ANALYSIS OF THE MICROCLIMATIC IMPACT OF GREENING IN HIGH RISE URBAN BUILT ENVIRONMENT USING SITE MEASUREMENTS AND SKY VIEW IMAGE PROCESSING TECHNIQUES

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Summary

Urban greening is believed to be capable of providing passive cooling by its shading and evaportranspiration[1]. High density in high rise milieu could influence greening cooling effects by altering solar and infra-red radiation exchange within so called urban canyons in ways differently with that within low rise settings. One of the most significant differences is that tall buildings can shade the greening at ground level instead of being shaded by them. In this scenario, an increase of built density could dilute cooling effect of greening by both shading and evapotranspiration in daytime, while increase of either building or tree canopy density could hamper irradiative cooling by reducing visible sky area at night. To test this hypothesis, site measurements at typical points in selected high rise residential developments in Shanghai is carried out. Microclimatic data and site-specific parameters are recorded in clear and calm days. A tool to measure built density and tree canopy density is developed using fish eye lens digital sky view imaging and WINSCanopy software. Temporal and spatial variations of microclimatic data are correlated to site parameters to evaluate their significant levels. The findings are useful for landscape and urban planning practice in high rise built environments with an aim to improve their bioclimatic performance and to mitigate urban summer heat islands.

1. Introduction

The economic booming of China is accompanied by the radical developments of many cities. However, the highest priority being given to economic growth in these cities causes various loads on the urban environment, which seriously affect the urban living standards. The urban heat island[2] is a particular phenomenon derived from these cities. It can give rise to many problems, such as the change of ecosystems of wildlife and vegetation, degraded outdoor thermal comfort, increasing number of heart stroke patients, expansion of infectious diseases (e.g. the SARS breakout in Hong Kong), and increasing demand for cooling energy consumption, and thus threaten the living environment and health of urban habitants.

Urban greening is believed to be capable of providing passive cooling by its shading and evaportranspiration (Kozlowski et al. 1997; Oke, 1987). But hitherto most of the relevant studies use built sites featuring low rise and high density, while study on greening cooling effect in high rise high density urban built environments, which are commonly found in modern Asian cities such as Hong Kong and Shanghai, is scarce.

2. Literature review

2.1 Previous research on cooling effect of urban greening

Bonan measured the microclimate of a low-rise residential area in a hot-arid climate, and found that plant species, water availability and housing density all contribute to forming a thermal-pleasing environment (Bonan, 2000). Shashua-Bar studies cooling effect of vegetation in various configurations of streets and small public spaces in cities with a hot-arid summer climate, by empirical modeling (Shashua-Bar et al. 2000). They conclude that site-specific effects (tree characters, site geometric configurations, water regime, etc.) are quite minor. This may be because that variation of site-specific effects among sites is small, and the finding could be different in a high-rise built setting in the subtropical climate of Shanghai.

The present study focuses on urban greening at micro scale. The aim is to assess the micro scale influence by greening as a joint function with other land use and built form variations. Unlike at larger scales, at micro scale, climatic impacts of greening is inevitably altered by urban built properties such as sky view factor,

[1] Evapotranspiration (ET) is the sum of evaporation and plant transpiration.
[2] The urban heat island is the temperature difference between developed areas and its surrounding undeveloped areas.

surface thermal properties, radiant environment, etc. (refer to Oke, 1989, for a detailed explanation of the energy exchange between urban trees and its street canyon environment.) Therefore, for study at this scale it is important to take all the above factors into consideration, for a comprehensive understanding of how greening performs in various urban settings. On the other hand, study of urban greening at this scale is scarce in sub-tropical Asian cities.

2.2 Research objectives

The present study aims to investigate the cooling performance of greening within a high rise residential development, and to understand the contribution of built density, land use and building layout to this cooling performance.

2.3 Brief description of the site under survey

The Brilliant City Project is located in Putuo District, Shanghai. The Suzhou River runs across by its southern side, and Shanghai Metro Line No.3 runs along its northern boundary. The site area is 49.5×10^4 m^2; the total floor area 160×10^4 m^2; Floor area ratio is about 3.2, and green cover ratio is 45%. The majority of the residential towers are at a height of 100m, the height defining high rise and super high rise buildings in China building codes. Because of the vast site area while the limit in man power and instruments, the site is divided into the east part and west part, divided by Zhongtan Road. Each site is to be surveyed on separated days.

Figure 01: Satellite image of the Brilliant City, Shanghai

3. Methodology

3.1 Selection of dependent and independent variables

Table 01: Lists of Dependent and independent variables

Descriptors	Independent Variables
Planning and Building design descriptor	Building View Factor (BVF) Sky View Factor (SVF) Ground Surface Albedo (AL)
Vegetation descriptor	Leaf Area Index (LAI) Tree View Factor (TVF) Green Coverage Ratio (GCR)
Natural descriptor	Wind Velocity (VW) Solar Radiation (SR)

Dependent variable: UHI_{day} and UHI_{night}, but only UHI_{day} is discussed in this paper due to page limit.

3.2 Measurement procedures

The site work can be divided into two parts: climatic measurement to record microclimatic variables such as temperature, wind speed, solar radiation etc. and site survey to measure design variables in planning, building design and land-use descriptors (Table 01) .

3.2.1 Climatic measurement

Measurement was carried out in Brilliant City West (referred to as BCW hereafter) on 26 September 2007 and in Brilliant City East (BCE) on 27 September 2007. In BCW 15 measurement stations were selected, and in BCE 14 stations. The criteria of selection are to maximize the possible variations in planning and design and land use variables. The overall sample size is 29.

The climatic condition of the dates under measurement is summarized in Table 02. Compared with institutional data, the on-site observation found that on 26 September it is quite cloudy, and mean solar radiation intensity measured on site (1pm to 6pm during mobile measurement) is 316.45W/m^2. It is considerably lower than 393.82 W/m^2 of 27 September.

Table 02: Climatic conditions on the survey days (from 0600 hours to 2200 hours)

Date (Sept.)	Air Temp. (^{o}C)			RH (%)	Cloud Cover (0800, 1400 and 2000)			Wind Velocity (m/s)		Solar duration (hr)	MSR (MJ/m^2) (0600 - 1800)
	Max	Min	Ave	Ave	08	14	20	Max	Ave		
26	29.7	21.8	26.6	77.1	7	4	0	2.6	1.48	8.4	1.50
27	32.3	23.7	28.6	72.5	1	3	0	2.9	1.24	8.6	1.50

Note: MSR - Mean hourly solar radiation
Data source: Shanghai Observatory

Among stations in each site, a pair of two stations was selected with similar building but different greening surrounding environments. A pair of Hobo weather stations was installed at these two stations, which records air temperature, relative humidity, wind speed and global solar radiation from 6am to 10pm at the height of 1.5m above ground. Another weather station was placed on rooftop of one of the residential buildings on site at the height of about 100m above ground. As it has the minimum obstruction of view to the sky, it is used as a reference of global radiation received on site. The effect of aerosol on radiation reduction is not considered in the study.

The rest of stations were covered by mobile measurement. Handhold Kestrel Pocket Weather Tracker was used to record air temperature, relative humidity, wind speed and wind direction 1.5m above ground. Mobile measurements covered the period from 1PM to 10PM and were taken every two hours. Totally 5 rounds were made at each station.

All on-site measured temperature readings were calibrated on a pro-rata basis to match the record timing at Nanhui Observatory, which is located to the south-eastern of the site and in rural area. UHI at a station is then calculated using measured temperature minus temperature recorded at the same time at Nanhui Observatory. The average UHI of round 1, 2 and 3 (1pm to 6pm) is taken as the daytime UHI; the average UHI of round 4 and 5 (7pm to 10pm) as the nocturnal UHI.

Table 03: Specification of the instruments in use

Instrument	Model	parameter measured	Accuracy	Operating Range
HOBO weather station kits	Temperature/RH Smart Sensor: S-THB-M002	Ta, RH	± 0.2^{o}C over 0 to 50^{o}C; ± 2.5%RH from 10 to 90% RH	- 40^{o}C to +75^{o}C; below 95% RH
	wind speed smart sensor: S-WCA-M003	WV	± 0.5 m/s ± 3% at 17 to 30 m/s ± 4% at 30 to 44 m/s	0 - 44 m/s
	Global radiation sensor: S-LIB-M003	GR	± 2% at 45^o from vertical	0 - 1280 W/m^2 over a spectral range of 300 -1100 nm
Kestrel Pocket Weather Tracker	Kestrel 4000	Ta	± 1 ^{o}C	- 45.0 to 125.0 ^{o}C
		RH	3.0 %	0.0 to 100.0 %
		WV	Larger of 3% of reading or least significant digit	0.4 to 40.0 m/s

3.2.2 Site survey

Site survey was conducted to measure on-site design variables including Sky View Factor (SVF), Building View Factor (BVF), Surface Albedo (AL), and greening variables including Tree View Factor (TVF), Green Cover Ratio (GCR), and Leaf Area Index (LAI).

To measure SVF, BVF and TVF, Hemispherical sky images were taken at each station using Nikon fish eye lens and digital camera, and then the magnitudes of SVF, BVF and TVF of each station were calculated using the image by WinsCANOPY™ software.

Surface properties of an about $1000m^2$ area with a radius of 17-20m centred by each measuring point were elaborately recorded using a site survey form. These properties include percentages of soft and hard paving materials. In soft materials a sub-categorization was done to classify various vegetation (grass, shrub and tree) and water bodies. In hard paving materials, sub-division was done based on colour and paving materials. GCR is directly calculated from the surveyed data. LAI is estimated by surveyed data and other research findings on LAI (Ong, 2003; Scurlock et al. 2001). AL is estimated using surveyed data and other research findings on thermal properties of urban materials (Oke, 1987; Santamouris, 2001; Taha, 1997).

4. Analysis and discussion

4.1 Impacts of tree canopies and building canopies on radiation and temperature

4.1.1 Comparison of two stations

In BCE measurement on September 27, 2007, two stations with similar built canopies but different tree canopies, No.8 and No.9 were installed with weather stations to monitor and compare their micro climatic environments. The profiles of air temperature and global solar radiation were plotted and related to their hemispherical sky images. (Figure 02)

Figure 02: measurement point P8 （Left） and P9 (Right)

Table 04: Comparison of P8 and P9 in surface and geometry properties

Stn No.	Ground Cover proposition (%) (within 17m radius area of stations)						Geometry: View Factor (%)		
	Soft paving					Hard paving	SVF	CVF	
	Green Cover ratio	*Grass*	*Shrub (<1m)*	*tree (>1m)*	*Water*			*TVF*	*BVF*
8	45	*0*	*0*	*45*	5	50	27.79	13.73	70.03
9	55	*5*	*40*	*25*	5	40	15.14	39.03	68.69

Note: CVF: canopy view factor, including TVF and BVF.

4.2.2 Analysis and discussion

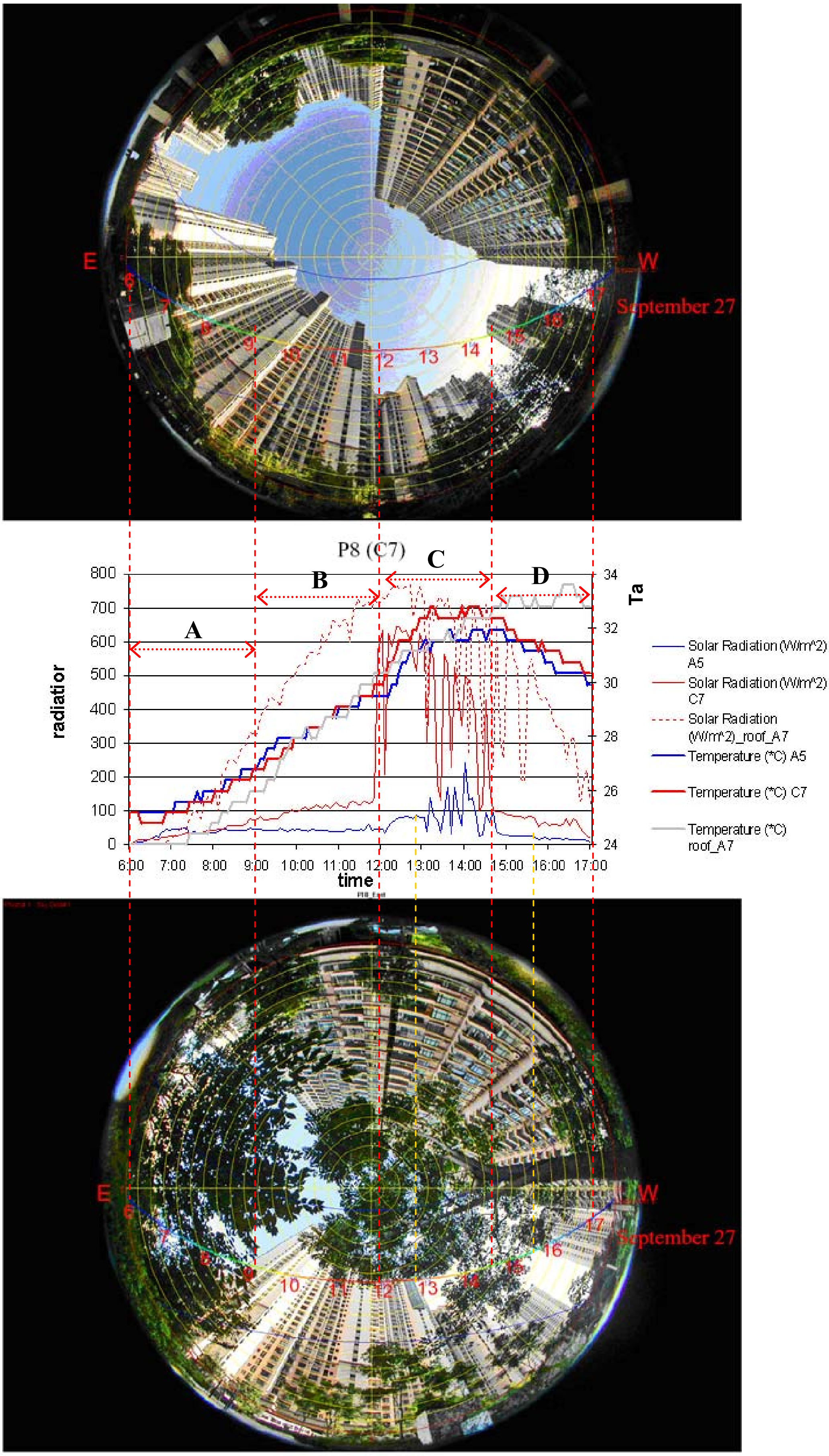
Other surface parameters being similar, the patterns of air temperature and globe radiation show significant variations due to different building and tree canopy densities (Figure 03):

6AM to 9AM (**Period A**): Temperatures show not much difference though T_9 is little higher (Max. 0.4^{o}C) than T_8 possibly because that shading by buildings blocks more solar radiation than tree canopies due to its porous nature.

9AM to 12AM (**Period B**): both points are shaded by buildings. T_8 grows up faster than T_9 and gradually outruns T9. This can be explained by the presence of tree canopies over P9: Although buildings intercept the same amount of direct radiation, tree canopies above P9 intercept a portion of reflected and diffused solar radiation (as can be seen from the Global radiation pattern), thus slowing its temperature increase.

12AM to 2PM (**Period C**): P8 is un-shaded and P9 is shaded by trees. The temperature shows significant differences (Max. 1.2^{o}C), as shaded P9 received much less radiation and thus are cooler than P8.

2AM to 5PM (**Period D**): both points are shaded by buildings. T_9 remains lower than T_8; the reason is the same with period B.



P9 (A5)

Figure 03: diagrammatic analysis combining sky view images and climatic patterns

Another comparison made at BCW yield similar findings. The above observation indicates tree canopy density as an important factor to lower air temperature, for its capability to intercept solar radiation, direct, reflected and diffused. Other greening factors such as grass cover and shrub cover seem not play an active role in environmental cooling. This is further discussed in the following section on regression analysis.

4.2 Multiple regression analysis

4.3.1 Daytime UHI in BCE: impact of greening variables

The first stage analysis focuses on each site, and regression was done using the six on-site design variables, in order to identify most significant combinations of variables. Because the main interest of study is on greening variables, the variable set containing three greening variables is used to build the base case model. (Because the R^2 of BCW model is quite low, only BCE model is presented in Table 05).

Table 05: Results of BCE regression analysis

	Coefficients					
	Model 1 (3 vars)	Model 2 (3 greening vars)	Model 3 (3 vars + SVF)	Model 4 (3 vars + AL)	Model 5 (3 vars + BVF)	Model 6 (all 6 vars)
Constant	*-1.135(.320)*	*2.595 (.000)*	*3.120 (.003)*	*3.564 (.000)*	*1.025 (.233)*	*-.586 (-.853)*
GCR	*.007 (.048)*	*.004 (.394)*	*.005 (.380)*	*.003 (.675)*	*.005 (.247)*	*.003 (.630)*
TVF	--	*-.025 (.101)*	*-.024 (.112)*	*-.028 (.053)*	*-.015 (.274)*	*-.010 (.550)*
LAI	--	*.225 (.264)*	*.151 (.499)*	*.309 (.117)*	*.103 (.567)*	*.196 (.349)*
BVF	*.041 (.006)*	--	--	--	*.023 (.061)*	*.036 (.173)*
SVF	*.023 (.111)*		*-.014 (.440)*	--	--	*.026 (.383)*
AL	--	--	--	*-3.909(.108)*	--	*-1.045(.716)*
R^2	.627	.385	.427	.546	.593	.674
F statistic	5.597	2.090	1.676	2.704	3.275	2.410
Case No.	14	14	14	14	14	14

Independent variable: UHI_{day}
Values in the parentheses are significant levels of variables.

As the first step stepwise regression is applied. The three most significant variables are BVF, SVF and GCR (Model 1). Secondly, regression analysis uses three variables representing variations in greening, i.e. GCR, TVF and LAI. The model generated explains 38.5% of variability in the dependent variable, and the F statistic is only 2.090, the model is not strong (Model 2). This suggests that variations in greening solely are not capable of explaining the majority of temperature variations. Based on this, the other three variables, SVF, AL and BVF were added to the model one at a time. It is found that, compared with Sky View Factor and Surface Albedo, the incorporation of Building View Factor significantly increase the R^2 (.593) and F statistic increases to 3.275. (Model 5) (In fact, in forward regression with sig. level set at 5%, only BVF is included in the model, with R^2=.379; F=7.330.) The model 5 suggests that an increase of 10% in Building View Factor increase UHI by 0.23%. As BVF indicates surrounding built density of the station, the finding shows the significance of including density parameters in study on greening in high rise built environments.

The magnitude of evapotranspiration (ET) of vegetation depends on the species of vegetation, local meteorological factors (solar radiation, temperature, air movement, humidity) and availability of moisture. In complex high rise building environment, ET of greening needs careful consideration. In all the five models in table 03, both coefficients of LAI and GCR show positive signs. This is possibly because that, for the outdoor area in Brilliant City, the ground is generally artificial surfaces with underground car parks. Unless regularly irrigated, the growing substrate for vegetation is usually shallow and unable to hold consistently enough water for one day period. During the survey, the author did not see any irrigating work in progress in the site. So insufficiency in moisture in soil could contribute to reduced ET of greening, and thus the cooling effect.

Further, as albedo tends to decrease with the increase of Green Cover Ratio and Leaf Area Index (Fig.04), so the stations with higher green cover and green biomass have higher net all-wave radiation, and thus more heat to dissipate (Grimmond et al. 1996). Since ET was suppressed as discussed above, the sensible heat fluxes were enhanced and so was higher the increase in air temperature.

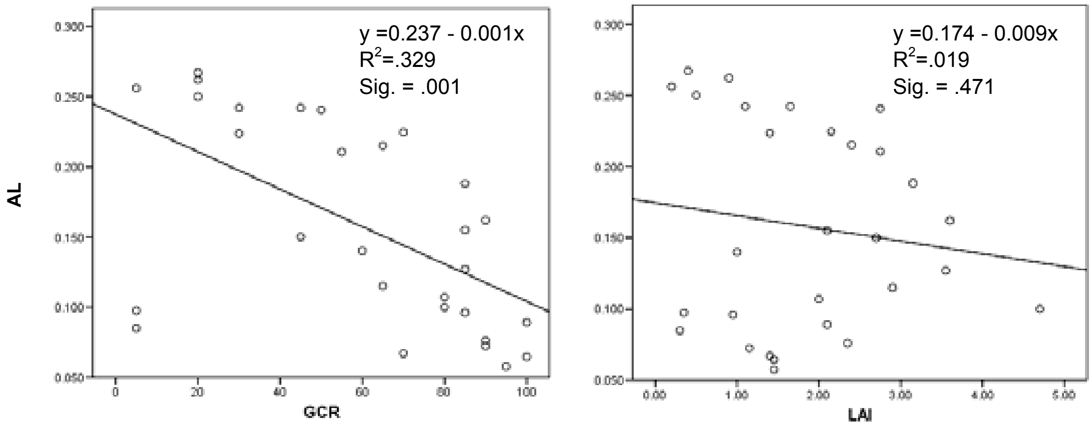


Figure 04: Albedo vs green cover ratio scatter plot (Up) and Albedo vs Leaf area index (down)

4.3.2 Daytime UHI in combined sites: impact of Building View Factor

Based on the findings from 4.3.1, the second phase regression analysis was carried out to test the hypothesis that high built density would dilute cooling performance of urban greening. All cases in two sites are included in the model, and natural variables WVD and SR are included. The results of regression models are presented in Table 06.

Table 06: Results of regression analysis with combined BCE and BCW

	Coefficients			
	Model 1: All cases (8 variables)	Model 2: All cases (4 variables)	Model 3: BVF<60% (4 variables)	Model 4: BVF>=60% (4 variables)
Constant	*-4.377 (.018)*	*-2.581 (.008)*	*-1.823 (.191)*	*-3.514 (.012)*
SR	*.013 (.000)*	*.014 (.000)*	*.013 (.006)*	*.017 (.000)*
TVF	*-.006 (.644)*	*-.018 (.047)*	*-.038 (.015)*	*-.007 (.551)*
LAI	*.110 (.447)*	*.129 (.209)*	*.467 (.025)*	*-.002 (.986)*
AL	*-1.162 (.515)*	*-1.377 (.312)*	*-3.650 (.114)*	*-.884 (.628)*
BVF	*.018 (.179)*	--	--	--
GCR	*.001 (.903)*	--	--	--
SVF	*.021 (.211)*	--	--	--
WVD	--[a]	--	--	--
R^2	0.667	0.631	0.745	0.768
F statistic	6.003	10.243	5.839	9.105
Case No.	29	29	13	16

Independent variable: UHI_{day}
Values in the parentheses are significant levels of variables.
Note: a. WVD is excluded from regression because of multicollinearity.

For linear fit estimation of each independent variable with the dependent variable, it is found the most significant variable is SR (R^2=0.525, F=29.827). The magnitude of SR in each site is the same, using the mean value from 1pm to 6pm. This finding suggests that despite variations in planning, building and greening descriptors, solar intensity still influences temperature pattern to a large extent. Secondly, stepwise regression was used to identify the variable set containing the most significant four variables. The four most significant variables are SR, TVF, LAI and AL (model 2 in Table 06). The model is totally different with model 1 in Table 05. This is because of the influences from the incorporation of SR and combination of cases of BCE and BCW.

As found in the previous sector, tree canopy cover intercepts solar radiation and helps lower air temperature. Therefore higher tree view factor should lead to lower UHI_{day}. In the BVF<60% model, the coefficient of TVF shows the right sign. While in BVF>60% model, although the sign remains negative, the coefficient is much smaller (-0.007 compared with -0.038) and the linear correlation is very weak (sig. = 0.551, compared with 0.015), it is therefore deduced that the higher building density, because of more radiation being blocked, introduces more uncertainty to shading and ET mechanism of vegetation at ground level, and is possible to dilute its cooling performance. Similar changes can be found in the impact of albedo. This is because in denser built surroundings, the cooling performance of high albedo surfaces is negated by enhanced multiple reflections between ground and vertical surfaces (Giridharan et al. 2004). But due to limited sample size in the models, further analysis with larger data sets is needed to confirm this finding.

6. Conclusion

1. Vegetation canopy above pedestrian level provides shade from solar radiation and reduce the increment of air temperature. A variable named Tree View Factor (TVF) used in this study is capable of quantifying vegetation canopies above pedestrian level at a certain point and it shows negative correlations with UHI in multiple regression models.

2. Green mass, quantified by Green Cover Ratio (GCR) and Leaf Area Index (LAI) are suppressed in evapotranspiration because of lack of water in substrate and high albedo in high rise residential developments in Shanghai. So they seem to have shown no cooling effect on outdoor air temperatures. But this still needs further study.

3. The combined impact of greening variables (TVF, GCR and LAI) cannot explain well the variations in UHI. Solar radiation has significant impact on UHI intensity. Building density is also found to have significant impact. In this study a variable named building view factor (BVF) is able to quantify the building density.

4. Higher building density blocks more radiation and introduces more uncertainty to shading and ET mechanism of vegetation at ground level, thus is possible to dilute its cooling performance. But further analysis with larger data sets is needed to confirm this finding.

7. Limitation and future study

Due to the logistic problem, this preliminary study measured only two sites with only one day period for each site. And the dates under measurement are not among the hottest days in Shanghai summer. These limitations could to some extent influence the data obtained and reliability of analysis. Despite all the limitations, the study yields reasonably good results, and testifies the method used in this study is reliable and applicable in larger scale data analysis. For future study, several issues should be addressed:

1. More extensive measurement is needed to be carried out in more sites with more diversified characteristics in building layout, surface material, green cover ratio etc. Each site is to be measured for a period of at least three days with similar weather conditions.

2. All wave radiation should be measured at each station, to calculate mean radiant temperature and other thermal index, in order to understand the impact of greening on human thermal comfort.

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