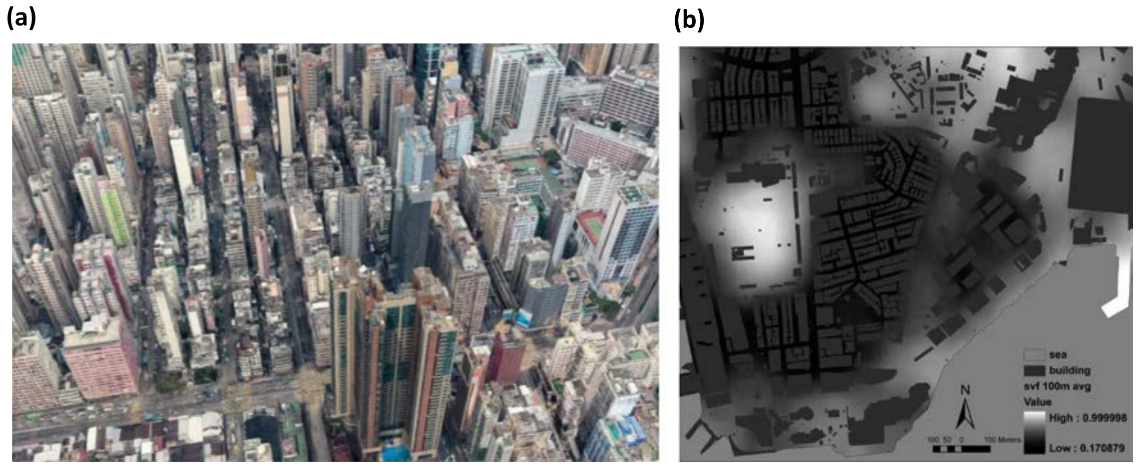


Fig. 3. (a)Typical Hong Kong urban morphology and buildings (source: Google images) (b) Sky-view factor distribution in the dense Tsim Shai Tsui area of Hong Kong (source: (Chen et al., 2012))

2. The "right tree, right place" approach for optimum urban heat mitigation

This section presents the "right tree, right canyon" selection approach which adopts the generalization procedure that enables the quantification of the trees' thermal effect for any urban location under a particular prevailing climate. The approach is applicable in any city across the globe using local datasets as required i.e. tree, urban morphology, and prevailing meteorological information. The step-by-step procedure is depicted in Fig. 1.

The first step is the local data gathering which involves detailed tree surveys in a situation when a robust plant database with information such as foliage density, trunk height, and tree height and crown diameter is not readily available. The stated parameters have been particularly

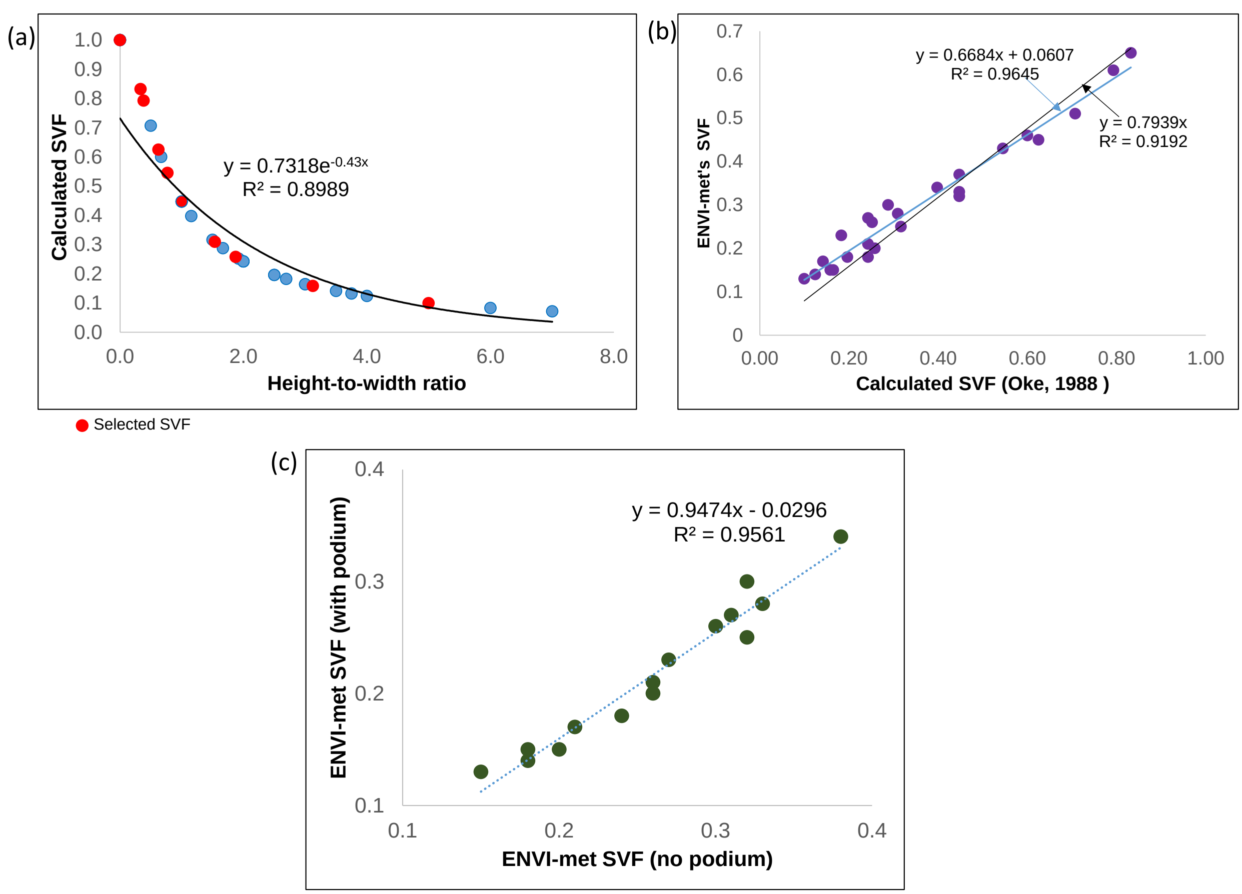


Fig. 4. (a) Relationship between aspect ratio and sky-view factor (b) Relationship between ENVI-met and Oke's method of SVF calculation (c) Comparing SVF in street canyons of bounding buildings with and without a podium.

found to be correlated to the cooling capacity of trees (Morakinyo et al., 2018; Lin and Lin, 2010; Shashua-Bar et al., 2011). By permutation and combination, several forms of trees which essentially represent different tree species can be derived. With the different combinations of the selected trees' structural parameters, 54 different tree forms are possible, and any tree across the world have a high chance of falling in one of the forms.

As an urban-focused methodology, the parameterization of the built environment is quite important. Due to the possibility of spatial visualization, the canyon's sky-view factor (SVF) defined as the degree of sky visibility within street canyons or open-space (Gong et al., 2018) is recommended as the urban morphology indicator and adopted in our implementation case study. It is important to note that SVF here does not consider the view factors of trees and other elements. Combining both the urban morphology and urban tree species datasets, we can have several test scenarios of tree forms (i.e. tree species) in different urban canyons (SVF).

In the second step, the heat reduction potential of each combination of tree form and urban morphology is evaluated using a validated numerical simulation under a prevailing typical summer climate condition on the location i.e. city or district or neighborhood. This is important as previous studies have revealed that the cooling capacities of trees (and other green infrastructure) are largely dependent on climate zone of the tree's location, for instance, similar tree or green coverage in hot-dry climate will relatively perform better than in a hot-humid climate (Kong et al., 2017). Thus, the estimated heat reduction potential from this approach is only applicable to cities within a similar climate zone. For the heat reduction indicator, several options such as air temperature, surface temperature, or thermal comfort (e.g. Physiological Equivalent Temperature, PET or Universal Thermal Climate Index, UTCI) can be selected.

As some tree forms might provide similar heat reduction potential some classification or re-categorization techniques such as clustering analysis can be applied to re-group trees based on their performance. The derived heat reduction potential metric can then be used to select the right tree (species) in the right place (urban canyon or open area) in the final step.

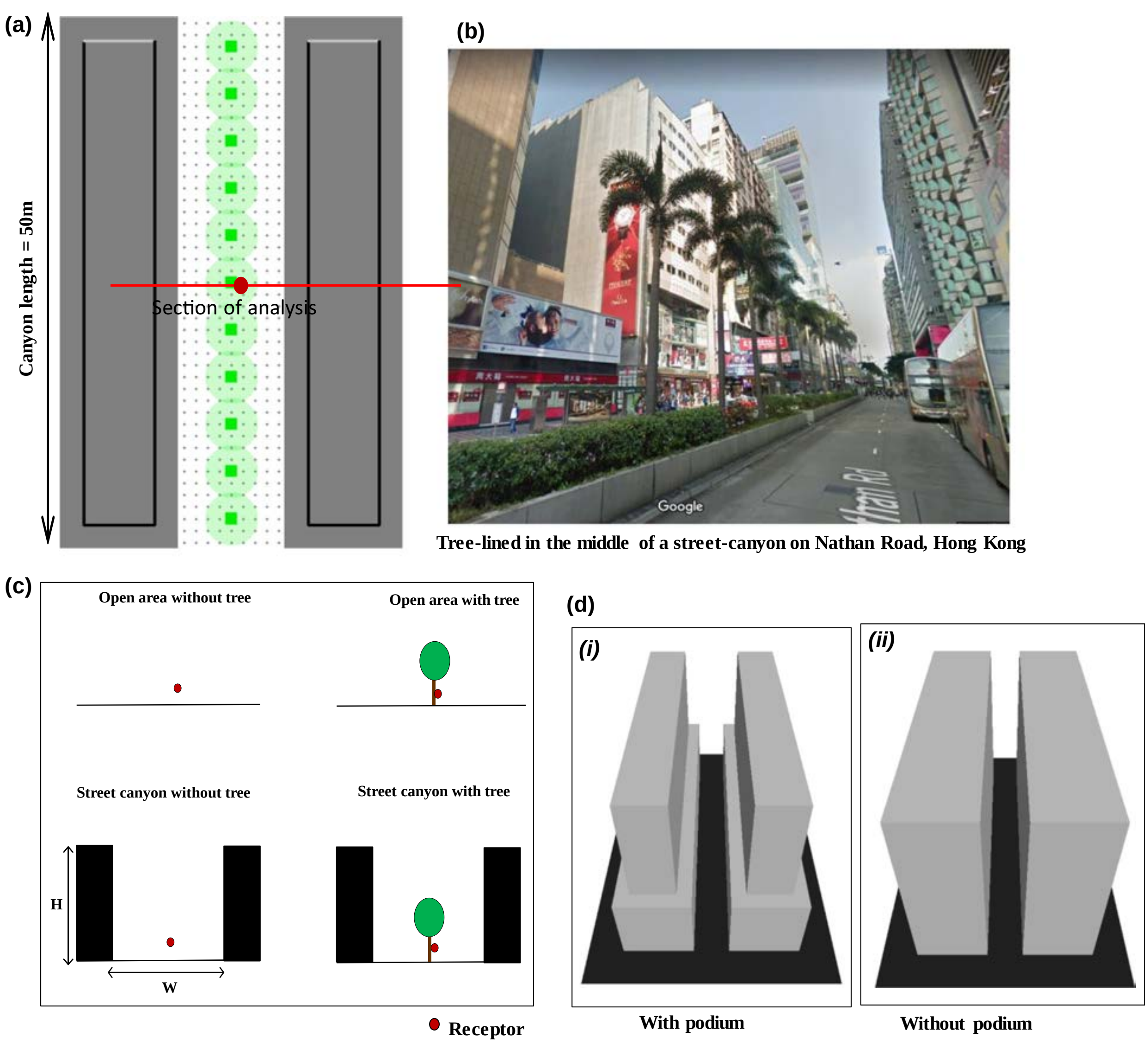


Fig. 5. (a) Schematic diagram of generic street layout with embedded features (b) four street layout with and without trees; (c) real-world example of our model design - trees lined in the middle of a street canyon on Nathan road, Hong Kong(source: Google); (d) visualization of building with and without podium in Hong Kong.

3. Implementation of methodology in a subtropical high-density city, Hong Kong

The proposed methodology described in Section 2 is demonstrated for a sub-tropical high-density city of Hong Kong. The case study workflow is presented in Fig. 2 while a detailed description of each step is given in this section.

3.1. Hong Kong and her climatic condition

Hong Kong, described is a high-density city is located at China's southeast coastline (22°15′N, 114°10′E) with an average altitude of 8 m and houses over 7 million residents. Due to her topography, built-up areas occupy about 22% (1104 km^2) of the territory's total land and sea area of 2754 km^2. Influenced by monsoons due to its proximity to the sea, Hong Kong experiences a sub-tropical climate with hot-humid summer months (May to September) being the hottest months, average daily temperature is around 28.5 °C and a relative humidity of around 80% (Chen et al., 2012) a combination that results in high thermal stress in the city. Coupled with this is the high-density morphology (low sky view) with tall buildings which led to limited urban ventilation and green spaces in the urban landscape (Fig. 3).

3.2. Urban morphology characterization

As part of the first step of the proposed approach, the Sky-View Factor (SVF) was applied as the urban morphology indicator. The SVF ranges from 0 to 1, with the maximum value signifying a non-obstructed sky-view and near-zero value representing a deep street canyon. Several analytical, empirical or numerical methods exist for the estimation of SVF (Chen et al., 2012), some of which are related to aspect ratio (i.e. building height to street width ratio, H/W) which is easier to estimate even though it is less employed in urban climate science. To describe the different combinations of typical building height (10–70 m) and street width (10–30 m) typical for Hong Kong (Chen et al., 2012; Xu et al., 2017) in term of SVF, we used the popular Oke's method (Oke, 1988) which shows that if the radiation morphology for a point at the centre of an urban canyon cross-section is considered with assumed first approximation that the street is infinitely long, then the view factor of each wall (φ_w) is

$$\varphi_w = \frac{(1-cos\theta)}{2} \tag{1}$$

where $\theta = \ tan^{-1}(\frac{H}{0.5W})$. Thus, the SVF of the canyon accounting for the view factors of both walls is

$$\varphi_s = (1-(\varphi_{w1} + \varphi_{w2})) \tag{2}$$

Computing with the above equations, an exponential relationship was found SVF and H/W ratio derived as presented in Fig. 4(a). The derived regression equation and fitted line compare well with the actual values except for underestimation with SVF > 0.7. Thereafter we intentionally selected 10 different SVF (in red dots in Fig. 4(a)) in the 0–1 range covering the high to low urban density and open-area. The corresponding H/W were then used to develop the urban morphology for our numerical experiment.

As earlier mentioned, several methods exist for the estimation of SVF, the applied method used in our employed numerical model, ENVI-met is different from the Oke's method used for our H/W selection. Thus, to ensure the reliable comparison between both techniques and thus reduce potential biases from the modeling, we compared both and found a near-perfect relationship as seen in Fig. 4(b). In Hong Kong, recent building development includes a podium layer of 15 -20 m high, on which a tower of desired height is built, essentially residential or commercial with tower must have a podium, a strategy employed to improve the urban wind environment of the city (Morakinyo et al., 2017b).

To perfectly represent the local urban morphology as required for a case study, we have verified the effect of the podium on ENVI-met's calculated SVF by comparing SVF at the middle of a street with and without podium when building height is >20 m (see Fig. 5(d) to compare the two building types). The result, shown in Fig. 4(c) revealed a near-perfect relationship indicating a negligible effect on SVF. Thus, our urban morphology described as SVF is void of biases that might arise from the calculation method and local building ordinance.

3.3. Generic tree classification and characterization scheme

We have developed a generalized tree classification scheme based on four physical or structural parameters (i.e. foliage density, tree height, trunk height, and crown diameter) and their sub-forms

Table 1
Classification scheme of trees physical characteristics.

Parameter	Sub-class	Value	Applied value
Foliage Density	**D**ense	LAI > 3.0	3.5
	Moderate	LAI = 1.5–3.0	2.5
	Sparse	LAI = 0.5–1.5	1.5
Tree height (m)	**T**all	16–24	20
	Medium	8–16	12
	Short	<8	6
Trunk Height (m)	**H**igh	>3	4
	Low	≤3	2
Crown diameter (m)	**N**arrow	≤4	3
	Medium	4–8	6
	Wide	>8 m	9

Table 2
Summary of input and test parameters, and the corresponding values for validation simulation of Kowloon Bay area of Hong Kong.

Parameter	Definition	Input value
Meteorological conditions[a]	Initial air temperature (°C)	30
	Relative Humidity (%)	75
	Inflow direction (°)	220
	Wind speed at 10 m (m/s)	2.83
	Soil temperature (°C)	
	Upper, Middle and Deep layer	27.7, 28.9, 29.0
	Solar adjustment	0.9
	Cloud cover (oktas)	2
	Lateral boundary condition	Open
Buildings'/roads' information	Street orientation	N-S
	Wall, road and roof albedo	0.3
Tree information	See Table 1	

[a] Obtained from Hong Kong Observatory (HKO).

Table 3
Thermal sensation classification for Hong Kong (Morakinyo et al., 2017b; Cheng and Ng, 2006; Ng and Cheng, 2012).

PET (°C)	Thermal Perception	Physiological stress
<13	Very cold	Extreme cold stress
13–17	Cold	Strong cold stress
17–21	Cool	Moderate cold stress
21–25	Slightly cool	Slight cold stress
25–29	Neutral	No thermal stress
29–33	Slightly Warm	Slight heat stress
33–37	Warm	Moderate heat stress
37–41	Hot	Strong heat stress
>41	Very Hot	Extreme heat stress

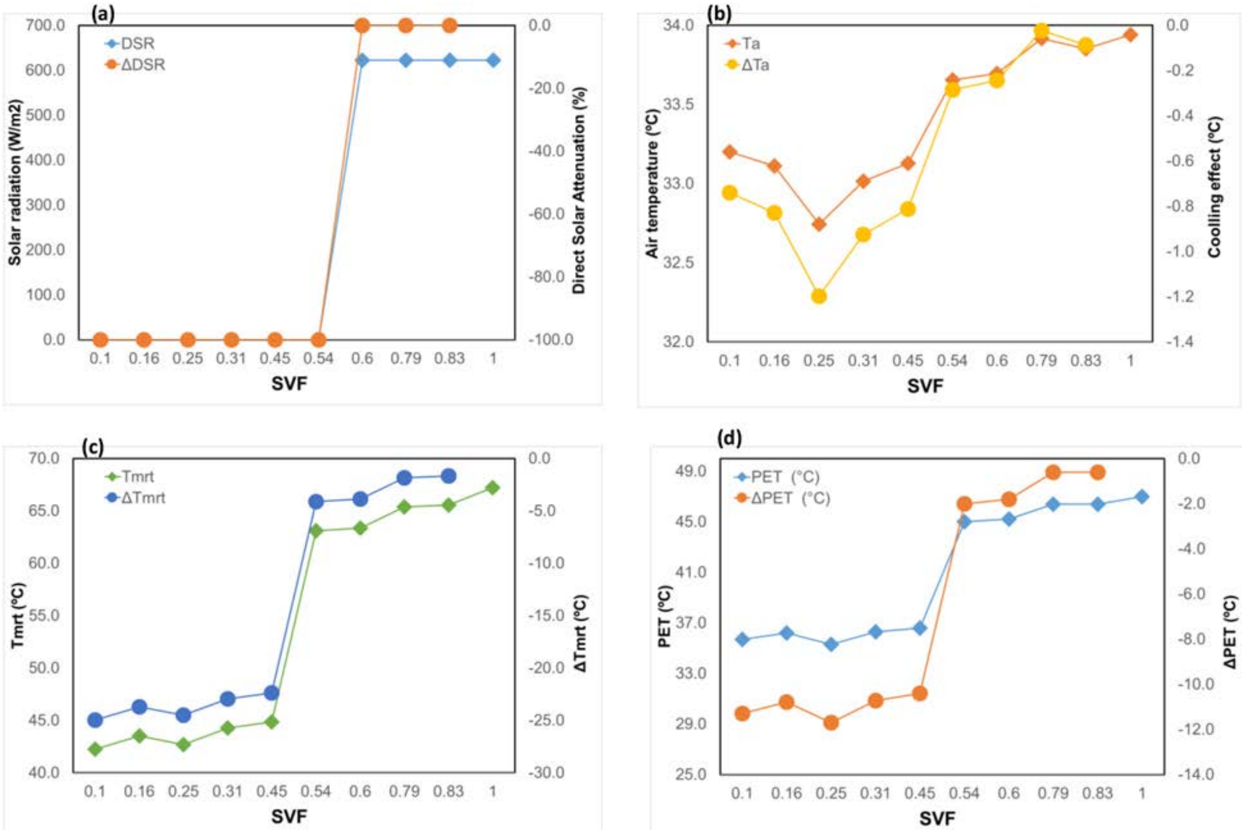


Fig. 6. Distribution of micro-climate variables and the impact of different urban morphology during the daytime.

determined mainly by recognized landscape tree database(Gilman, 2015; Talhouk et al., 2015; National Parks, Nparks, 2013) (see Table 1). For instance, the foliage density of trees is sub-classed into three i.e. "sparse", "moderate" and "dense" with values ranging 0.5–1.5, 1.5–3.0 and > 3.0, respectively. Combinations of these four physical parameters and their respective sub-forms yield a possible permutation of 54 forms of trees implying a high chance of any urban tree around the world to be classified into one of this possible fifty-four forms using this format: <*Foliage Density*>/<*Tree height*>/<*Trunk height*>/<*crown diameter* > and coded with the first letter of the subclass in Table 1 e.g. "DTLM", "MMHN", "SSHW" tree means "**D**ense foliage-**T**all-**L**ow trunk with **M**edium canopy", "**M**oderate foliage-**M**edium height-**H**igh trunk with **N**arrow canopy" and "**S**parse foliage-**S**hort-**H**igh trunk with **W**ide canopy" tree, respectively. More importantly, this parametrization scheme is helpful in modeling trees in the ENVI-met's vegetation model – ALBERO. The

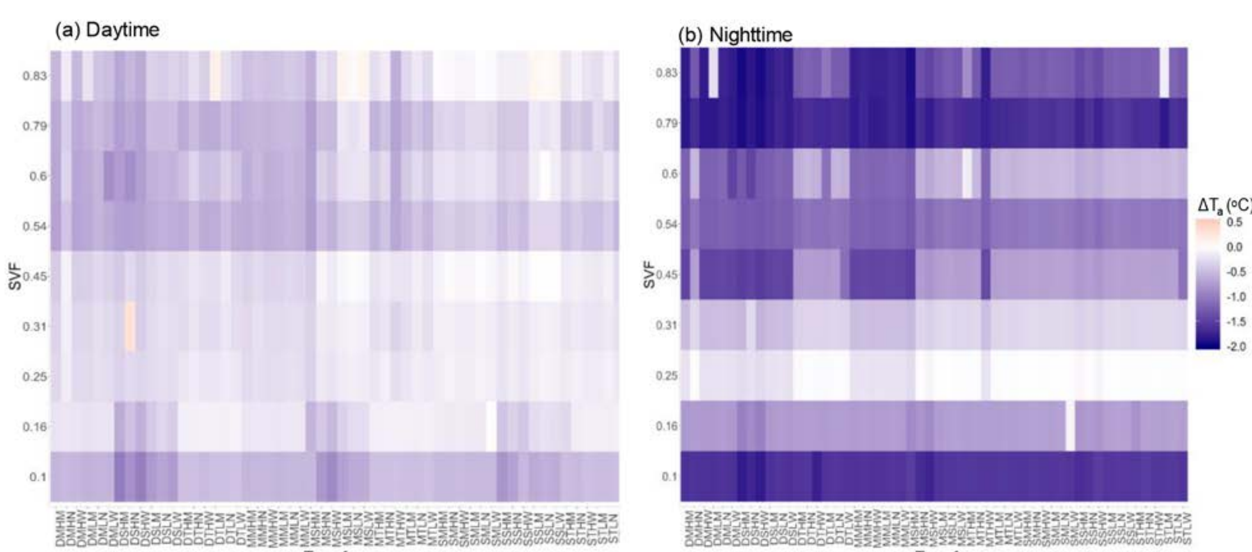
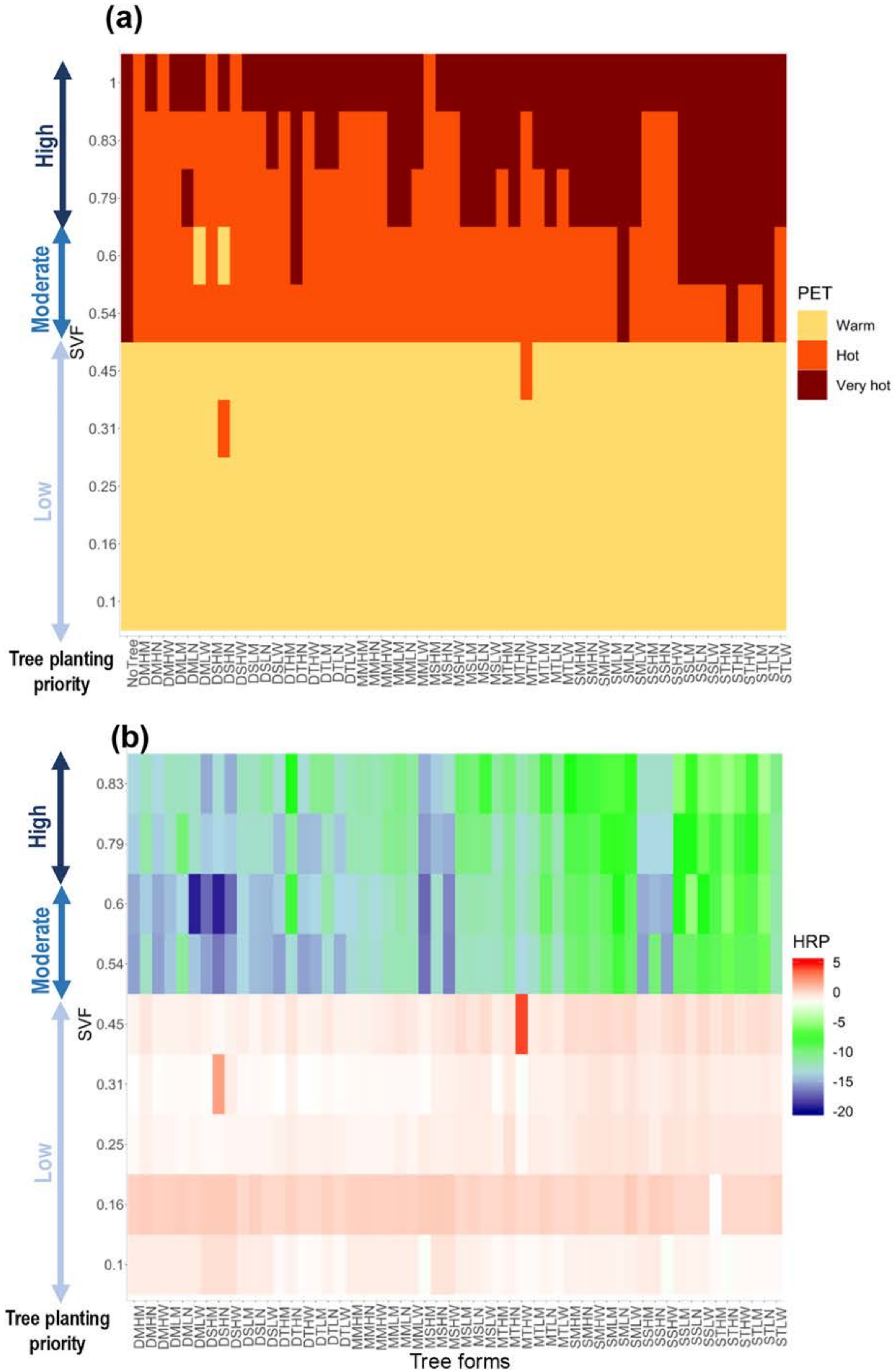


Fig. 7. Heat regulation capacity of tree forms in each urban morphology during (a) daytime (b) nighttime expressed in terms of air temperature only.


(a)
High
Moderate
Low
SVF
1
0.83
0.79
0.6
0.54
0.45
0.31
0.25
0.16
0.1
PET
Warm
Hot
Very hot
Tree planting priority
NoTree DMHM DMHN DMHW DMLM DMLN DMLW DSHM DSHN DSHW DSLM DSLN DSLW DTHM DTHN DTHW DTLM DTLN DTLW MMHM MMHN MMHW MMLM MMLN MMLW MSHM MSHN MSHW MSLM MSLN MSLW MTHM MTHN MTHW MTLM MTLN MTLW SMHM SMHN SMHW SMLM SMLN SMLW SSHM SSHN SSHW SSLM SSLN SSLW STHM STHN STHW STLM STLN STLW
(b)
High
Moderate
Low
SVF
0.83
0.79
0.6
0.54
0.45
0.31
0.25
0.16
0.1
HRP
5
0
-5
-10
-15
-20
Tree planting priority
DMHM DMHN DMHW DMLM DMLN DMLW DSHM DSHN DSHW DSLM DSLN DSLW DTHM DTHN DTHW DTLM DTLN DTLW MMHM MMHN MMHW MMLM MMLN MMLW MSHM MSHN MSHW MSLM MSLN MSLW MTHM MTHN MTHW MTLM MTLN MTLW SMHM SMHN SMHW SMLM SMLN SMLW SSHM SSHN SSHW SSLM SSLN SSLW STHM STHN STHW STLM STLN STLW
Tree forms

generalized 54 forms of trees are tested in each of the selected 10 SVFs described in Section 3.1.

3.4. ENVI-met model description

The parametric studies simulations were conducted using the urban micro-climate model, ENVI-met (Bruse and Fleer, 1998; Huttner and Bruse, 2009) selected for its ability to simulate at high spatial(0.5 to 5 m) and temporal (1 to 5 s) resolution the surface-plant-air interactions resulting in near-accurate modeling of micro-climatic parameters in a complex environment with buildings and surfaces of a diverse materials and green infrastructures. In ENVI-met, plants are porous, living and dynamical bodies with modifiable structural features and can interact through evapotranspiration and energy absorption with the surrounding environment. This specification is important for this study given the aim to apply the understanding of the relationship between urban morphology and detailed tree structural characteristics with reasonable accuracy. The model has been adopted by a wide range of practitioners and researchers interested in evaluating the effectiveness of certain urban heat mitigation and adaptation strategies such as urban greenery and water bodies. Further information on the model, including all embedded equations, documentation and downloads can be found at http://www.envi-met.info.

3.5. A parametric study, model setting, initialization, and model validation

To develop a relationship between urban morphology (i.e. SVF) and tree structural characteristics (i.e. tree forms/species), 540 case studies which are combination of the selected 10 SVF values between 0 and 1, and 54 tree forms were simulated in the ENVI-met model to derive the micro-climate modification and urban heat mitigation potential of each tree form per SVF. The generic layout of our setup is given in Fig. 5(a) which shows the canyon length of 50 m but variable building height to street width ratio corresponding to the associated SVF. Trees with overlapping crowns were planted in the middle of the street canyon while data for analysis was extracted at 1.5 m the centre of the canyon (red dot) or corresponding point in an open area. A real-world example of the model design is depicted in Fig. 5(b) which shows row of trees lined in a street canyon on Nathan road, Hong Kong. Four street layouts shown in Fig. 5 (c) were considered: 'Open area without trees' which represents open-street with no nearby buildings and trees; 'Open area with trees' represents open-street with no nearby buildings but with tree-shades; 'Street canyon without trees' represents a tree-free street canyon and 'Street canyon with trees' represents street canyons with trees.

The computational domain with constant length of 50 m but variable width depending on the case's street width all have grid size with 2 m × 2 m × 2 m while ten (10) nested grids were also added to the computational domain to ensure enough distance before the upstream building and after the downstream building and also to minimize edge-effect.

To initialize the simulation a previously validated ENVI-met model setting fully reported our previous study (Morakinyo et al., 2018) was employed. The setting mimicked a hot summer day in Hong Kong with initial hourly air temperature was set to 30 °C, relative humidity at 75%, prevailing wind speed at 2.83 m/s and direction 220. Table 2 provides a summary of all the input parameters and values for the validation simulation exercise. With the setting, a good correlation of $R^2 = 0.79–0.81$ and 0.70–0.74 for air temperature and mean radiant temperature, respectively was found between the measured values and simulation results (see Fig.A1). Further analysis revealed a relatively low RMSE corresponding to MAPE of 3.7% (for tree-shaded air temperature), 5.1% (for unshaded air temperature), 7.7% (for tree-shaded mean radiant temperature) and 13.2% (for unshaded mean radiant temperature) was found. As a reasonable agreement with the minimal error was found between the ENVI-met modeled and observed dataset corroborated by other previous studies in Hong Kong and elsewhere(Müller et al., 2013; Tan et al., 2017; Srivanit and Hokao, 2013; Lee et al., 2016; Ng et al., 2012), thus, the model setting was adopted for this study.

3.6. Heat reduction potential and Indicator

The thermal performance of each tree form in each urban morphology (SVF) was characterized as Heat Reduction Potential (HRP) which is the potential time-dependent human thermal comfort improvement or otherwise in a vegetated against the reference canyon. For further analysis, we selected the period of maximum temperature (15:00) to represent the daytime situation while 00:00 was selected for the nighttime. The choice of thermal comfort PET ahead of air temperature as the heat indicator is because of the subtropical hot-humid climate experienced in high-density of Hong Kong where heat stress is beyond air temperature but also very crucial are relative humidity, radiative fluxes and wind speed(Cheng et al., 2012; Lau et al., 2019).

The HRP equation uniquely represents the cooling potential of trees relative to the heat-stress in a reference open area without trees. It can be estimated thus:

$$HRP_{PET,j} = \left(\frac{PET_{sc\_wt} - PET_{sc\_tf}}{PET_{oa\_tf}}\right) \times 100\% \quad (3)$$

where

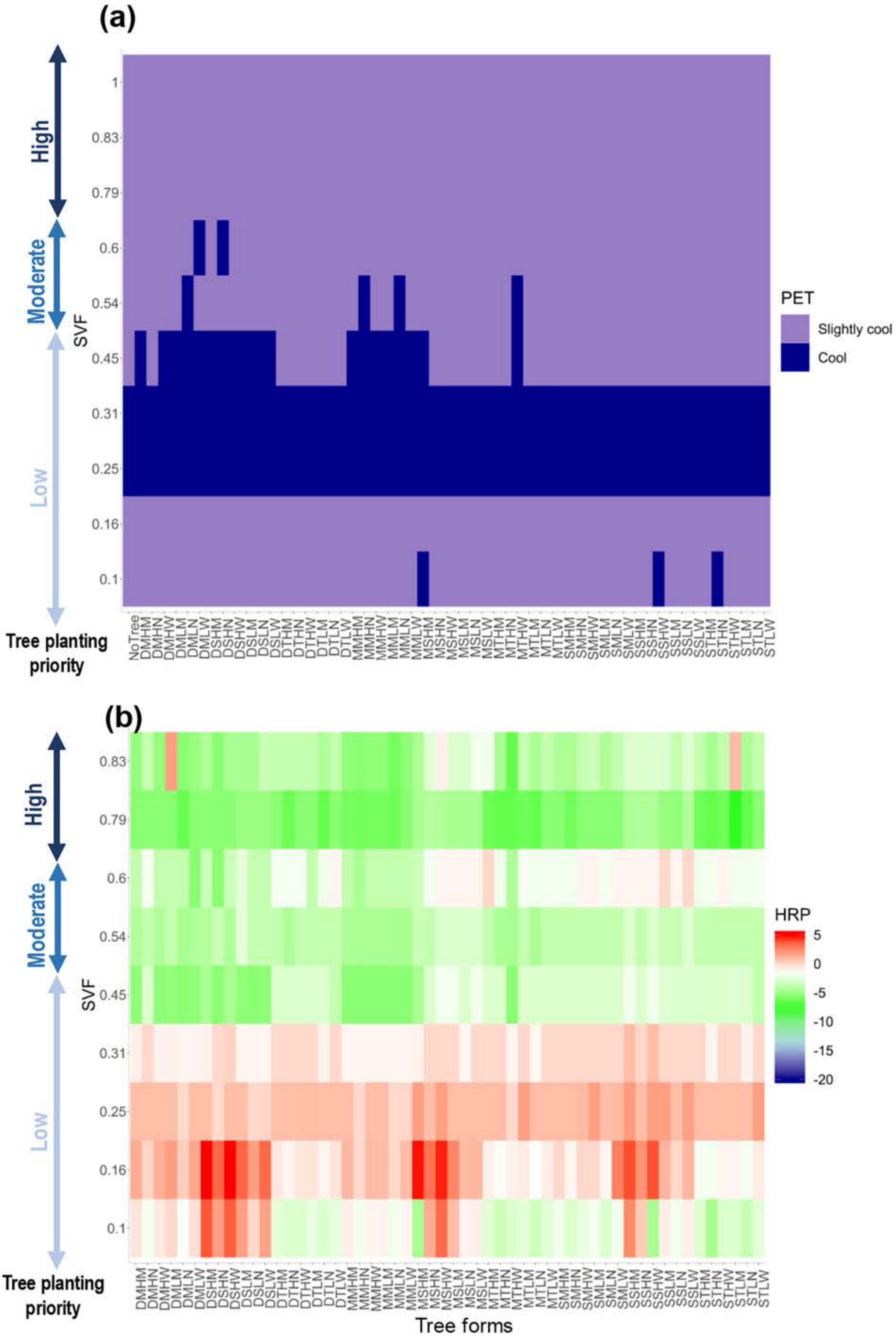
$HRP_{PET,j}$ = Heat Reduction Potential in % in terms of thermal comfort (PET)
PET_{sc_wt} = PET in street canyon with trees
PET_{sc_tf} = PET in street canyon without trees
PET_{oa_tf} = PET in open area without trees

The Physiological Equivalent Temperature (PET) is defined as the air temperature at which, in a typical indoor setting (without wind and solar radiation), the heat budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed(VDI, 1998; Höppe, 1999). It considers the impact of radiative fluxes on body heat balance in the outdoor environment, making it more acceptable and suitable for assessing outdoor human thermal comfort. For its calculation, the ENVI-met simulated micro-climate data (air temperature, specific humidity, wind speed and mean radiant temperature) were imported into an appended software, i.e. BioMet for a standardized person (Age: 35 years, Weight: 75 kg, Height: 1.5 m; work metabolism: 80 W of light activity, and 0.9 clo of heat resistance). Thereafter, the resulted values were classified into thermal sensation categories for Hong Kong given Table 3:

3.7. Clustering analysis

We further re-grouped the tree forms based on their heat reduction potential in each urban morphology. This classification is useful in practice as it helps recognize a set of tree form (species) with

Fig. 8. (a) Distribution of daytime (a) thermal comfort condition in street canyons without trees and with tree forms (b) heat reduction potential of tree forms (species) in varying urban morphology.


(a)
High
Moderate
Low
Tree planting priority
SVF
1
0.83
0.79
0.6
0.54
0.45
0.31
0.25
0.16
0.1
PET
Slightly cool
Cool
NoTree DMHM DMHN DMHW DMLM DMLN DMLW DSHM DSHN DSHW DSLM DSLN DSLW DTHM DTHN DTHW DTLM DTLN DTLW MMHM MMHN MMHW MMLM MMLN MMLW MSHM MSHN MSHW MSLM MSLN MSLW MTHM MTHN MTHW MTLM MTLN MTLW SMHM SMHN SMHW SMLM SMLN SMLW SSHM SSHN SSHW SSLM SSLN SSLW STHM STHN STHW STLM STLN STLW
(b)
High
Moderate
Low
Tree planting priority
SVF
0.83
0.79
0.6
0.54
0.45
0.31
0.25
0.16
0.1
HRP
5
0
-5
-10
-15
-20
DMHM DMHN DMHW DMLM DMLN DMLW DSHM DSHN DSHW DSLM DSLN DSLW DTHM DTHN DTHW DTLM DTLN DTLW MMHM MMHN MMHW MMLM MMLN MMLW MSHM MSHN MSHW MSLM MSLN MSLW MTHM MTHN MTHW MTLM MTLN MTLW SMHM SMHN SMHW SMLM SMLN SMLW SSHM SSHN SSHW SSLM SSLN SSLW STHM STHN STHW STLM STLN STLW
Tree forms

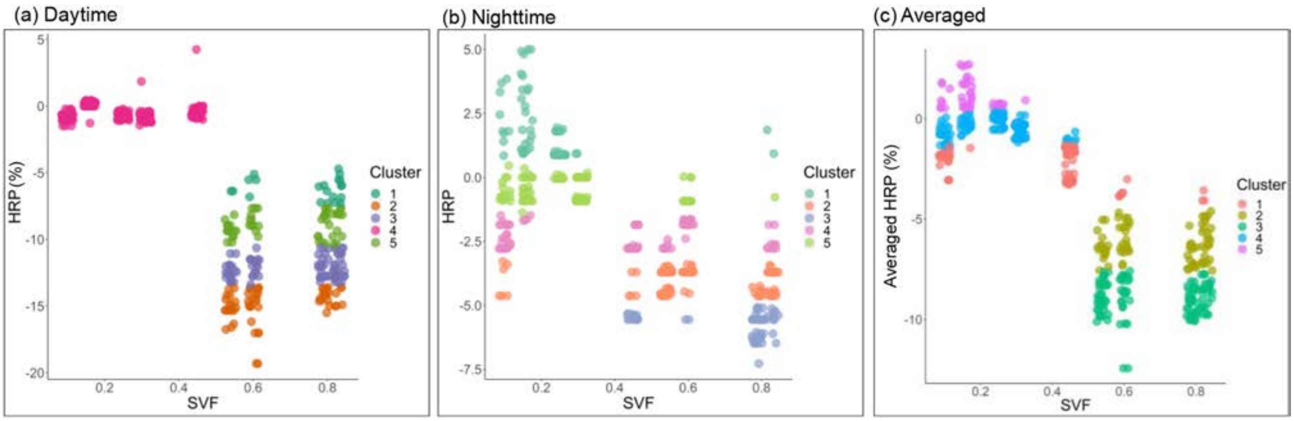


Fig. 10. Clusters distribution of tree's HRP in different urban morphology during (a) daytime, (b) nighttime, (c)averaged.

similar heat mitigation capacity thereby aiding decision making in selecting the right set of species for the right urban canyon. To achieve this, we applied the K-means clustering method implemented in the R Software. To implement this method, the number of desired clusters has to be specified, we set this as 5 at first, and thereafter the algorithm uses iterative refinement for centroids to obtain the optimal clusters in aggregation with the most similarities.

4. Results and discussion

4.1. Effect of urban morphology on urban micro-climatic condition

A comparison between the microclimate parameters that determine the human thermal comfort condition of an open area and the urban canyons (i.e. SVF) is given in Fig. 6. During the daytime (15:00), the direct solar radiation at SVF ≥ 0.6 was 622 W/m^2 while there was no solar gain in SVF < 0.6 at the same time (Fig. 6(a)). This pattern influences the micro-climatic condition obtainable in each SVF during this time; air temperature reduction due to urban morphology i.e. building shading effect ranges between 0.1 and 1.2 °C, higher reduction 0.7–1.2 °C was found in deep canyons (SVF < 0.45) while the reverse was observed in higher SVF canyons indicating lowered air temperature in deep than shallow canyons (Fig. 6(b)). The coolest and most heat-regulated canyon was SVF = 0.25 which was found to have the widest street of our considered urban morphologies and consequently, the most ventilated, thus, the dilution/diffusion of heat is higher due to the stronger wind speed. This corroborates the observation of urban cool island in the high-density area during the daytime relative to the surrounding areas by a previous study (Yang et al., 2017). In terms of ventilation, the observed wind speed ranges between 2.0 and 2.3 m/s irrespective of SVF with a negligible SVF impact of between −12% and 8% (not shown). The maximum reduction observed in the low SVF canyons signifying deeper canyon have the potential to experience relatively lower ventilation. However, the impact is dependent on wind direction (Morakinyo and Lam, 2016) which wasn't considered in our simulation case studies. For mean radiant temperature (MRT), a pattern liken to that of solar attenuation was observed, a reduction of 22.4–25 °C was found in SVF < 0.45 while slight reduction of 1.7–4.1 °C was found in SVF ≥ 0.54 echoing the lower radiant energy experienced as the canyons deepen (Fig. 6(c)). This in particular and combined with other micro-climatic parameters earlier discussed culminate to develop a clear partitioning of the PET profile mainly driven by the urban morphology as shown in Fig. 6(d); PET = 35.7–36.6 °C i.e. "warm" thermal sensation in SVF ≤ 0.45 while PET = 45–46.4 °C (i.e. "very hot" thermal condition) was observed in SVF ≥ 0.54. Overall, this finding suggests that on its own, urban morphology can mitigate urban overheating and human heat stress during the daytime (see Fig. A2). Specifically, we found that the human comfort level can improve in deep canyons by up to two forms i.e., from "very hot" to "warm" relative to an open-area.

At nighttime (see Fig. A3), the deeper canyon which had no solar penetration i.e. low energy absorption on the surface for the most part of the daytime also had less energy to dissipate resulting in lower MRT and T_a in deeper than shallow canyons. In general, the SVF effect on thermal comfort was not significant, a range of 1.2 – (+1.4) °C was observed with the negative effect more pronounced in high SVF due to higher radiant energy from the wall-absorbed during daytime which was impeded in deeper canyons (see Fig. A2).

4.2. Air temperature regulation capacity of trees in different urban morphology

Trees inside street canyons were found to reduce daytime and nighttime overheating in terms of air temperature by variable magnitude depending on the tree form and urban morphology as shown in Fig. 7. For an unbiased comparison, we expressed the temperature regulatory effect of the trees in urban canyons with trees relative to their tree-free counterparts. Note that in the subsequent figures tree forms have been intentionally ordered primarily by foliage density which is the major driver of the overheating mitigation (Morakinyo et al., 2017b; Morakinyo and Lam, 2016). In general, we found between 1 °C reduction to 0.3 °C increase depending on the tree form and urban morphology as shown in Fig. 7(a) during the daytime. The later occurred rarely in 8 of the 540 cases and mostly in the SVF = 0.83 with sparse foliage trees. In this canyon, there is relative larger unshaded area which implies higher surface heating and convection of hot air within the canyon. No distinct pattern was observed for the daytime temperature regulation among the tree forms; however, we found the highest air cooling in the deepest canyon, SVF = 0.1 for most of the tree forms and SVF ≥ 0.54 for most of the moderate to dense foliage trees.

During the nighttime, simulation results show the absolute temperature regulation i.e. urban heat island mitigation of between 0.0

Fig. 9. (a) Distribution of nighttime (a) thermal comfort condition in street canyons without trees and with tree forms (b) heat reduction potential of tree forms (species) in varying urban morphology.

Table 4
Ranked top 10 urban heat mitigators tree form for each urban morphology.

SVF	Top heat mitigators tree form	Hong Kong's equivalent species	Dominant characteristic description
0.10	MSHM, SSHW, STHN, STLN MTHN, MTLN, DTHW, STHM, STHW, STLM		***Foliage density*** *– Sparse, Moderate;* ***Tree height*** *–Tall* ***Trunk Height*** *– High;* ***Crown diameter*** *– Narrow, Moderate*
0.16	STHM, STHN, STLN, MTHN MTLN, SMLN, STHW, STLM, MTHW, MTHM		***Foliage density*** *– Sparse, Moderate;* ***Tree height*** *–Tall* ***Trunk Height*** *– High, Low;* ***Crown diameter*** *– Narrow, Moderate*
0.25	DMLN, DSHN, MTHW, MMHN, DSLN, MMLW, MMLN, DSLW, DMHM, DSHM		***Foliage density*** *– Dense, Moderate;* ***Tree height*** *– Moderate, short;* ***Trunk Height*** *– High, Low,* ***Crown diameter*** *– Any*
0.31	MTHW, DMHW, DSLM, MMHM, MSHM, DMLN, MMHW, DSLW, MMHN, DSHM		***Foliage density*** *– Dense, Moderate;* ***Tree height*** *– Moderate, short;* ***Trunk Height*** *– High;* ***Crown diameter*** *– Any*
0.45	DSHN, DSLN, DMLN, MMHN, MMHM, DMHW, MMHW,DMHM, DMLM, MMLM		***Foliage density*** *– Dense;* ***Tree height*** *– Moderate* ***Trunk Height*** *– High;* ***Crown diameter*** *– Any*
0.54	MSHM, DSHN, DMHW, DSHM, DMHM, DSHW, MSHW, DTHM, DTHW, DTLM	*See Appendix 4*	***Foliage density*** *– Dense;* ***Tree height*** *– Any;* ***Trunk Height*** *– High;* ***Crown diameter*** *– Any*
0.60	DMLW, DSHN, MSHM, DSHW, DSHM, DMHM, DMHW, DSLW, DSLN,DMLM		***Foliage density*** *– Dense;* ***Tree height*** *– Short, Moderate;* ***Trunk Height*** *– High;* ***Crown diameter*** *– Any*
0.79	MSHM, DTHW, DTHM, DTLM, DTLW, MTHW. DSHM, DSHW, DMHM, DMHW		***Foliage density*** *– Dense;* ***Tree height*** *– Any;* ***Trunk Height*** *– High;* ***Crown diameter*** *– Any*
0.83–1	DSHM, DSHW, MSHM, DMHW, DMHM, DSHN, MTHW,, DMLN, DMLW, MMHW		***Foliage density*** *– Dense;* ***Tree height*** *– Short, moderate;* ***Trunk Height*** *– High;* ***Crown diameter*** *– Any*

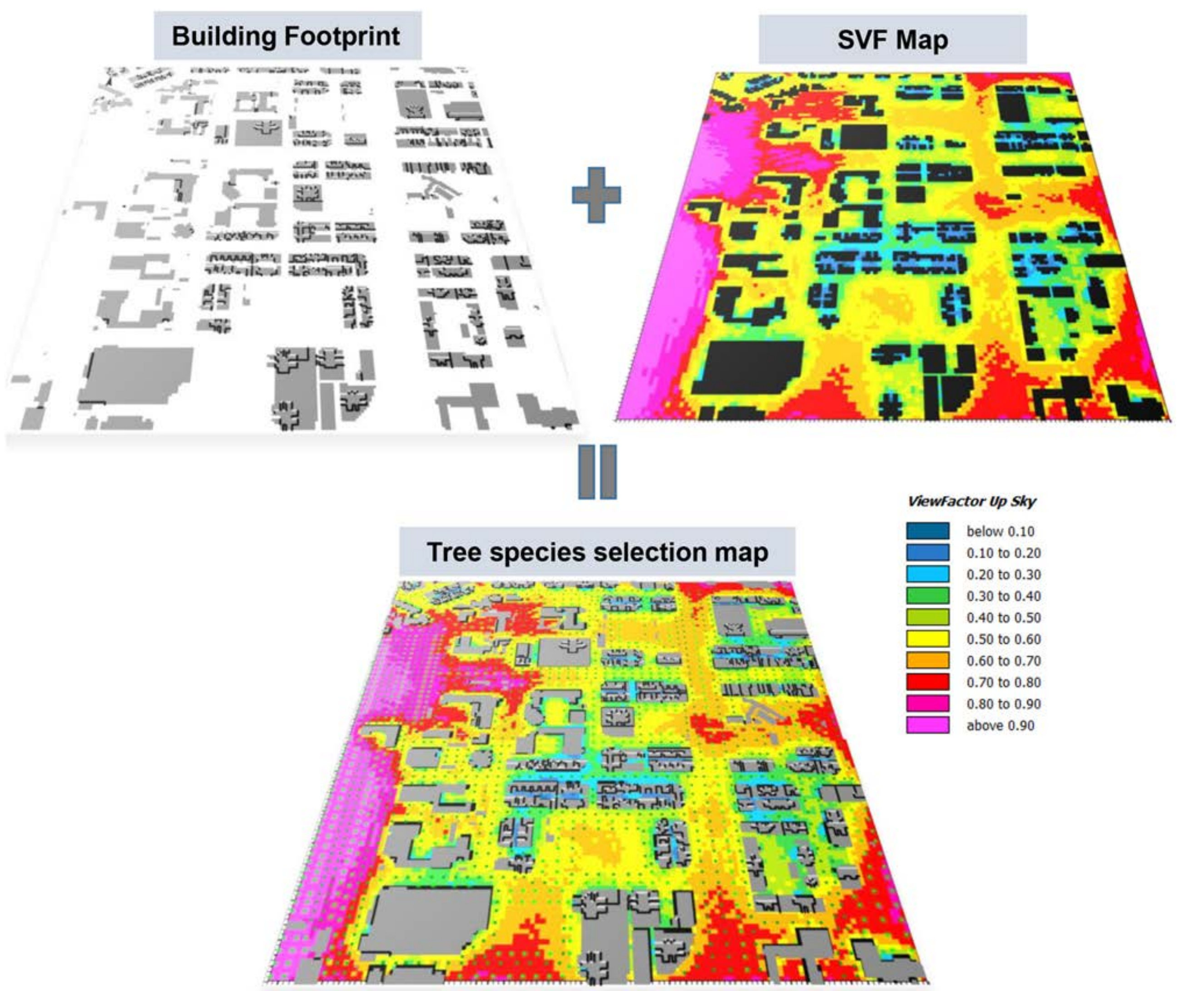


Fig. 11. Building footprint Yuen Long area of Hong Kong overlaid on the sky-view factor distribution map of the same area for tree species selection for optimal urban heat mitigation*(green dots = trees)*. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and 1.9 °C (see Fig. 7(b)) depending on canyon morphology and tree form. It was found that the trees provide optimum cooling in SVF = 0.1 (very deep canyon) and open canyons while minimal cooling was found in SVF = 0.25–0.31. The magnitude of temperature reduction at this period is dependent on the unshaded-shaded total surface area ratio which determines the amount of heat storage during the daytime and ventilation reduction. The larger the shaded surface, the less the heat storage and consequently air temperature reduction. This was the situation with the maximum reduction in very deep and open canyons. This results generally echoes the role of vegetation in mitigating nighttime heat islands effect as found in other previous studies (Gousseau et al., 2011; Santamouris et al., 2018).

4.3. Heat reduction potential of tree forms in different urban morphology

In this section, we present the results of the estimation of the HRP of individual tree form per SVF, classified by five scales at 5% interval. The HRP was computed with respect to PET as indicated in Eq. (3) to holistically account for all micro-climate variables that determine urban heat mitigation. The best and worst-performing trees are classified as "Very High" and "Very Low" HRP, respectively. Furthermore, we applied the k-means clustering technique to group tree forms of similar performance in each SVF, thus aiding the development of tree selections recommendations.

Fig. 8(a) represents the PET classification in each SVF and tree form. Without trees, SVF ≤ 0.45 experience "Warm" comfort level (35.3–36.6 °C) while SVF ≥ 0.54 experience "Very Hot" (45–46.4 °C) with 47 °C observed in the reference open area (SVF = 1). The figure also reveals the tree-planting priority in different SVF based on observed absolute PET values in reference canyons with 3 distinct forms: Low priority (SVF = 0.1–0.45), moderate priority (SVF = 0.5–0.6) and high priority (SVF > 0.6). However, with trees, thermal comfort, often remained unchanged in SVF ≤ 0.45 irrespective of the tree form. This reveals that trees have minimal impact on thermal stress in deep street canyons, which is because the building shading or shadow-cast effect outweighs the tree shading impact in these canyons as shown in other previous studies (Morakinyo et al., 2017b; Tan et al., 2017). This finding supports the classification of these canyons as "low-priority" for tree planting as their actual impact not significant for heat mitigation. However, in SVF ≥ 0.54 we found that different results showing variable effects of the tree forms: some tree forms were capable of reducing the thermal sensation from "very hot" to "hot" and rarely to "warm" while some others were unable to influence an improvement in the concerned canyon's thermal condition (Fig. 8(a)).

Relative to the thermal condition in a reference open area, we have classified the Heat Reduction Potential during the daytime (15:00) of each tree form and urban morphology presented Fig. 8(b). Generally, maximum and minimum daytime HRP observed was −20% and + 2%, respectively.

In SVF ≤ 0.45, all tree forms exhibit "low" to "very low" HRP. In these canyons, even the foliage density had a marginal impact on the HRP as the thermal comfort condition remained unchanged by the addition of trees in the street canyons reiterating the "low priority" status of these SVFs.

However, in "moderate and high priority" canyons (SVF > 0.6), the performance of tree forms ranges from "moderate" to "very

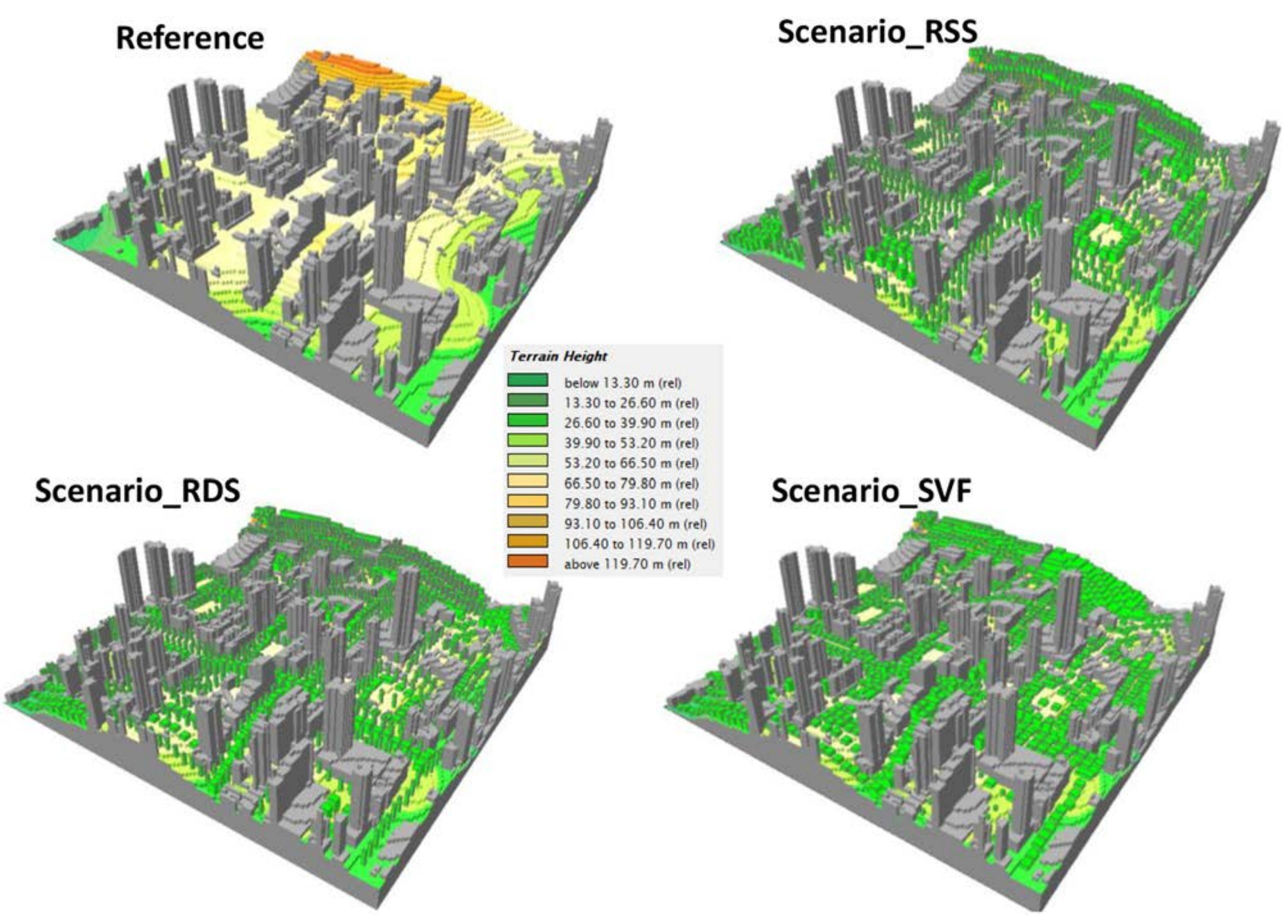


Fig. 12. 3D view of the study area (with DEM implementation): simulated scenarios with different tree selection approaches.

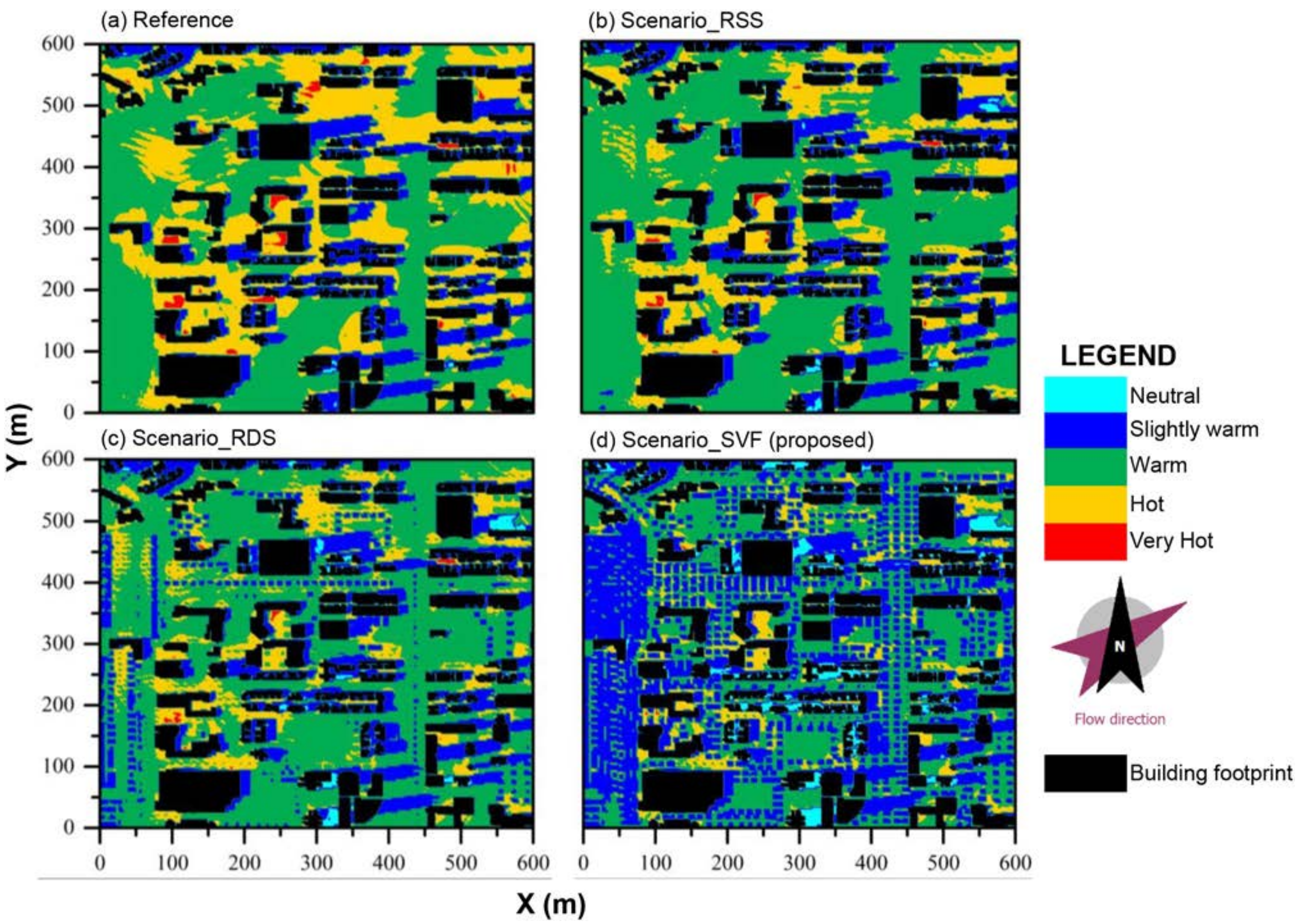


Fig. 13. Time-averaged distribution of thermal comfort (PET) in the study domain with different tree species selection scenario.

high" HRP. The most profound optimal performance was observed with the "Dense" foliage tree forms and "moderate priority" canyons. It is also important to note that some sparse foliage trees tree form have "high" to "very high" HRP which are SSH trees i.e. sparse foliage, short with high trunk tree. Interestingly a further investigation reveals that the strong influence of these trees was not determined by the foliage density as their dense and moderately dense counterparts also produced the best results. Rather it because the leaves are aggregated at the top of the tree. This implies that, rarely, even short trees with sparse (but not scattered leaves) could yield optimum HRP in any urban morphology.

Considering the thermal comfort condition at night, results revealed a range of between "slightly cool" and "cool" with or without trees, respectively. Nonetheless, the presence of vegetation slightly impacts PET values. Results reveal −7.3% to 5.3% HRP during the night equivalent to between "low" and "very low" depending on the tree form and urban morphology (see Fig. 9). Thus, these changes are not enough to changes the human comfort sensation level since the absolute value is not >2 °C even though most of the positive change (worsened thermal comfort) were observed in the deepest canyon ("moderate" to "low" priority) which is due to the trapping of longwave radiation at nighttime.

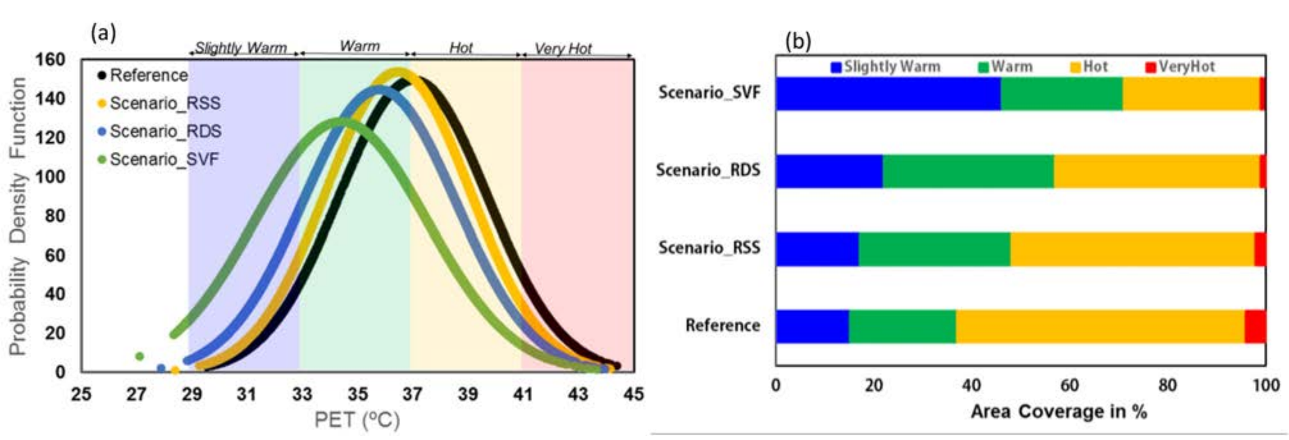


Fig. 14. (a) Probability density distribution of domain and time-averaged PET values for all scenarios (b) Area coverage of thermal forms in different scenarios on at pedestrian level.

4.3.1. Categorization of tree based on their HRP using K-means clustering

The clustering analysis results presented in Fig. 10 shows the categorization of tree's heat reduction potential in each urban morphology. The daytime, nighttime and averaged HRP of the 54 tree forms in each SVF were subjected to five possible clusters while the presented result summarizes the similarity or dissimilarity of performance. It is important to mention that set of trees in each cluster are not necessarily the same for different time of the day. The descriptive statistics of HRP clustering is given in the supplementary information.

Daytime HRP better differentiates the cooling potential among tree forms along the SVF. Cluster 4 trees with very low HRP values indicated that in low SVF canyons (≤0.45), the potential of all trees in improving PET in the street canyon is limited during the daytime due to the overweighing impact of shadow-effect of the tall bounding buildings. However, in high SVF canyons (≥0.54), clusters 2, 3, and 5 trees were seen to provide remarkable heat reduction. Among them, the trees with dense crown have the highest heat reduction potential (Cluster 2), which corresponds with the previous study that the shading is the utmost important in open spaces where SVF is high for subtropical areas(Morakinyo et al., 2017b; Tan et al., 2017; Shashua-Bar et al., 2011). As for nighttime, trees have a negligible effect on HRP as earlier explained. At this time, cluster 1 trees moderately enhance nighttime heat and cluster 5 shows little modification for the thermal environment. However, clusters 2 and 3 trees are the best heat mitigators in high SVF canyons ((≥0.54) while all trees in clusters 2 and 4 are better in deeper canyons (SVF ≤ 0.45). The limited effect of trees during the nocturnal period is due to a lack of direct shortwave radiation at this time.

4.3.2. Selecting the right tree, for the right urban canyon: Science to practice

To fight urban overheating across the day and nighttime hours, trees species with high HRP across these periods must be identified and selected. Our analysis has revealed that trees in subtropical climate are more responsive to changes in the thermal conditions indicated by thermal comfort daytime and air temperature at nighttime. More so, in a subtropical hot-humid high-density city like Hong Kong, heat stress is beyond air temperature, also very crucial are relative humidity, radiative fluxes, and wind speed thus, thermal comfort i.e. PET. Therefore, the final tree species selection per SVF was determined based on the averaged HRP i.e. (daytime + nighttime HRP)/2. Thereafter, the averaged HRP was clustered and the best heat mitigators trees in each urban morphology were ranked to derive recommendations for implementation.

The clustering analysis results of averaged HRP is shown in Fig. 10 (c) reveals clusters 1 and 4 trees as the best heat mitigators in SVF ≤ 0.45 while in SVF ≥ 0.54, cluster 3 trees mitigate heat the best. For urban planning and design, the trees in each clusters per SVF has been ranked (see Supplementary file) while the top 10 tree forms per SVF are listed in Table 4 with their dominant characteristic description and real-world Hong Kong's examples of tree species derived from a pilot tree survey in a dense urban neighborhood of Hong Kong shown in Appendix 3.

Based on the dominant characteristics of top heat mitigators trees, the following tree selection recommendation can be concluded:

1) ***In low priority canyons (SVF ≤ 0.45)***: Although, the urban canyons in this SVF range are "low priority" for tree planting because of the stronger effect of building shadow-cast on radiant and air temperature as supported by previous finding (Norton et al., 2015). Incidentally, there abound numerous urban greening challenges therein such as limited space, soil water deficiency, and traffic pollution. Nonetheless, greenery is encouraged to be innovatively integrated irrespective of urban morphology for enhanced cooling and other ecosystem services. Based on our results, we specifically recommend tall, sparse to moderate foliage density with high trunk trees in the very deep canyons (SVF ≤ 0.2) while moderate foliage trees, with between average and short height but high trunk are best heat mitigators in (SVF = 0.2–0.45) and thus, recommended. The trees' morphological characteristics ensure that ventilation is not overly reduced thereby enhancing the dispersion of traffic–related pollutants (Morakinyo and Lam, 2015).
2) ***In moderate priority canyons (SVF = 0.45–0.6):*** These urban canyons are the balance between the tree-shading and shadow-cast effects of buildings on urban overheating. Our ranking analysis of tree forms HRP reveals that short, dense foliage trees with the high trunk are the best heat mitigators herein. Depending on the availability of space, the canopy width can be extended.
3) ***In High priority canyons (SVF ≥ 0.6):*** The canyons are a high priority of tree-planting mainly due to largely reduced effect of shading benefit of low height or absence of buildings. Thus, shading can only be achieved by trees and artificial elements. Hence, short trees with leaf density (preferably higher than tested in this study) with the high trunk are the best heat mitigators herein. Additionally, large crowns are more desirable effective here due to available ground coverage to be cooled.

4.4. Implementation and evaluation of the morphology-based tree species selection strategies

To evaluate the proposed tree selection strategies in a real-world urban environment, we have selected a realistic 600 × 600 m^2 urban neighborhood located in the Yuen Long district of Hong Kong. The main criteria used for choosing this area is the variable distribution of SVF which is the "predictor" of the corresponding top heat mitigators trees to be selected for planting. Fig. 11 shows the building footprint, the neighborhood's SVF and the overlaid image used to guide the tree form to be planted.

For illustrative purpose, four scenarios have been developed to evaluate the effectiveness of the proposed morphology-based tree species selection approach as shown in Fig. 12 which indicate the 3D built environment of the selected area with the implementation of a NASA SRTM's 30 m resolution digital elevation model (DEM) from used in the ENVI-met model. A brief description of each scenario is given below:

1. *Reference:* Scenario with no trees
2. *Scenario_RSS:* Represents an uninformed tree species selection coincidentally with sparse foliage tree species. Thus, none of the top heat mitigators trees of the sparse foliage tree form were selected. This scenario is hypothesized to be a worst-case scenario given the absoluteness of dense foliage trees on the plantable spaces.
3. *Scenario_RDS:* Represents an uninformed tree species selection coincidentally with dense tree species. Thus, none of the top heat mitigators trees of dense foliage form were selected. This scenario is hypothesized to be the best-case scenario of the four under consideration given the absoluteness of dense foliage trees on the plantable spaces.
4. Scenario_SVF: Represents an informed tree species selection in respective urban canyon based on the proposed morphology-based tree species selection method.

Comparison of heat reduction effect with tree species selection approaches.

To illustrate the urban heat mitigation optimization of the proposed morphology-based tree selection approach, Fig. 13 shows the spatial distribution of time-averaged PET at the pedestrian level. The PET value probability density function curve (in Fig. 14(a) reveals the minimum, maximum and mean values of PET were 29.5 °C, 44.4 °C and 37.0 °C (Reference case); 28.3 °C,44.1 °C and 36.5 °C (Scenario_RSS); 27.9 °C,44 °C and 35.8 °C (Scenario_RDS) and 27.1 °C,43.7 °C and 34.4 °C (Scenario_SVF), indicating the significant thermal comfort improvement with the proposed morphology-based tree species selection approach in terms of magnitude and area coverage. Comparison between each tree-planted scenario and the reference i.e. reveals a minimum and maximum of −4 °C and 1.2 °C; −8.7 °C and 2.6 °C; and − 11.4 °C and 3.0 °C, respectively for the *scenario_RSS, scenario_RDS* and proposed *scenario_SVF*, which correspond to a domain averaged value of −0.55 °C, −1.22 °C and − 2.62 °C. This finding clearly indicates the proposed approach's capability in improving the thermal comfort twice as much as the *scenario_RDS* which is the best case with an uninformed tree selection approach.

Furthermore, we have investigated thermal class conversion from one to another of unbuilt grids within the domain for each tree-planted scenario relative to the reference as shown in Fig. 14(b). It shows the area coverage (in %) per thermal class for all scenarios under consideration. Four thermal forms i.e. slightly warm, warm, hot and very hot accounted for 99.8% unbuilt grids in the domain. In the reference case, ~4% of the unbuilt grid had a "Very Hot" (i.e. PET >41 °C) condition which was reduced to 2.1%, 1% and 0.5% in the *scenario_RSS, scenario_RDS* and proposed *scenario_SVF*, respectively. Moreover, "Hot" thermal condition was observed in ~60% of the unbuilt grids in the reference scenario but reduced to 50%, 42% and 28% in the *scenario_RSS, scenario_RDS* and proposed *scenario_SVF*, respectively. In the case of "warm" condition, the percentage of area coverage increased from 22% in the reference to 31%, 35% and 25% in the *scenario_RSS, scenario_RDS* and proposed *scenario_SVF*, respectively. However, the slightly warm area coverage (%) increased from 15% to 17%, 22% and 46% in the *scenario_RSS, scenario_RDS* and proposed *scenario_SVF*, respectively. Relative to the RDS case – the supposed best-case scenario, the profiles of scenario_SVF, shows more grids were transformed to the slightly warm condition (46% compared to 22%) especially from "Hot" condition. In general, with our proposed the right tree, right canyon tree selection approach, over 70% of the unbuilt grids experience below "Hot" thermal condition against the 36%, 48% and 57% in the *reference, scenario_RSS and scenario_RDS*, respectively reiterating the significant effect of the proposed approach.

5. Planning recommendation, limitation and conclusion

This study has proposed and evaluated a morphology-based approach to select the right tree for the right location for optimum urban heat mitigation. The approach is applicable globally since generic urban morphology (i.e. SVF) and tree classification (54 generic tree forms) were used in the development. Our findings on the relationship between trees' cooling performance and urban morphology reveals that the tree's heat reduction potential is variable depending on the species (tree forms) and location with the urban domain. Even though other tree morphological characteristics such as tree height, trunk height, and crown diameter are determinants of tree's heat reduction potential, the main determinant of heat reduction efficiency is the foliage density which is corroborated by our previous studies' finding where 60% of temperature regulation is attributed to foliage density(Morakinyo et al., 2018). In general, tree species with high foliage density are generally high heat mitigators and vice-versa for low foliage density trees. However, depending on the location, the heat reduction potential of trees can be hampered i.e. a tree species can be underutilized if placed in the wrong place. For instance, high foliage density trees are at their best when placed in open-areas or low sky-view factors area, but due to the competing shadow-cast shading effect from the building, such trees underperform in high-density areas. The reverse is true for the sparse foliage trees. Thus, the prioritization of tree-planting within the entire range of urban morphology (sky-view factor) has been categorized into three i.e. Low (SVF ≤ 0.45): Moderate (SVF = 0.45–0.6) and high (SVF > 0.6) priority. It is important to mention, that the magnitude of heat reduction potential will be dependent on the prevailing climate either hot-humid, hot-dry, temperate or cold climate. Also, local tree database and descriptive statistics are required to translate to tree forms to actual tree species for implementation. The proposed approach has been tested under the Hong Kong's hot-humid climate condition, thus the reported HRP magnitude are the limited to areas with similar climate condition.

The findings from the parametric and confirmation by the evaluation study in Hong Kong can be applied to the urban greening strategies of the city: we particularly recommend a performance-based approach to tree-planting in the city which implies a paradigm shift from generalizing trees to a need-based and thermal sensitive tree species selection in the right location. To achieve this we recommend the updating of tree species selection suggestions in the current district-level Greening Master Plan (GMP) with our proposed morphology-based tree species selection approach so as to optimize urban heat mitigation and significantly reduce dysfunctional in the city's landscape in the short and long -term. A larger scale tree database should be developed with heat reduction as a categorization factor. Furthermore, at building and site-scales, the greening sections of the sustainable building design guideline (APP-152) (HKBD, 2014) and the chapter 4 of the Hong Kong Hong Kong Planning Standards and Guidelines (HKPSG, 2011) should be modified to include proposition of the characteristic heat mitigators relative to the locations sky-view factor, thereby improving the thermal condition of the immediate environment among other benefits.

There are some limitations to this study which are mainly related to the adopted ENVI-met model: first, all buildings in our simulation are of single material i.e. concrete whereas, there are mixes of facades types in the city domain. Secondly, the dominant wind parameters during the summer period in Hong Kong were applied and are kept constant during the simulation which is in contradiction to the real atmospheric condition. Also, our generic tree classification scheme included only four parameters which are actually the most important. However, other physical or morphological parameters of trees, such as leaf shape, texture and colour have been found to also contribute to the cooling magnitude of trees (Lin and Lin, 2010). Nevertheless, our results have shown that tree's heat mitigation potential varies among species and placement within the urban landscape, essential knowledge for the planning and design of green spaces with optimum thermal benefits. In the future, we will extend this by investigating and comparing the heat reduction potential in variable climate zones around the world. Through this, a global morphology-based tree species selection database can be developed and utilized.

CRediT authorship contribution statement

Tobi Eniolu Morakinyo: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Project administration. **Wanlu Ouyang:** Software, Data curation, Formal analysis, Writing - original draft, Writing - review & editing. **Kevin Ka-Lun Lau:** Validation, Writing - review & editing, Project administration, Funding acquisition. **Chao Ren:** Writing - review & editing, Supervision, Funding acquisition. **Edward Ng:** Conceptualization, Supervision, Funding acquisition, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1

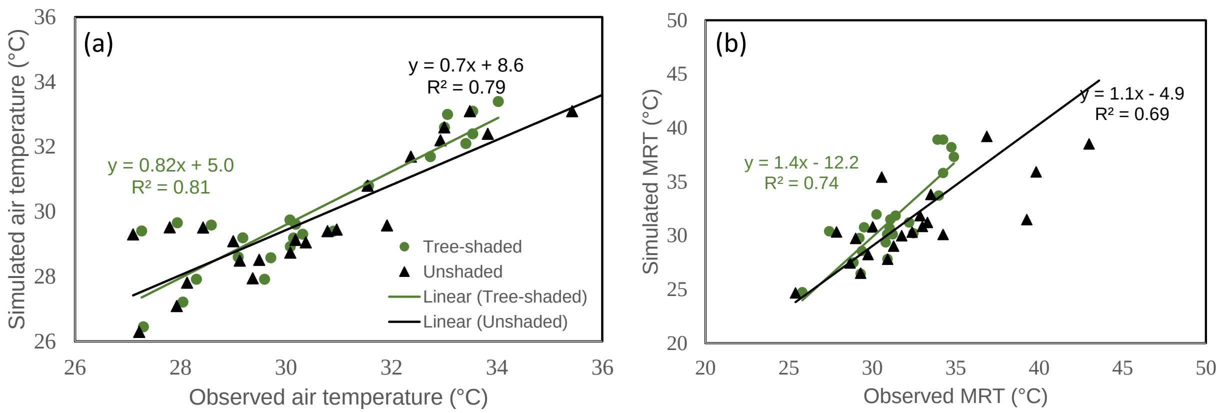

Fig. A1. .Relationship between ENVI-met simulated and observed (a) air temperature and (b) mean radiant temperature, MRT at tree-shaded and unshaded location on 23rd August,15th and 17th October 2016 (09:00–17:00 local time) (source: (Morakinyo et al., 2018)).

Appendix 2

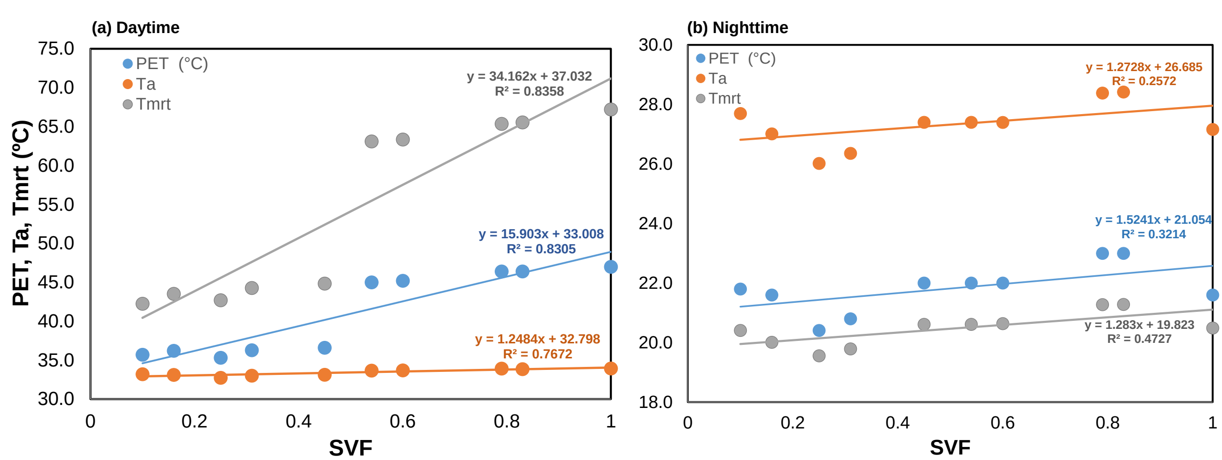

Fig. A2. Relationship between urban morphology and urban heat indicators during day and night time.

Appendix 3

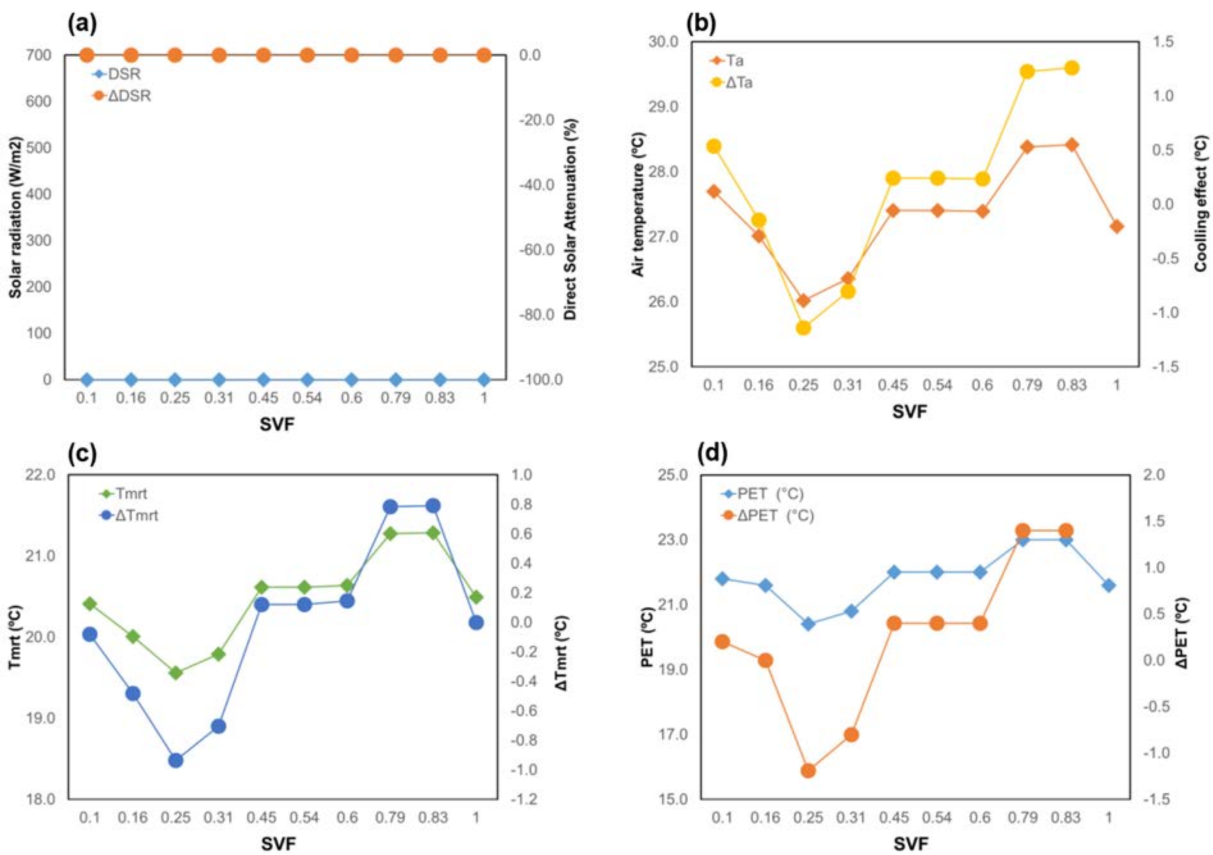

Fig. A3.. Distribution of micro-climate variables and the impact of different urban morphology during the nighttime

Appendix 4. A full list of the 54 forms and corresponding tree species found in Hong Kong based on a pilot tree survey

Tree form	Tree species	Count
DTHN		0
DTHM		0
DTHW		0
DTLN		0
DTLM		0
DTLW		0
DMHN		0
DMHM	*Aleurites moluccana, Elaeocarpus apiculatus, Mangifera indica, Macaranga tanarius* var. *tomentosa, Bischofia polycarpa, Cordia dichotoma, Ficus variegata* var. *chlorocarpa*	7
DMHW	*Ficus elastica, Ficus religiosa, Macaranga tanarius, Lophostemon confertus*	4
DMLN	*Cerbera manghas*	1
DMLM	*Ficus benjamina, Araucaria heterophylla, Ficus altissima,*	3
DMLW	*Ficus microcarpa, Artocarpus altilis, Erythrina indica 'Picta', Morus alba, Ficus virens*	5
DSHN	*Cinnamomum camphora*	1
DSHM	*Cassia javanica* var. *indochinensis*	1
DSHW	*Syzygium cumini*	1
DSLN	*Juniperus chinensis, Bischofia javanica,Terminalia mantaly cv. 'Tricolour', Callistemon viminalis, Erythrina variegata, Ficus benjamina'Variegata', Juniperus chinensis L.var*	7
DSLM	*Crateva unilocularis, Ailanthus fordii, Dillenia excelsa*	3
DSLW	*Hibiscus tiliaceus*	1
MTHN		0

(*continued*)

Tree form	Tree species	Count
MTHM		0
MTHW	*Peltophorum pterocarpum*	1
MTLN		
MTLM		
MTLW		
MMHN	*Archontophoenix alexandrae,Melaleuca cajuputi,Grevillea robusta,Liquidambar formosana*	4
MMHM	*Bauhinia × blakeana,Delonix regia,Michelia x alba,Terminalia mantaly,Acacia confusa,Eucalyptus torelliana,Cassia fistula,Casuarina equisetifolia,Acacia mangium,Bauhinia variegata* var. *candida,Alstonia scholaris,Adenanthera microsperma,Thevetia peruviana*	13
MMHW	*Bombax ceiba,Khaya senegalensis,Spathodea campanulata,Albizia lebbeck,Celtis sinensis,Fraxinus griffithii,Swietenia mahagoni*	7
MMLN	*Lagerstroemia indica*	1
MMLM	*Schefflera actinophylla*	1
MMLW	*Teminalia catappa,Tabebuia donnell-smithii*	2
MSHN		0
MSHM	*Bauhinia variegata,Cinnamomum burmannii,Ilex rotunda,Xanthostemon chrysanthus,Phanera variegate*	5
MSHW	*Elaeocarpus grandifloras*	1
MSLN	*Dypsis lutescens,Magnolia grandiflora,Caryota maxima,Caryota mitis,Tabebuia chrysantha,Leucaena leucocephala,Polyalthia longifolia,Podocarpus macrophyllus,Lagerstroemia floribunda,Elaeocarpus hainanensis,Syzygium jambos,Chukrasia tabularis,Oroxylum indicum*	13
MSLM	*Lagerstroemia speciosa,Plumeria rubra cv. acutifolia,Caryota ochlandra,Crateva trifoliata,Cassia surattensis,Bauhinia purpurea, Sterculia lanceolate*	7

(*continued*)

Tree form	Tree species	Count
MSLW		
STHN		
STHM		
STHW	*Peltophorum tonkinense,Eucalyptus citriodora*	2
STLN		
STLM		
STLW		
SMHN	*Melaleuca quinquenervia*	1
SMHM	*Roystonea regia,Senna siamea,Plumeria rubra,Eucalyptus robusta,Melaleuca cajuputi* subsp. *cumingiana*	5
SMHW	*Melia azedarach,Corymbia citriodora,Toona sinensis*	3
SMLN		
SMLM	*Erythrina speciose*	1
SMLW		
SSHN		
SSHM	*Jacaranda minosifolia*	1
SSHW	*Ficus virens* var. *sublanceolata*	1
SSLN	*Phoenix roebelenii,Senna surattensis,Garcinia subelliptica*	3
SSLM	*Livistona chinensis,Plumeria obtusa,Cassia siamea*	3
SSLW		
	Total	109

Appendix 5. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.137461.

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