THE ROLES OF URBAN BUILDINGS AND VEGETATION IN ADJUSTING SEASONAL AND DAILY AIR TEMPERATURE

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ABSTRACT:

Exploring the spatiotemporal patterns of the relationships between urban indicators and urban temperature is essential to improve the mitigation effectiveness when we intend to adjust built environment for moderating urban thermal environment. In this study, RS, GIS technology and statistical methods were involved to investigate the spatiotemporal patterns of the impacts of urban buildings and vegetation on Air Temperature (AT). Building Density (BD) and Normalized Difference Vegetation Index (NDVI) are the indicators for urban buildings and vegetation respectively. The objectives of this study are: 1) to determine an appropriate scale for examining the building-AT relationships and vegetation-AT relationships; 2) to explore the seasonal and daily characteristics of these relationships; and 3) to compare the effects of urban buildings and vegetation. The results show that, for both summer and winter, a scale of 200-250m is optimal for examining building-AT relationships, and 960-1020m is the desirable scale for studying vegetation-AT relationships. Based on the optimal scales, we find that for both buildings and vegetation, they only significantly impact night-time temperature in both summer and winter. For seasonal comparison, the building-AT relationships and vegetation-AT relationships are relatively stronger in summer than in winter, which are indicated by R-square of the regression results. When comparing the effects of urban building and vegetation, we find that increasing vegetation is more effective than reduce buildings to achieve the same air temperature reduction. Our findings are conducive to generating space-time targeted Urban Heat Island (UHI) mitigation strategies.

1. INTRODUCTION

1.1 Urban Heat Island

The Urban Heat Island (UHI) is a phenomenon caused by the intensifying urbanization (Arnfield, 2003; Kalnay & Cai, 2003; Rizwan et al., 2008), and it is a widespread issue that is plaguing more and more cities. UHI can increase the demands of cooling energy (Santamouris, 2014) and irrigation water (Brazel et al., 2007), which lead to consume more energy and resources. Furthermore, it can even cause heat-related illness and even death (Sheridan et al., 2012; Hajat et al., 2014), which extremely decreases human well-being. To improve urban thermal environment, urban planning can be an effective tool for urban environment management (Eliasson, 2000; Ng, 2012), but detailed and profound understandings about UHI and how it is influenced by urban settings are necessary.

It is demonstrated that urban buildings have heating effects (Perini & Magliocco, 2014) and urban vegetation has cooling effects (Zhang et al., 2018), which signifies that optimizing buildings and vegetation can adjust urban thermal environment effectively. However, this kind of knowledge is too crude without considering the spatiotemporal patterns of these effects, which is one of the reasons why cities still hesitate to take corresponding actions (Lan & Zhan, 2017) for UHI mitigation. From the practical perspective, we need to know the specific

location and spatial scope for certain strategy. Therefore, to identify the location and determine the spatial scope, it is essential to know the spatiotemporal patterns of different potential mitigation strategies.

1.2 This Research

Based on the background, this study aims to investigate the spatiotemporal patterns of the impacts of urban buildings and vegetation on Air Temperature (AT), so as to provide more space-time targeted UHI mitigation strategies. Building Density (BD) and Normalized Difference Vegetation Index (NDVI) are the indicators for urban buildings and vegetation respectively. The objectives of this study are: 1) to determine an appropriate scale for examining the building-AT relationships and vegetation-AT relationships; 2) to explore the seasonal and daily characteristics of these relationships; and 3) to compare the effects of urban buildings and vegetation.

2. DATA AND METHODS

2.1 Study Area

The city of Wuhan is the fifth most populous city in China. It exhibits a typical subtropical monsoon climate with extremely hot summer and cold winter. The hottest month is July and the coldest month is January. The extent of the study area (Fig. 1) is

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45*36 km, which covers the entire downtown Wuhan and reaches into the rural surroundings.



Fig 1. Study area and 30 weather stations

2.2 Air Temperature

The AT was obtained from the 30 hourly monitoring weather stations (Fig. 1). The data used in this study was collected in 2012, and July and January were chosen to typically represent the situations of summer and winter. There are several principles for AT data selection: 1) the day with wind speed < 2m/s to exclude the impact of wind; 2) the day did not rain to exclude the influence of humidity; and 3) monitoring data is intact. Finally, we chose four days for summer (including July 16th, 17th, 24th, 25th, labelled as D716, D717, D724, D725) and four days for winter (January 6th, 9th, 10th, 25th, labelled as D106, D109, D110, D125). For each day, the daily average AT was calculated for each station.

2.3 Urban Buildings

Building Density (BD) was selected as the indicators for urban buildings. The computation of BD is performed in ArcGIS system based on the geographically referenced building data of 2012. Centred with the weather stations, we calculated BD at 20 different scales, square sizes from 50m to 1000m in increments of 50m. BD is calculated in the way that in each calculation size, the total area of building divided by the square area.



Fig 2. Square sizes for BD (a)) and NDVI (b)) calculation

2.4 Urban Vegetation

Normalized Difference Vegetation Index (NDVI) was employed to mirror urban vegetation in the study area. The NDVI was derived from Satellite images of Landsat-7. Considering defoliation of many plants, the images obtain in May 17th, 2012 and January 26th, 2012 were used to represent the vegetation condition of summer and winter respectively. The calculation formula for NDVI is:

NDVI = (B4-B3)/(B4+B3) (1) Where B3 is the third band of images, and B4 is the fourth band of images. The calculation was processed in ENVI 4.8.

Similar with BD, the NDVI was also calculated at different scales, 25 square sizes from 60m to 1500m in increments of

60m. We use 60m as the increment size for the convenience of calculation since the original pixel size of the images is 30m. 60m is a multiple of 30m, which would ensure that each station will include the same number of pixels at each calculation scale, so as to reduce the statistical errors.

2.5 Statistical Analyses

The simple linear regression was applied to examine the scaling effects and temporal patterns of building-AT relationships and vegetation-AT relationships. For the dynamic relationships at different scales, we analysed the bivariate relationships between AT and BD, NDVI at varying scales. The daily average temperature is used here to represent the overall temperature level. The analyses were conducted for each selected day to avoid the occasionality of the results. We observed the trend of R^2 with respect to varying scales to better understand the scaling effects. This investigation provided important information about which scales are desirable for examining the effects of urban buildings and vegetation on air temperature, and these are also the scales at which maximum mitigation effects would be achieved when we adjust urban buildings and vegetation for UHI mitigation.

Based on the optimal scales for BD and NDVI, we conducted similar analyses to explore the temporal patterns of building-AT and vegetation-AT relationships by performing hourly simple regressions between AT and BD, NDVI for each selected day. This is conducive for us to understanding the daily and seasonal variations of building-AT and vegetation-AT relationships more clearly and profoundly, which is particularly important if we want to mitigate UHI in a time-targeted approach.

After the exploration of scaling effects and temporal patterns, multiple regression was employed to 1) elucidate the combined effects of buildings and vegetation, and 2) compare their effects. All of the regressions were performed in MATLAB.

3. RESULTS

3.1 Scaling Effects on BD-AT Relationships and NDVI-AT Relationships

BD is a scale-determined indicator that we will obtain different values in different calculation scales. Accordingly, the building-AT relationships will also fluctuate in varying scales. From the scalograms (Fig. 3) of BD-AT relationships, we observed that for both summer and winter, the regression coefficients are all positive, implying the warming effect of urban buildings. In summer (Fig. 3 a)), the R^2 of the regression model reveal a trend of increasing with a steep slope at first and then flattened afterward. The turning point is around 200m-250m, which means beyond 250m, the proportion of the AT variance that is predictable by BD would not significantly increase with the scale increasing. The regression coefficients show a similar trend in most cases, except D725, the turning point is around 250m-300m. Therefore, a scale of 200-250m is preferred in examining BD-AT relationships in summer. In winter (Fig. 3 b)), the turning point is also around 200m-250m for both the R^2 and regression coefficients. Although R² increases continually afterward, the first turning point should be the optimal one since an overly large scale could potentially lead to a substantial loss of information. Hence, the desirable scale for examining BD-AT relationships in winter is 200m-250m. Therefore, the air temperature at one location is actually influenced by the buildings within 250m.



Fig 3. Scalograms showing the scaling effects on BD-AT relationships: a) the R² and the coefficients of the bivariate model between BD and AT in summer; b) the R² and the coefficients of the bivariate model between BD and AT in winter.



Fig 4. Scalograms showing the scaling effects on NDVI-AT relationships: a) the R² and the coefficients of the bivariate model between NDVI and AT in summer; b) the R² and the coefficients of the bivariate model between NDVI and AT in winter.

To study the case of urban vegetation, similar analyses are also performed in NDVI-AT relationships (Fig. 4). In both summer and winter, NDVI is negatively correlated with AT, indicating a cooling effects of vegetation. The trends of R^2 and regression coefficients are very similar in summer and winter. The R^2 is very low and unstable at first (from 60m-180m in summer, and 60m-300m form winter), and the increases drastically and stably until 960m-1020m, afterward, the variations of R^2 are slightly and slowly. Therefore, the preferable scale for examining NDVI-AT relationships is 960m-1020m for both summer and winter. Thus, the air temperature at one point is affected by the overall vegetation condition in a range of 1020m.

In short, BD-AT relationships and NDVI-AT relationships vary with scale sizes, and the optimal scales for the two are different. Urban building elevates air temperature and 200m-250m is a desirable scale to examine the warming effects. Urban vegetation can lower air temperature and 960m-1020m is the reasonable scale to study the cooling effects. Move over, it is also signified that adjusting urban buildings and vegetation in the optimal scales can achieve more significant mitigation effectiveness for moderating urban thermal environment.

3.2 Seasonal and Daily Patterns of BD-AT Relationships and NDVI-AT Relationships

To clarify the seasonal and daily patterns of BD-AT relationships and NDVI-AT relationships, hourly simple regressions between BD and AT at the scale of 250m and hourly simple regressions between NDVI and AT at the scale of 1020m were performed for each day in summer and winter. Fig. 5 shows the frequencies that the regression models cannot reach the significance level (0.05) at each hour for summer and winter. The results indicate that in both summer and winter, BD and NDVI only have significant impact on night-time AT, and their relationships with daytime AT cannot pass the significant tests. That is to say, the spatial differences of AT during night-time are tightly associated with urban buildings and vegetation, but buildings and vegetation are not determined factors that impact daytime AT. Thus, adjusting urban buildings and vegetation can only be an effective approach to moderate night-time UHI.



Fig 6. R² of Hourly regressions in summer and winter: a) R² for BD-AT regression in summer and winter; a) R² for NDVI-AT regression in summer and winter;

To give a closer scrutiny of the daily variations of the BD-AT and NDVI-AT relationships, we observe the dynamic hourly R^2 in Fig. 6. For all of the four situations, the R^2 of each day reveals a consistent trend that the R^2 maintains a high level at first and drops down sharply in the morning, and keeps the low level until dusk, and then increases rapidly reaching to a relatively higher level.

For BD, the R² in summer is relatively higher and more stable than in winter, especially during the evening (19:00 p.m. – 23:00 p.m.), implying a stronger impact in summer. And in summer, the decrease time for R² in the morning is 6:00 a.m.-8:00 a.m., the increase time is 16:00 p.m. -19:00 p.m. While in winter, the decrease time is 8:00 a.m.-10:00 a.m., two hours later than summer; the increase time is 17:00 p.m. - 19:00 p.m. For NDVI, the NDVI-AT relationships are also slightly stronger in summer than in winter according to the value and variation of R² in different days. In summer, the falling time for R² in the morning is 6:00 a.m. - 9:00 a.m., and the rising time is 16:00 p.m. -19:00 p.m. In winter, the falling time is 8:00 a.m. - 11:00 a.m., the rising time is 17:00 p.m. - 20:00 p.m.

Therefore, in summer, AT can be significantly adjusted by urban buildings and vegetation during 19:00 p.m. -6:00 a.m.; and in winter, it is during 20:00 p.m. -8:00 a.m., which indicates that the effects of buildings and vegetation are obviously influenced by sunlight. Further, adjusting urban buildings and vegetation can achieve relatively more effectiveness in summer than in winter.

3.3 The Effects of Urban Buildings and Vegetation

To compare the effects of urban buildings and vegetation, we applied multiple linear regression models (Table. 1). Only the night-time average AT (i.e. average AT during 19:00 p.m. -6:00 a.m. in summer days, and average AT during 20:00 p.m. -8:00 a.m. in winter days) is involved in the models. Comparing the R^2 with simple regression in section 3.2, the combined effects of BD and NDVI account for more AT variance than individual factor, indicating that optimizing urban buildings and vegetation simultaneously will achieve more AT reduction than only adjusting one. For the R² of different days in summer and winter, we observed a more stable relationships in summer than in winter. The regression coefficients of BD are relatively stable (from $2.3 \sim 4.7$) in different seasons, while the fluctuation range of NDVI's coefficients is wider (from -4.0 \sim -10.0). When comparing the regression coefficients of BD and NDVI, the absolute values of NDVI's coefficients are higher than BD's, and it is especially significant in winter, implying that to achieve the same AT reduction, planting more trees would be an easier way than decreasing building density. This is an ideal case that both increasing vegetation and reducing building density are applicable. In most case, the area with intense UHI is the dense area that removing buildings is infeasible, and adding vegetation is also a more preferable approach. Besides, it is equally important to consider the current conditions of BD and NDVI when we are determining mitigation strategies.

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Summer								
	D716 Night		D717 Night		D724 Night		D725Night	
variable	Coefficients	Sig.	Coefficients	Sig.	Coeffici ents	Sig.	Coeffici ents	Sig.
BD	2.790	0.006	2.749	0.002	3.595	0.010	4.700	0.005
NDVI	-4.360	0.006	-4.064	0.004	-5.804	0.008	-6.113	0.017
Constants	26.010		26.160		29.216		29.706	
R ²	0.538		0.580		0.502		0.501	
Winter								
	D106 Night		D109 Night		D110 Night		D125Night	
variable	Coefficients	Sig.	Coefficients	Sig.	Coeffici ents	Sig.	Coeffici ents	Sig.
BD	3.894	0.002	2.631	0.007	2.342	0.005	3.247	0.066
NDVI	-8.919	0.001	-4.037	0.055	-5.966	0.002	-10.016	0.014
Constants	1.785		4.276		5.094		-3.232	
\mathbb{R}^2	0.563		0.385		0.518		0.347	

Table 1. Multiple regression results for BD and NDVI.

4. **DISCUSSION**

4.1 The UHI Mitigation Implications of the Scaling Effects and Temporal Patterns

Urban surface is spatially heterogeneous instead of homogeneity, since some elements (e.g. transportation networks, interspersed centres) count more during the process of urbanization, which can be reflected from the sector theory (Hoyt, 1939) and multiple nuclei theory (Harris & Ullman, 1945). This characteristic inevitably impacts urban surface related climate issues such as temperature. Our study demonstrated that the impacts of urban buildings and vegetation on air temperature are scale-determined, which means buildings and vegetation would not significantly impact air temperature at any scale. Thus, adjusting buildings and vegetation at appropriate scale is crucial to obtain significant mitigation effectiveness. Besides, the optimal scales for different elements are also various. Whether in scientific research or application level, it is irrational to choose a scale arbitrarily and use the same scale for all elements.

Temperature is influenced by many different factors, including buildings, vegetation, anthropic heat and even weather condition. And it is a temporal dynamic phenomenon that changes continuously with time. Thus, the relative importance of these factors in determining temperature would also fluctuate with time. Our findings suggest that urban buildings and vegetation are main factors that impact air temperature during night time, especially summer night, but their effects during daytime are neglectable. This knowledge implies that reducing building density or increasing vegetation can only be effective strategies for the areas that are suffering night-time UHI.

To achieve more mitigation effectiveness, taking full considerations of the scaling effects and temporal patterns of the potential strategies are necessary. Besides, the current conditions of the involved elements (e.g. BD, NDVI, etc.) cannot be ignored either. Therefore, in order to give a specific spatial planning of the strategy implementation, there are at least three steps: 1) describing the current conditions of the involved elements (e.g. calculating BD in the whole study area at the scale of 250m); 2) analysing the temporal patterns of UHI; and 3) determining strategies for each area based on both the current conditions of the involved

elements and temporal patterns of local UHI. For instance, for the area with intense night-time UHI and very less vegetation, planting trees can be the preferable strategy.

4.2 Further Study

This study only investigated BD and NDVI, more indicators (e.g. three-dimensional indicators, urban water area, pavement etc.) could be involved in further study. To demonstrate the validity of the results, similar researches with various methods or from different perspectives can be helpful. Besides, it is also possible to bring this spatiotemporal research into other urban issues (e.g. air pollution, noisy pollution, etc.).

5. CONCLUSION

This study employed RS, GIS technology and statistical methods to investigate the spatiotemporal patterns of the impacts of urban buildings and vegetation on air temperature. The results show that 200m-250m and 960m-1020m are optimal scales for examining BD-AT relationships and NDVI-AT relationships respectively. Both BD and NDVI are only significantly impact night-time temperature in both summer and winter. The impacts of buildings and vegetation on AT are relatively stronger in summer than in winter. Increasing vegetation would be more effective than reduce buildings to achieve the same air temperature reduction. Our findings are conducive to generating space-time targeted UHI mitigation strategies.

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