Simulation of Cooling Effectiveness of Trees to Improve Outdoor Thermal Environment on Different Climate-Sensitive Urban Forms during A Summer of Bangkok

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Abstract

This study aim to delineate an urban planning metric for greenery called the green plot ratio (GPR). The GPR is based on a common biological parameter called the leaf area density (LAD), which is defined as the portion of the single-side leaf area per unit volume of tree canopy. The study will investigate the effectiveness of GRP for urban greenery to maximize cooling benefits and potentially improve the daytime heat effect. Four climate-sensitive areas for tree planting with different Bangkok's urban morphologies are evaluated through an urban micro-climate simulation performed by the ENVI-met model. Simulation results indicated that the cooling effect of GPRs is highly associated with urban form. Maximum air temperature reduction (a 1.2 °C reduction at the pedestrian level) is the most profound for the very high-density urban form on summer diurnal range of tropical climate, whereas the average air temperature vary linearly is reduced during the peak heat of day by 0.02°C–0.12 °C by increasing GPRs. These findings will help urban planners offer better guidelines for planting and establishing urban trees to mitigate extreme heat in the hot-humid tropical environment.

Keywords: green plot ratio, thermal environment, hot-humid tropical climate, micro-climate modelling

1. Introduction

Urban warming has negative effects on both humans and the thermal environment that are expected to increase in the future, especally in tropical climatic. The inclusion of green infrastructure in urban environments has been identified as an effective way to mitigate severe thermal conditions through evapotranspiration, which associated with trees results in the release of water vapour from leaves into the air that reduces the surrounding ambient air temperature through an evaporative cooling process (Gill et al., 2008; Ballinasa and Barradasa, 2015; Saaroni et al., 2018; Choruengwiwat et al., 2019). In addition, the transpiration of green space and tree canopy shading can cool the environment by directly blocking solar radiance and preventing the heating of the land surface and air, which is usually referred to as the urban cooling island effect (Rahman et al., 2015; Yang et al., 2017; Zhou et al., 2017).

In the past ten years, the growing attention to the importance of green spaces, and especially in urban areas, in the creation of cooling effect has led to the publication of many research works with different methodologies and at different scales in relation to this subject (Farhadi et al., 2019; Lai et al., 2019; Qunshan et al., 2018; Zölch et al., 2016; Norton et al., 2015; Chow and Brazel, 2012; Wong and Yu, 2005). A relatively new method in this field of research is computer simulation, which allows research and analysis variables to be adjusted as desired (Farshid et al., 2019). In this context, one of the most widely employed the popularization of dynamic simulation tools for urban microclimate analysis (Toparlar et al., 2017) is the ENVI-met model, developed by Michael Bruse at the Rurh University of Bochum (Bruse and Fleer, 1998). One of the first works in which the cooling effect of green spaces was analyzed with ENVI-met was a study conducted in Hong Kong during 2012, this study found that planting sidewalk trees in urban spaces result in a better cooling effect than building green surfaces such as green roofs (Ng et al., 2012). In another recent study (Zhao et al., 2018), ENVI-met software was used to evaluate differences in outdoor microclimates and human thermal comfort by simulating different tree layouts (clustered, equal interval, or dispersed) in a residential neighborhood in the City of Tempe, USA. Based on the ENVI-met simulation, an equal interval two trees arrangement provided the most microclimate benefits in the neighborhood due to the importance of shading in the hot arid desert environment, following by clustered tree arrangement without canopy overlap.

Based on the above-mentioned evidence, the computer simulation has greatly facilitated the qualitative analyses that put more emphasis on the effect of vegetation type and quality and the placement of green spaces, but evaluating its effectiveness has not been widely researched especially in urban areas located in hot and humid climates. Therefore, in this study, we tried to (1) investigate the effectiveness of urban trees to improve thermal environment on the differentiation of urban form by analyzing cooling from trees using ENVI-met simulation model. Moreover, (2) propose a tree planting strategy that enables landscape planners to determine the optimal tree coverage in the hot-humid climate of Bangkok.

The main outcome of this method is a micro-climate simulation tool to investigate green spaces of urban forms according to measurements and empirical findings on the relationship between the urban landscape planning, the microclimate conditions and the urban configurations. In this way, this process will contribute to urban landscape planning practices as a decision-support tool to provide guidelines for the construction of climate-sensitive urban forms (Figure 1). In this study, the outdoor thermal environment is one of the main parameters evaluated for the quality of urban life. This heat stress in the open spaces affects the pedestrian activities altering the liveability of the urban area.

2. Methods

2.1 Selecting prototype of climate-sensitive urban forms

Urban climate modeling is usually performed on the local scale, a district is extracted from its context and explicitly represented, with building forms, materials, natural surfaces, etc (Oke, 2006). Urban classification has been proposed to split the territory according to a thermal climate zone (TCZ) definition of Bangkok Metropolitan Area (BMA) (Srivanit et al., 2014). By BMA's surface properties differentiation, the urban-rural continuum yields a hierarchy of 7 TCZs. TCZs can provide input data for numerical climate models that incorporate urban canopy parameters into their formulations to forecast the climatic conditions. For the determination of the LCZs, we have chosen a four typical for the nearest the mean class centroid of TCZ for simulations including; medium density (MD) as the compact midrise urban areas where located mostly in the out edge of urban core area, high density (HD) as the BMA's old CBD area, was located mostly in the historic core district of Yaowarat, very high density (VHD) was located mainly along the Sukhumvit road, near the Asok district, and extremely high density (EHD)

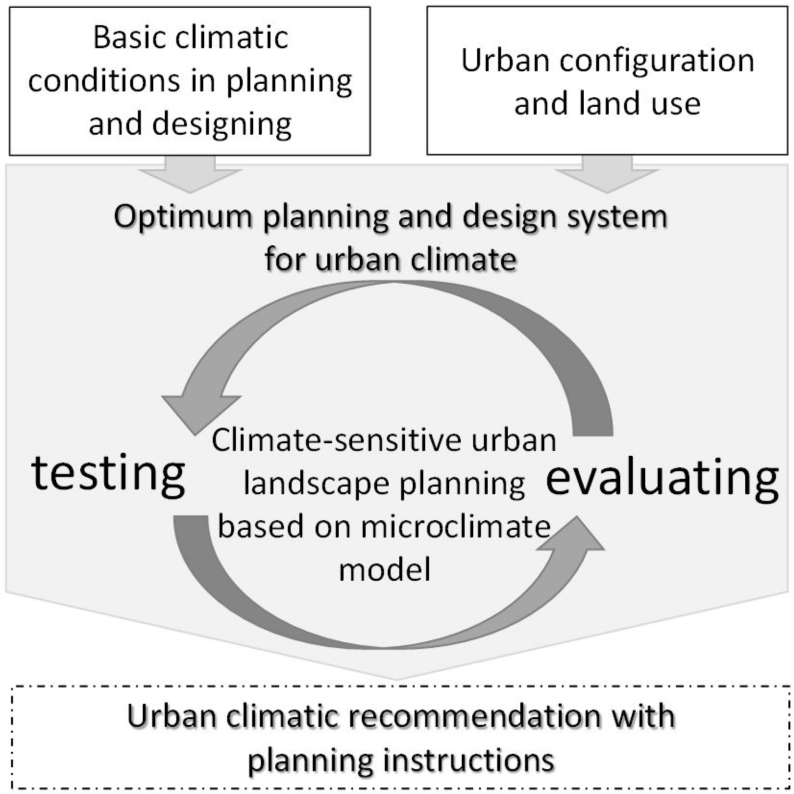

Figure 1. The concept of the climate-sensitive urban forms.

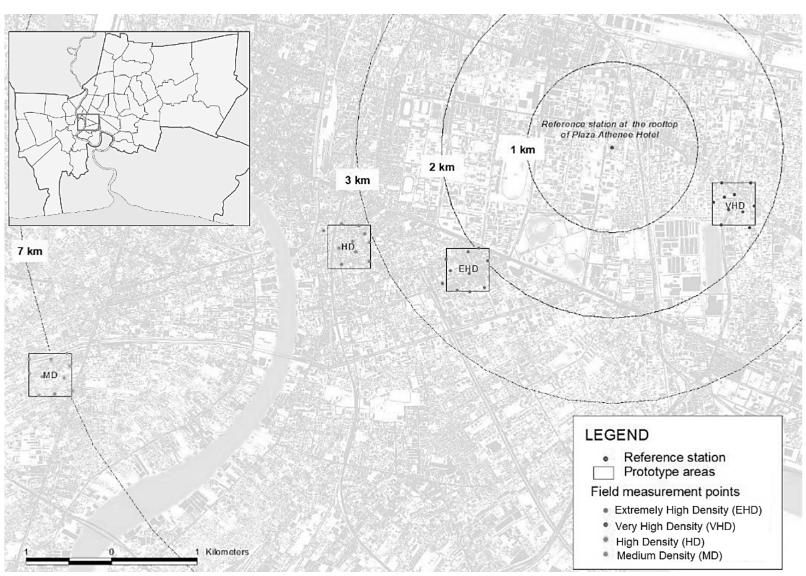

Figure 2. Location of four climate zones to simulations in ENVI-met to determine the software's capability to analyzing cooling from trees and a fixed reference weather station.

as in the urban center or compact high-rise was located in Silom district, the central business district of BMA (Figure 2 and Figure 3).

2.2 Field measurement

Two types of field measurements are used for the verification. The first one is an on-site spot measurement covering spatially distributed locations considering the spatial variation of the local climatic condition of the site. On-site field measurements were conducted between 10:00 and 14:00 local time during April 16th to May 26th, 2012 in summer. This period was used to obtaining variable climatic data during peak daylight hours in the summer. Each study sites more than 10 observation points were selected. Two different sets of mobile meteorological instruments were used in this study, including (Figure 4a). The first instrument, an Amenity Meter (AM-101), was placed on a camera tripod and contained sensors that simultaneously measured air temperature and relative humidity (RH). The wind velocity sensor was capable of measuring outdoor convection air speeds of between 1 m/s and 5 m/s with an accuracy of 0.5 m/s. A 38 mm diameter black globe thermometer was used to measure the globe temperature. The second instrument, a pyranometer UIZ-PCM01, was connected to a UIZ3635-50mV data logger that recorded data every 10 s. The accuracy range of these instruments agreed with ISO recommendation 7726. To consider thermal effects at the pedestrian level, these instruments were installed at a height of 1.5 m above the ground and were calibrated before on-site operation. Up to 10 min occurred between measurement points. The second one is a tall tower meteorological monitoring of a reference station that is operated by the Friend in Need (of "PA") Volunteers Foundation, Thai Red Cross was used to acquire climate conditions as providing insight into the hourly mean air temperature and relative humidity, with consideration to 5-year intervals (as shown in Figure 4b). This station was used to obtain other climatic parameters, such as wind speed and wind direction with an anemometer.

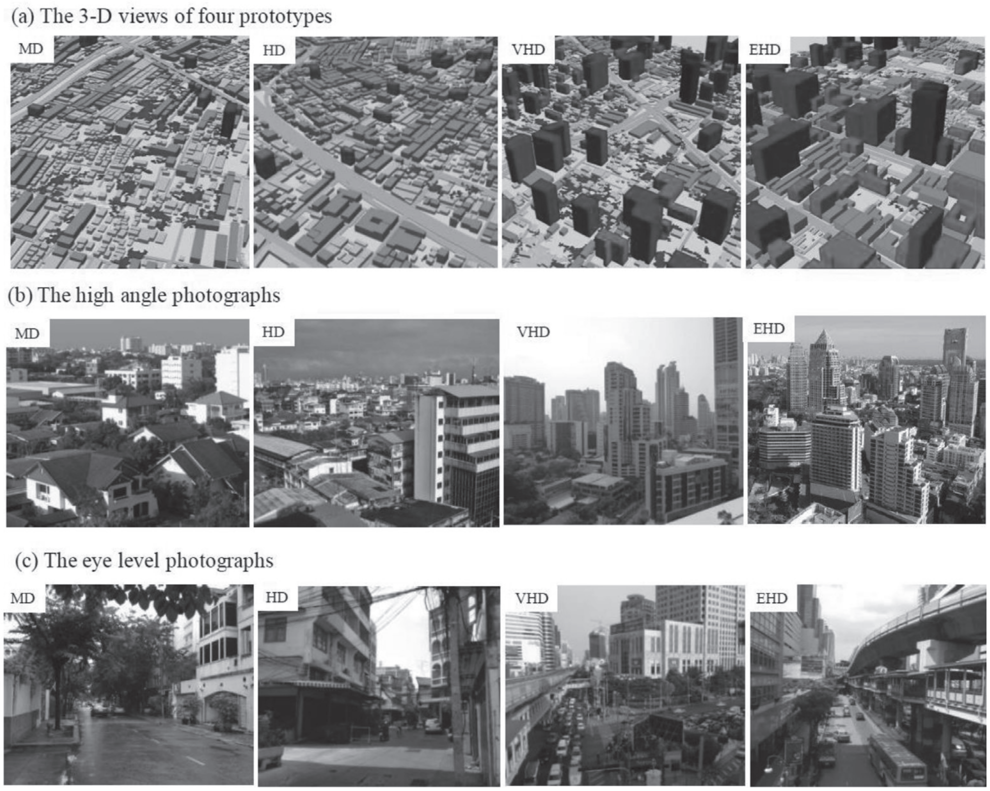

Figure 3. The four urban field sites characteristics is selected as the prototypes with obvious differences urban form properties: (a) 3-D views, (b) high angle photographs and (c) eye level photographs, Including medium density (MD), high density (HD), very high density (VHD) and extremely high density (EHD).

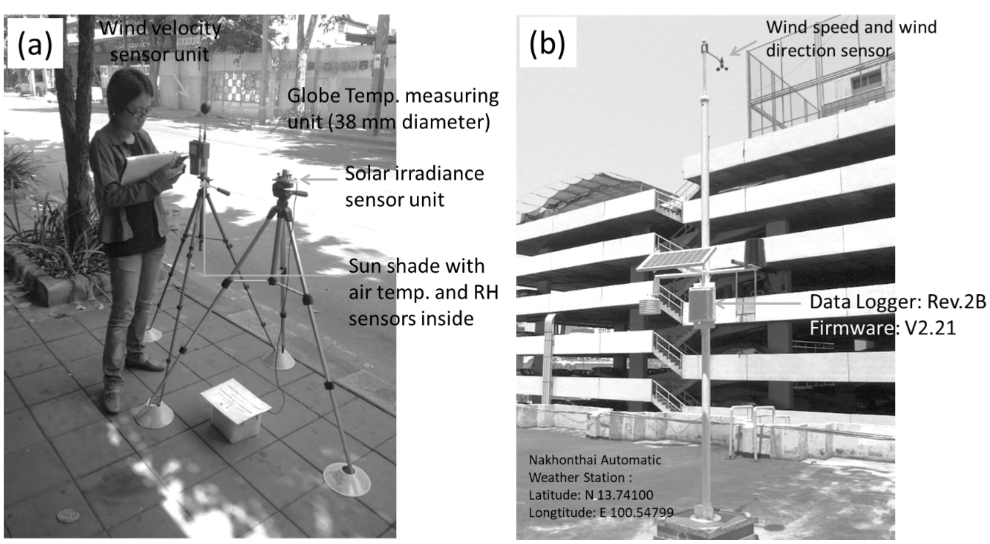

Figure 4. (a) Set of mobile meteorological instruments, including an (a) amenity meter AM101 and pyranometer UIZ-PCM01, and (b) reference fixed weather station that was operated by the Friend in Need (of "PA") Volunteers Foundation, Thai Red Cross.

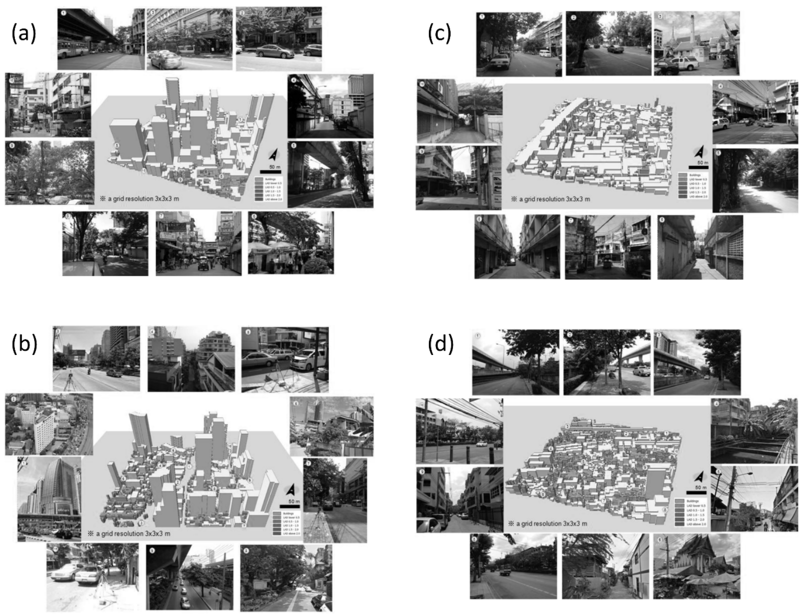

Figure 5. Initial ENVI-met model geometry settings with different environments in the area of: (a) EHD, (b) VHD, (c) HD, and (d) MD.

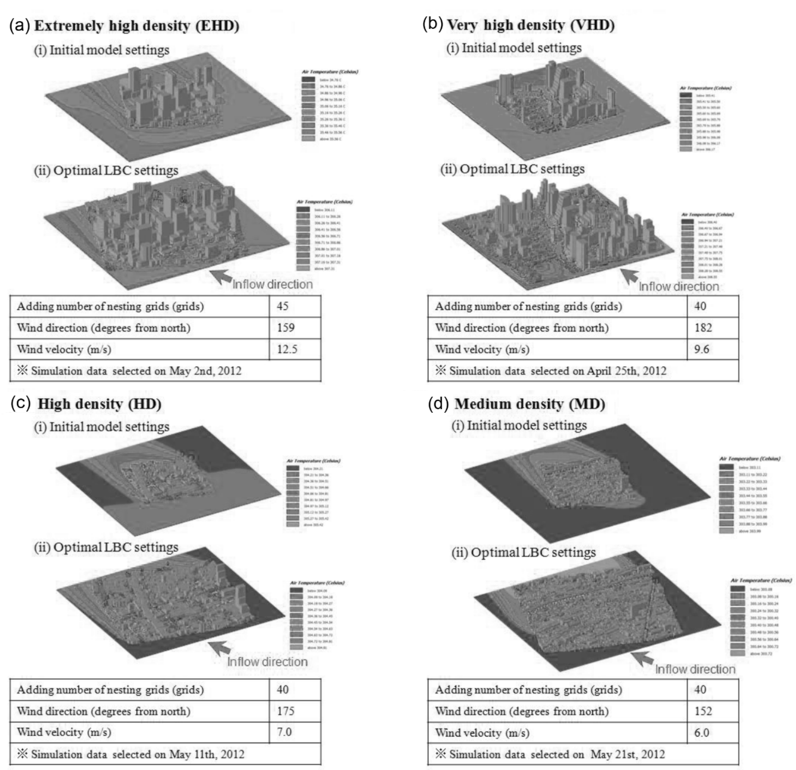

Figure 6. Process of achieving valid ENVI-met model for each area: (i) initial model settings and (ii) calibrated model settings.

2.3 ENVI-met model calibration and validation

The urban's morphology influence on the air temperature distribution in a built up area can be studied through climate models using the 2D/3D geometry of the city by using ENVI-met model. For the ENVI-met model geometry settings in this study, the simulated base model domain was constructed based on aerial images. In addition, a geo-referenced building footprint map in the area of interest was used, which was made available in digital geographic information system (GIS) data format by the Department of City Planning and Urban Development, Bangkok Metropolitan Administration. Each domain model area spanning 300x300 m, there was the configuration of the mesh of a 100×100 cell grid, notably encompassing a horizontal grid of 3×3 m. The cell grids' vertical size was 3 m for each area (Figure5).

The ENVI-met model is a variation of the CFD (Computational Fluid Dynamics) model. The accuracy of this model depends on a set of boundary conditions that are not reliable at the model boundaries and need to be determined to improve the accuracy of the model. Thus, we can move these borders (by adding any grids as nesting areas) as far away as possible from the core area of interest. The aim of the systematical calibrated ENVI-met model for outdoor environments is to predict the environmental conditions that agree with the on-site measurements. The input parameters are varied to simulate the environment accurately (Srivanit and Hokao, 2013). Thus, each initial ENVI-met models were created based on the actual site geometry and on the on-site field measurements (as shown in Figure 5). Next, the computational domain size was evaluated. Various runs of the initial ENVI-met model were performed with different numbers of nesting grids. These simulation results were verified to analyze the on-site measurements of climatic conditions.

Site	Paired Differences			95% Confidence Interval of the Difference		*t*	*df*	*Sig.**
	Mean	Std. Dev.	Std. Error Mean	Lower	Upper			
1. EHD	0.003	0.329	0.104	-0.232	0.239	0.031	9	0.976
2. VHD	0.078	0.450	0.142	-0.244	0.400	0.546	9	0.599
3. HD	0.050	0.175	0.055	-0.076	0.175	0.895	9	0.394
4. MD	0.059	0.228	0.072	-0.104	0.222	0.818	9	0.434

Note: ** Significant at 0.05 level (2-tailed)*

Table 1. Paired samples test for the validation criteria with air temperature that compare the on-site measured and calibrated data from each ENVI-met simulation model.

The model was improved by setting the inflow wind boundary as the average mean wind speed and direction. In the final validation stage, the model validation is accepted when a minimum mean of difference occurs between the field measurement and simulated results (Figure 6).

After the calibration process, a paired t-test was used to determine if a significant difference occurred between the average measured values that were made under different conditions (between the values measured on-site and the simulated values). The t-test results from the validation criteria display the relationships between the paired differences within a 95% confidence interval. Table 1 indicates that the significance value (Sig.) is greater than 0.05. Thus, no significant difference occurred and the null hypothesis cannot be rejected. Therefore, the calibrated ENVI-met model predictions agreed with all validation criteria and accurately represented the real environment (Figure 7). Each ENVI-met model results that accurately represented the real environments, which were accepted after the systematic calibration process, are illustrated in Figure 8.

2.4 Assessing the cooling effectiveness of trees

The tree type that was used to replace the existing situation was Pterocarpus indicus (also called "Padauk"), which is one of the most common trees at the BMA (Thaiutsa et al., 2008). It is desirability as an appropriately sized species that provides shade and has few management problems.

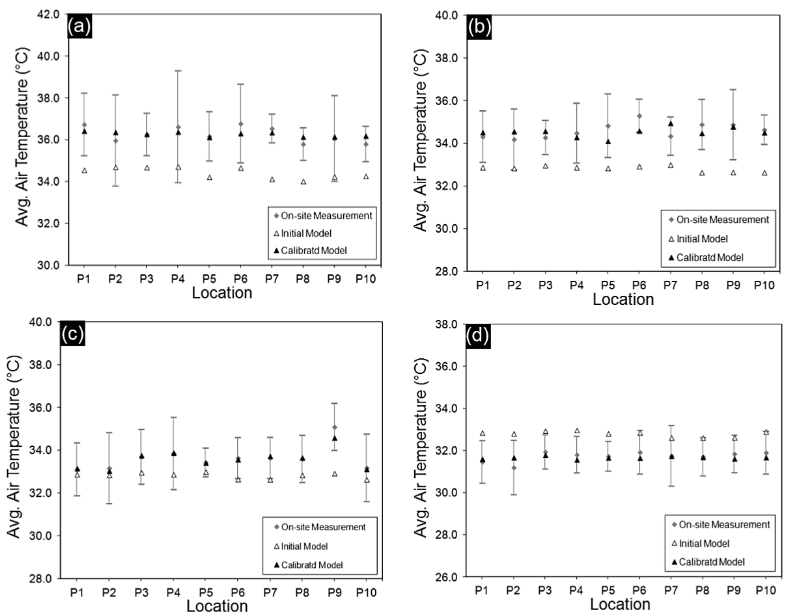

Figure 7. Comparison of the simulated and measured air temperature results in the area of: (a) EHD, (b) VHD, (c) HD, and (d) MD.

The majority of these trees often reach a height of approximately 10 m dense distinct crown trees and Leaf Area Density (LAD) for each height segment from bottom-up are 0.075, 0.075, 0.075, 0.075, 0.250, 1.150, 1.060, 1.050, 0.920, and 0 m^2/m^3, respectively. A total of 40 study cases were tested by varying a 10 percent increase of green plot ratio (GPR) in the hottest places for each area. To compare how GPRs influence the outdoor thermal environments, we extracted 1.5m air temperature at the hottest time in the summer afternoon (14:00) for all urban form prototypes. We selected the area of evaluation at the model domain area (Figure 5) and calculated the mean temperature of their entire all mesh cells to represent the neighborhood temperature.

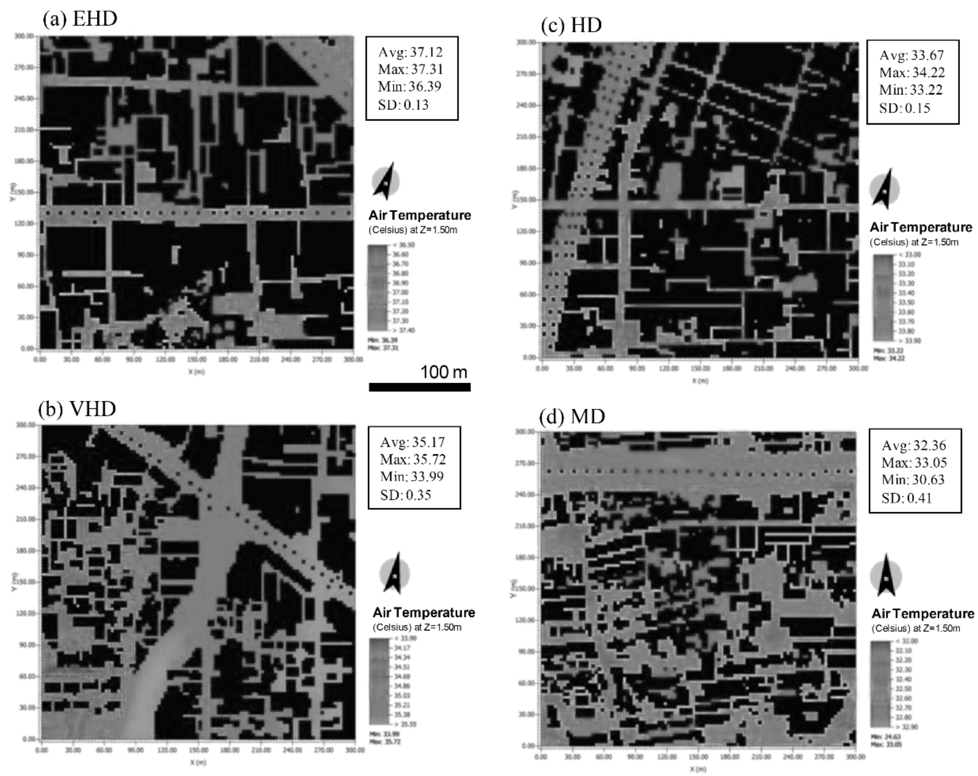

Figure 8. The ENVI-met model results that accurately represent the real environments that accepted after the systematically calibration process in each domain model area.

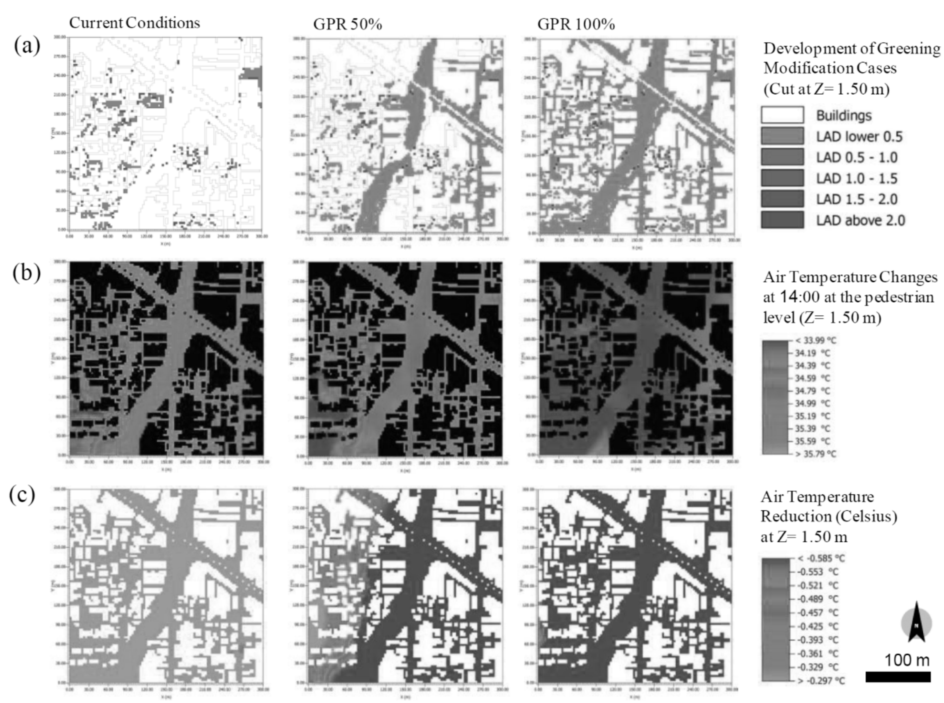

Figure 9. An example of the cooling potential of greening modifications that more effectively by GPR in a very high density prototype area:
(a) modification conditions,
(b) near-surface air temperature changing and (c) air temperature reduction form current condition.

Results associated with the different tree arrangement for differentiating urban forms were compared and evaluated in a peak temperature on 2 May 2012 at 1.5 m for each area (Figure 9).

3. Results and Discussion

Figure 9 shows the simulated air temperature comparison in each area at 14:00 at 1.5 m. It's was that the average air temperature is reduced during the peak heat of day by 0.02°C–0.12 °C by increasing GPRs from 10% to 100% (Figure 10 and Table 2), very high density (VHD) form is more efficient than other forms in reducing the air temperature with maximum differences of up to 1.2 °C (see Figure 11b). The reductions of the temperature vary linearly with the increasing GPRs, but slightly linearly with the increasing GPR of EHD. This study also shows that initial cooling potential for trees does not have less substantial cooling effectiveness on the EHD. Finally, maximizing trees improve urban thermal environment by reducing the average air temperature by up to 1.18 °C, 0.41 °C, 0.36 °C and 0.30 °C for VHD, HD, MD and VHD respectively at the pedestrian level.

Our simulation model demonstrated that effective amount of trees by green plot ratio (GPR) can improve outdoor thermal environments. The research results first confirm that despite various urban forms and tree planting was in general beneficial by the temperature reduces to take best advantage of the cooling benefit of the local climate and cooling extend, also helps to reduce the urban morphology's contribution to the urban heat-island effect at BMA in the summer. Further, the comparison between different GPRs and urban forms reveals the importance of arranging tree patterns. Further, the comparison between different GPRs and urban forms reveals the importance of the planting arrangement of tree patterns.

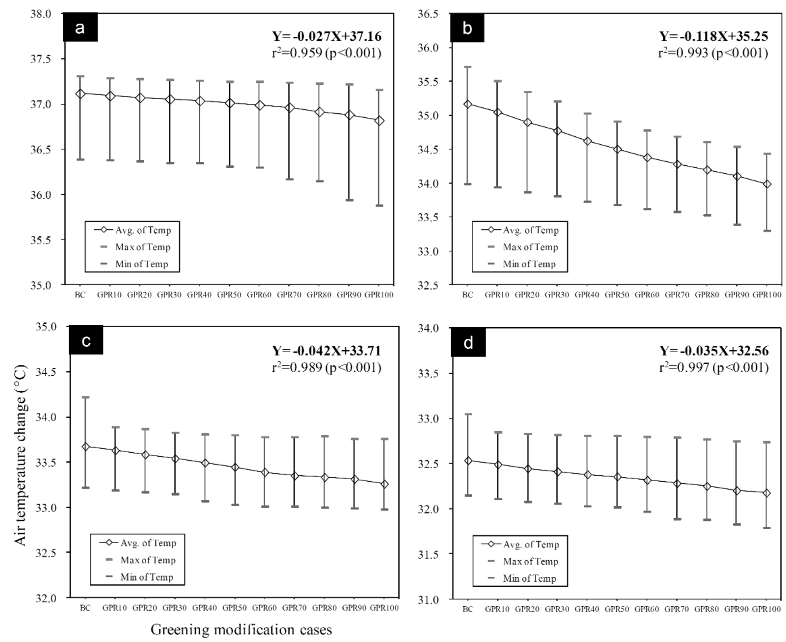

Figure 10. Error-bar charts of the simulated air temperature comparison under different the amount of GPRs in each area; (a) EHD, (b) VHD, (c) HD, and (d) MD.

Table 2. Summary of linear regression equations based on air temperature and GPR.

Climate-sensitive urban forms	Linear regression equations	R^2	*Sig.*
EHD	Y=-0.027X+37.16	0.959	<0.001
VHD	Y=-0.118X+35.25	0.993	<0.001
HD	Y=-0.042X+33.71	0.989	<0.001
MD	Y=-0.035X+32.56	0.997	<0.001

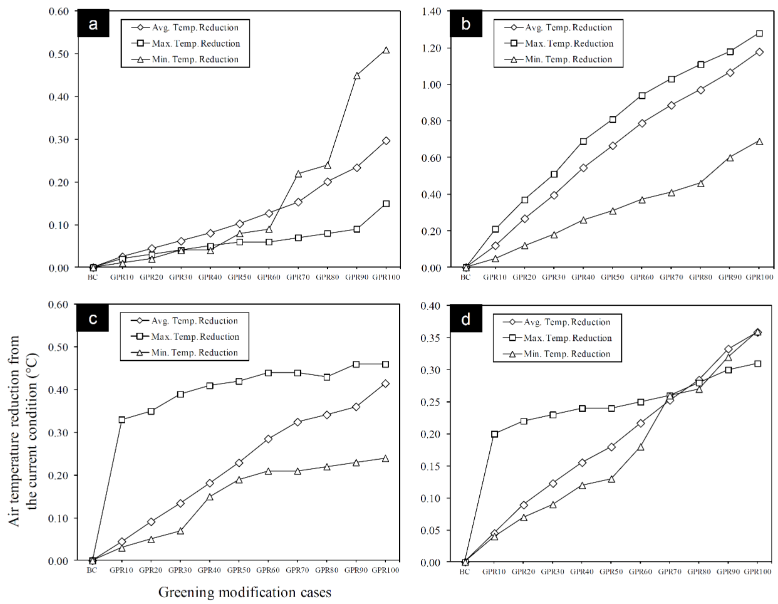

Figure 11. Cooling effectiveness of GPRs at 1.5 m of air temperature calculated by ENVI-met in the area of: (a) EHD, (b) VHD, (c) HD, and (d) MD.

4. Conclusions and recommendations

Trees provide important benefits to outdoor thermal environments in the hot-humid climate. This research uses microclimate numerical simulation to explore how the volume of tree coverage to benefit urban neighborhoods. The flexibility of numerical models makes it possible to simulate and compare the urban microclimates under a wide range of tree volumes. This research is one of the pioneering attempts to explore the importance of tree coverage and canopy volumes, and investigate cooling benefits for different climate-sensitive urban neighborhood forms. The research results will help guide the design of urban vegetation and GPR regulations for the long-term sustainability of urban desert environments. The present study has certain limitations in the following aspects: (1) measurement period and (2) tree diversity. First, our measurement period only covered just a reference day of the hottest month in Bangkok. A longer sampling period, preferably the whole season, is required to collect a more representative set of data. Second, this study only focused one single tree species. Other trees with different dimensions, leaf area indices and physiology are also worth investigation to provide more species options for urban landscape designers, which can indirectly augment species diversity in the climate of tropical cities. Although urban tree plantation may incur certain management costs, the collateral ecosystem services and socioeconomic benefits provided by urban trees should also be taken into account in the decision process. Further analysis of the life-cycle costs and benefits of a tree and a human-made shelter as a landscape element in urban areas will be useful for urban planners.

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