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To cite this article: Wanlu Ouyang *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **329** 012043

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The Cooling Efficiency of Urban Greenery Coverage in a High-density City

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Abstract. Urban greenery especially trees has been identified as one of the most effective measures for urban climate moderation through the mechanism of evaporative cooling and shading. For subtropical high-density cities like Hong Kong, intense heat stress arises from the compact urban form, poor ventilation, and the high percentage of impervious urban cover. Thus, concerted actions are being taken to harness the cooling potential of urban greenery for improved microclimate. However, the cooling effects of urban greenery vary based on multiple factors, including background climates, urban morphology, anthropogenic heat emission, vegetation types and quantity, etc. This study aims at quantifying and comparing the cooling efficiency of different urban greenery coverage for a typical residential neighbourhood in Hong Kong. The questions guiding our research are: what is the relationship between tree coverage and ambient environment, including air temperature and thermal comfort during a typical summer day in the selected neighbourhood? To achieve this objective, we employed a previously validated ENVI-met model setting of a typical summer day to conducted parametric studies of cooling benefit of variable tree coverage ratio from 0 to 30% at the interval of 2% on a typical summer day. The results verified the greenery had a higher cooling potential during period of maximum temperature than the whole diurnal time, 1 °C and almost 0.8 °C respectively for air temperature. This study also showed that increasing greenery coverage indeed lowers diurnal temperatures, but this relationship is logarithmic instead of linear. The ratio of change in cooling effects to greenery increase and then decreased gradually. Between the coverage ratio of 8%-35%, the cooling potential would be underestimated in a linear relationship. Greenery measures may lead to ineffective results if greening principles have not been comprehensive understood, such as greenery abundance, composition and types. The present study allows urban planners and managers to understand more in greenery amount for urban micro-climate in high-density cities.

Keywords: Urban greenery; ENVI-met; High-density cities

1. Introduction

Urban heat island (UHI) describes a phenomenon of higher temperature within urban areas is apparently higher than surrounding rural areas [1], which is attributed as the outcome of urbanization, abundant impervious surfaces and increasing anthropogenic heat emission [2]. Extensive and rapid urbanization also increase both the city size and urban density. With compact urban form and concentrated population, multiple benefits have been brought up, such as maximizing the potential of land resources, reducing transportation costs, etc. However, compact urban development without proper guidance in planning and design can lead to serious thermal stress and damage residents' health and wellbeing [3].



Hence, there is a pressing need to evaluate mitigation and adaptation strategies for UHI in the context of high-density.

As one of the main strategies to mitigate UHI effects, there is a growing interest in applying urban greenery into urban planning and design for climatic regulation [4]. Previous studies have proved urban greenery can attenuate urban overheating by reducing daytime heat storage and facilitate night-time heat cooling [5]. Through the mechanisms in surface shading, evapotranspiration, and wind pattern alteration [6], temperature regulation effect of urban greenery have been reported to be 1-7 degrees [7, 8]. Nevertheless, our knowledge in the most optimum types, abundance and distribution of urban greenery that is necessary to alleviate heat at neighbourhood and street canyon levels is still insufficient [9]. In addition, the effectiveness of urban greenery to certain urban and neighbourhood contexts has not been fully assessed [10]. Specifically, in high-density cities like Hong Kong, most of the land is covered by buildings and roads, where there is limited land resources for greenery. In hot-humid climate, the main contribution of urban greenery is shading, and increasing humidity and reducing speed at pedestrian level are undesirable from the thermal comfort perspective [11].

Therefore, the main research question guiding this study is: what is the relationship between tree coverage and thermal environment during daytime in summer, for a typical residential neighbourhood in Hong Kong? To answer this question, parametric studies based on a validated ENVI-met model setting were conducted. The contribution of this study lies in extending our understanding in urban greenery quantity and its benefits in climatic regulation. Although this study was taken in Hong Kong, the result of it can be a reference to other cities in high-density and subtropical regions.

2. Methods

2.1. Model's description

ENVI-met is a holistic, three-dimensional, non-hydrostatic, and grid based microclimate model, which is designed for simulating the complex interactions among surface, vegetation and air in urban environment. Been constantly evaluated as acceptable accuracy for simulating bio-meteorological conditions, it has been widely using in micro-climate and greenery studies [12]. ENVI-met V4 was firstly released in 2010 [13], and was applied for numerical simulations in this study. The main inputs for ENVI-Met are buildings and vegetation elements, ground and wall surface properties, initial soil temperature and wetness profiles, as well as meteorological data. The outputs of this model include variety of climatic parameters, such as air temperature, relative humidity, mean radiant temperature, and thermal comfort index like PET, PMV, and UTCI, etc.

2.2. Model validation

Numerical models need observation to initiate and validate the simulations for synthetic weather conditions [14]. In this study, we have applied the validated settings of a typical extreme summer day in Hong Kong in which the simulated and measurement air temperature (AT), and mean radiant temperature (MRT) comparison where reported [15]. Their results reveals a good correlation of $R^2 = 0.79 - 0.81$ and $0.70 - 0.74$ for AT and MRT respectively between the measured and simulation results which corresponds to a low RMSE and MAPE¹ of 3.7% (for tree-shaded Ta), 5.1% (for unshaded Ta), 7.7% (for tree-shaded MRT) and 13.2% (for unshaded MRT).

¹ RMSE: Root Mean Square Error; MAPE: Mean Absolute Percentage Error

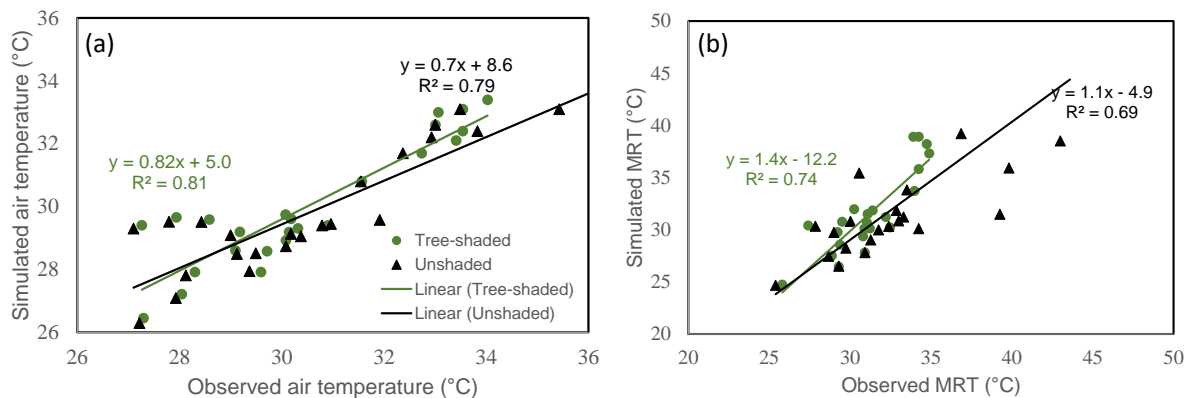


Figure 1. Relationship between ENVI-met simulated and observed (a) air temperature and (b) mean radiant temperature, MRT at tree-shaded and unshaded location on a typical summer day (Source: [15])

2.3. Experimental design

2.3.1. *Model initialization.* Mong Kok is a typical densely built district in Hong Kong with a high population density of 130,000 /km² [16]. This area is featured with high commercial towers with residential buildings and is characterized as LCZ-1 [17]. This study was based on a simplified neighbourhood where the building height is 30 meters on average, street width is 20 and 32 meters, and building coverage is 44%. The simulation domain contains 170 × 200 horizontal grids at 4-meter resolution, which equal a 680 × 800 m² domain. And there were 27 vertical grids were 1-m resolution with 15% telescoping after 2 meters building height. In addition, 10 nesting grids were added around the simulation area to ensure enough space between buildings and model border. A schematic layout is shown in Figure 2.a.

2.3.2. *Experiment scenarios.* The parametric studies include 16 scenarios -one reference consisting of only street and building elements without no greenery, while the remaining contains greenery coverage increasing from 2% to 30% at 2% interval. The building coverage ratio was set as 44% and constant in all scenarios. The initial meteorological conditions came from Hong Kong Observatory², which is a government department for weather forecast and meteorological information provision. In this study, a typical extreme hot day was chosen as the simulation day for the meteorological conditions because 2016 has the 38 very hot days (daily maximum temperature ≥ 33.0 degrees), which has been the highest records since 1884. Therefore, a typical extreme hot day with meteorological conditions in initial air temperature as 29.6 °C, initial relative humidity as 87%, wind in east direction and speed of 3.75 m/s, which was similar to that of the validation study, was adopted and used as the initial condition for parametric simulations.

In this study, *Aleurites moluccana* was selected for the main tree species for the following reasons: 1) it has a high air cooling capacity in the previous studies [15]; 2) It is a common landscape tree in the residential sectors in Hong Kong [18]. The tree height, trunk height, crown height, crown width and leaf area index (LAI) were obtained from a study [15], which was listed for details in Table 1. The tree model was built in the 3D vegetation module in ENVI-met at the basis of pixel. Besides, in order to exclude the effects of the spatial composition of urban greenery, the trees were located evenly throughout the whole domain (Figure 2.b). To show the experimental setting as well as the scenarios, Figure 2 shows the configuration setting as well as the analysis domain.

Table 1. Tree parameters in the model

Tree height	Trunk height	Crown Height	Crown Width	LAI
9 meter	3 meter	6 meter	7 meter	2.77

² HKO website: <https://www.hko.gov.hk/>

2.3.3. *Statistical analysis.* The analysis domain cut the surrounding building pixels and minimize the edge-effects furtherly (Figure 2.b). The simulation results were extract from LEONARDO and the analysis parameters include air temperature, relative humidity, mean radiant temperature, and thermal comfort index PET. The pre-processing was implemented with a VBA code and visualized in R software. The statistics showed distribution pattern of the climatic parameters within the neighbourhood and across both diurnal period (09:00-17:00 local time), and period of maximum temperature (14:00-15:00 local time).

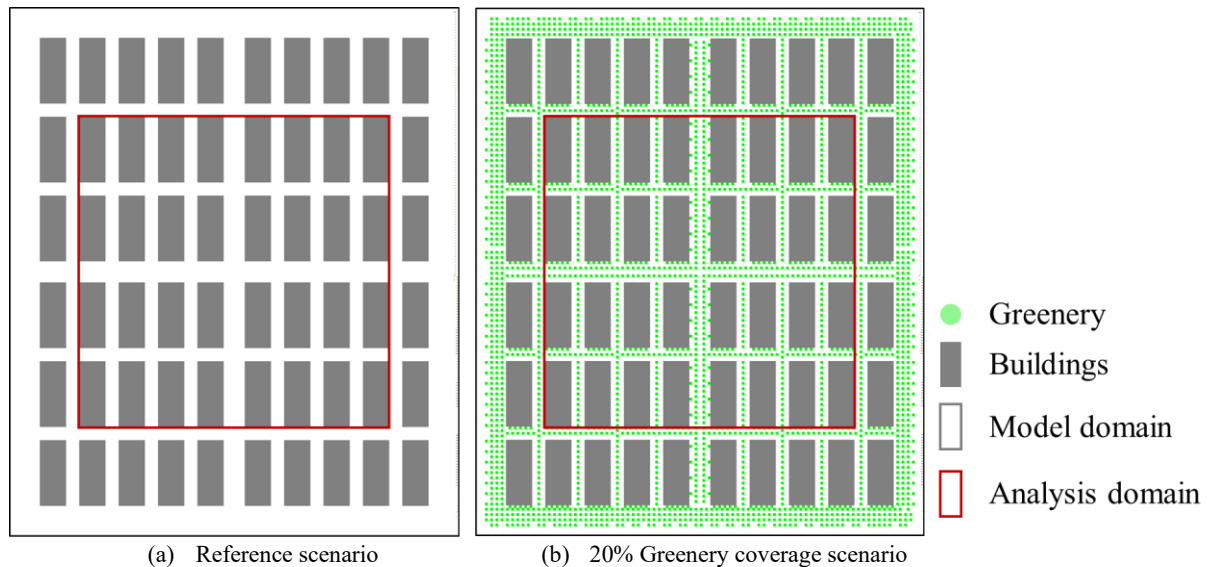


Figure 2. Model schematic layout and scenarios examples (Building coverage ratio = 44%)

3. Results and Discussion

3.1. Cooling Effects of urban greenery

Extracting the data within the analysis domain (Figure 2), the average values for air temperature (AT), Universal Thermal Climate Index (UTCI), physiological equivalent temperature (PET) were calculated for different greenery coverage ratios. The cooling magnitude during the period of maximum temperature (14:00 – 15:00) was larger than that in the whole diurnal time (9:00 – 17:00). The maximum AT reduction could be 1 °C for the whole area compared with the base case without greenery, which fit the range indicated in a previous study in Hong Kong [3]. As for outdoor thermal comfort, the thermal benefits reached over 2 °C and 8 °C for UTCI and PET, respectively. All these highest cooling potentials were achieved by the 56% coverage, which means that the resting areas besides buildings were covered as greening.

3.2. The relationship between greenery coverage and cooling effects

Based on the trend pattern of R^2 , the relationship between greenery coverage and its cooling benefits was logarithmic than linear as shown in Figure 3. The pattern increased sharply as the greenery coverage ratio increased within the lower end of the coverage range, and the rate slowed down gradually with the coverage increasing. When greenery coverage reached between 20-30%, the cooling benefits seemed to level off. The results in this study kept corresponding to Grimmond's findings [19]. They simulated and compared surface energy balance among a dozen cities in North America, noting that proportional latent heat flux came to be stable when the vegetated fraction reached 0.2-0.3. If there were less coverage classes, the relationship would be recognized as linear and the cooling effects would be overestimated between the coverage of 8-35%. Therefore, our study illustrated the necessary to conduct parametric study at fine interval of greenery coverage.

However, there are also other studies indicating that there was linear relationship between greenery coverage and air temperature. In a study for hot and arid climate, a parametric study was conducted for air temperature at 3:00 pm local time and tree coverage ratio [10]. This study found there was a strongly linear relationship between these two factors. The reason for the contradiction between findings of our study and reference study is possibly because the difference background climate. In the arid climate, greenery provides cooling effects through both shading, evapotranspiration, while for subtropical climate in our study, higher humidity decreases the cooling rate and effects.

In addition, the trend of PET was not identical as AT and UTCI, it showed generally no pattern among different coverage ratio. One possible reason is that the PET is more sensitive with wind speed than UTCI. Another explanation for this different is that the standard clothing index ($clo = 0.9$) for PET, and UTCI adjusts clothing based on meteorological conditions accordingly. These should be tested in the future studies.

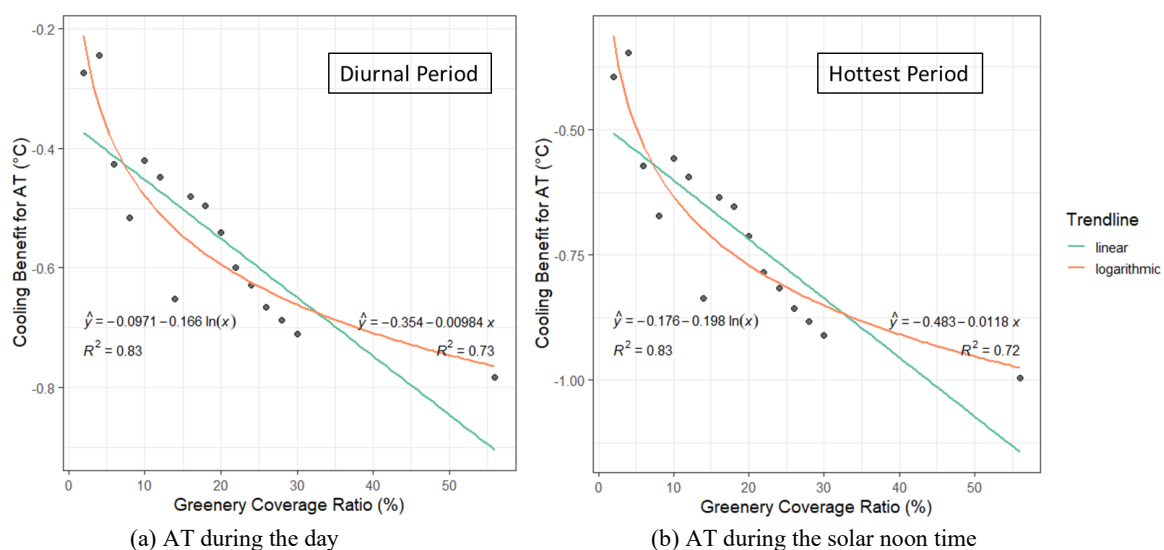
Besides, only one species of trees was used for simulation and analysis. The selection of species was referring to a previous study in Hong Kong, which compared different cooling performance of tree species with different height and LAI [15]. Considering the objective of this study is to explore the cooling efficiency for street trees, it is acceptable to conduct parametric studies in controlled variables. Further studies could explore the sensitivity in tree species with different features, as well as boundary conditions, grid resolution and time-interval for simulations for uncertainty analysis and testing.

4. Conclusion

Based on previously validated ENVI-met model setting, this study conducted parametric studies for exploring the cooling effects regarding to different greenery coverage ratios. In the context of subtropical climate background and high-density urban form, a neighbourhood in Hong Kong was selected as a case study. The results showed that the maximized cooling magnitude of the trees was 1 °C and 2 °C and 8 °C reduction in air temperature, UTCI and PET, respectively.

With coverage ratio increasing, the cooling effects of urban greenery presented a logarithmic trend instead of linear as some previous studies indicated. The results in this study emphasizes the necessary of investigating the cooling potential of urban greenery within the lower end of the vegetated coverage ratio range. This is especially significant for a high-density context that is an irreversible trend, and for some places where land resources are limited.

In the planning standards and guidelines published by the Planning Department of Hong Kong, the green coverage is suggested to be 20-30% in the residential development. This study corresponded to this regulation and illustrated the scientific consideration for environmental design, as this range utilizes and maximizes the cooling efficiency of greenery.



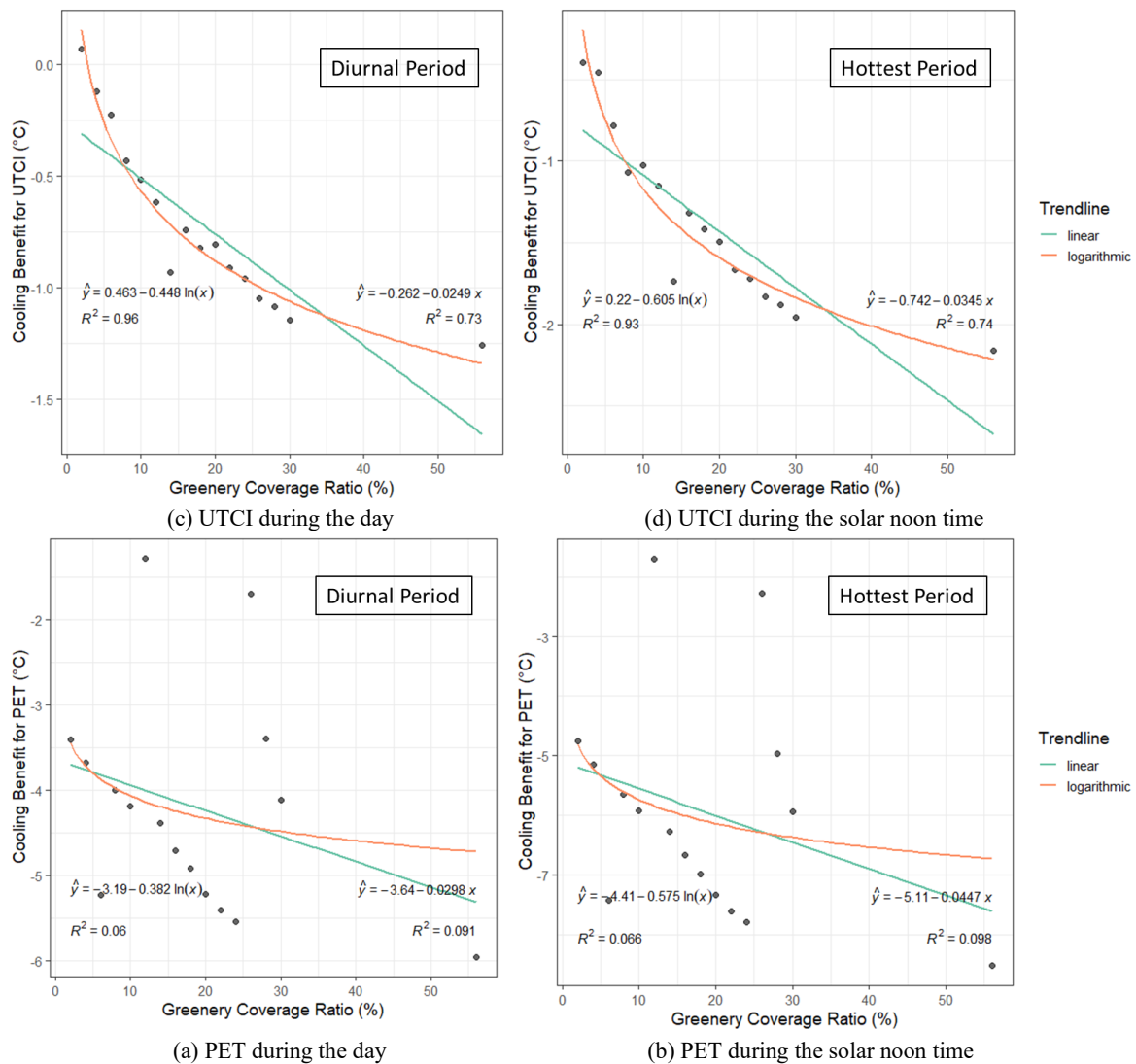


Figure 3. Logarithm patterns between climatic parameters and greenery coverage ratio (during the day refers 09:00-17:00 local time, solar noon time refers 13:00-14:00 local time)

Acknowledgments

This study is supported by the Post Graduate Scholarship (PGS) grant from The Chinese University of Hong Kong. Any opinions, findings, and conclusions or recommendations expressed in this article are those of the authors and do not necessarily reflect the views of the sponsoring agency.

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