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Effects of urban form on the urban heat island effect based on spatial regression model

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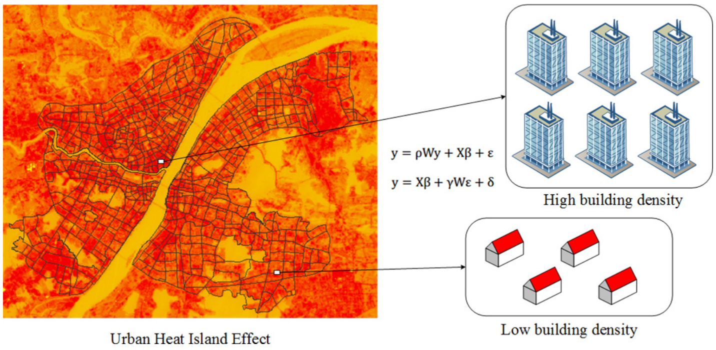
HIGHLIGHTS

- Building density is a key indicator in mitigating UHI effect.
- Spatial regression is a promising method for dealing with problems related to the urban thermal environment.
- Regulatory planning management unit was recommended for analyzing the relationships between urban form and the UHI effect.
- Attention should be paid to the influence of urban form on UHI effect in urban planning.

GRAPHICAL ABSTRACT



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ABSTRACT

The urban heat island (UHI) effect is becoming more of a concern with the accelerated process of urbanization. However, few studies have examined the effect of urban form on land surface temperature (LST) especially from an urban planning perspective. This paper used spatial regression model to investigate the effects of both land use composition and urban form on LST in Wuhan City, China, based on the regulatory planning management unit. Landsat ETM+ image data was used to estimate LST. Land use composition was calculated by impervious surface area proportion, vegetated area proportion, and water proportion, while urban form indicators included sky view factor (SVF), building density, and floor area ratio (FAR). We first tested for spatial autocorrelation of urban LST, which confirmed that a traditional regression method would be invalid. A spatial error model (SEM) was chosen because its parameters were better than a spatial lag model (SLM). The results showed that urban form metrics should be the focus for mitigation efforts of UHI effects. In addition, analysis of the relationship between urban form and UHI effect based on the regulatory planning management unit was helpful for promoting corresponding UHI effect mitigation rules in practice. Finally, the spatial regression model was recommended to be an appropriate method for dealing with problems related to the urban thermal environment. Results suggested that the impact of urbanization on the UHI effect can be mitigated not only by balancing various land use types, but also by optimizing urban form, which is even more effective. This research expands the scientific understanding of effects of urban form on UHI by explicitly analyzing indicators closely related to urban detailed planning at the level of regulatory planning management unit. In addition, it may provide important insights and effective regulation measures for urban planners to mitigate future UHI effects.

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1. Introduction

Extensive urban expansion and population growth have triggered a series of environmental problems, such as resource crises (Liu et al., 2013), local climate change (Parmesan and Yohe, 2003), air pollution (Yuan et al., 2017), traffic congestion (Evans and Carrère, 1991), and so on. One of the most serious problems is the significant variability of land surface temperature (LST), which results in the urban heat island (UHI) effect. The UHI effect describes the phenomenon when atmospheric and surface temperatures are higher in urban areas than in surrounding rural areas (Oke, 1995). Persistent high temperatures due to the UHI effect may threaten the habitability of a city, and cause an increase in ecological and environmental issues, such as biodiversity loss (Li and Norford, 2016) and excess water consumption (Lowe, 2016). Excessive heat may also affect the comfort level of living and lead to greater health risks, especially among the elderly (>65 years) (Chang et al., 2007) and the very young (<2 years) (Ellis et al., 1975) who are sensitive to higher temperatures. Therefore, much attention should be paid to rising LST and its harmful UHI effects.

As noted above, the UHI effect consists of air temperatures and land surface temperatures (Sun et al., 2012). Air temperature is usually measured by the canopy layer heat island and the boundary layer heat island, while land surface temperature is typically derived from satellite-based remote sensing data. Although similar relationships and spatial patterns between air and land surface temperatures have been reported in some studies, they are not consistent (Sheng et al., 2017). Air temperature UHI generally exhibits greater spatial variability at night, while land surface temperature UHI usually occurs during the daytime (Zhou et al., 2011). Methods for acquiring LST have become more convenient with the development of 3S technology. A variety of image data, such as MODIS (Pu et al., 2006), Landsat TM/ETM+ (Weng et al., 2004), and Quick bird (Xu et al., 2017), has been used to evaluate the spatial patterns of LST. Therefore, we focused on remotely-sensed land surface temperature UHI in this study, or surface UHI.

The UHI effect is influenced by many factors. With the increase of artificial ground cover in large areas and the loss of ecological land through urbanization, the thermodynamic properties of the underlying surface gradually results in an increased heat capacity and high thermal conductivity (Radhi et al., 2013). At the same time, artificial heating sources contribute to the UHI effect by providing large quantities of energy for urban production and life (Kotharkar and Surawar, 2016). In addition, environmental problems due to urbanization, such as air pollution, can influence solar reflectance, which leads to higher temperatures (Tan et al., 2010). Accordingly, it is urgent and necessary to study on the patterns of the UHI effect and how to reduce it. This paper selected Wuhan City in China as a case study to analyze the spatial distribution of urban LST and adopted a spatial regression method to explore the relationship between the UHI effect and its factors of influence at the level of the regulatory planning management unit.

2. Literature review

2.1. Analysis indicators review

Considerable attention has been paid to the spatial patterns of surface UHI and the quantitative relationship between surface UHI and its factors of influence: both social-economic aspects (Huang et al., 2011) and objective physical factors (Ren et al., 2016). In general, income (Mitchell and Chakraborty, 2014), education level (Kinney et al., 2008), and racial or ethnic characteristics (Huang et al., 2010) may affect residential locations and living conditions, causing unbalanced spatial heat effects. Indeed, most of studies point out that LST varies significantly across different land cover classes (Li and Tan, 2014; Rinner and Hussain, 2011). LST is always higher in built-up areas, such as those for residential and industrial land use, and bare surfaces. It is lower in vegetated areas, water bodies, or in parks and other recreational land use areas (Li et al., 2016; Sun et al., 2012). It seems that increasing ecological land use can be an effective way to mitigate UHI effects in urban areas. However, land use for urban greening is usually limited for social-economic development. Consequently, how to mitigate UHI effects by optimizing the proportion and structure of land cover types is a focus of recent research. Scholars have begun to understand the influence of landscape patterns from diverse land-use types on the UHI effect, because landscape pattern metrics can quantify land cover proportion and structure. There are two fundamental aspects of landscape pattern: composition and configuration, both of which influence the UHI effect. Composition refers to the quantity and proportion of land cover features without considering their spatial characteristics and structure, while configuration, in contrast, refers to the spatial arrangement of land cover features (Gustafson, 1998). Therefore, a large number of landscape pattern metrics have been used to measure the relationships between the two (Chen et al., 2014). For example, higher patch density (PD) would mitigate the UHI effect, whereas higher largest patch index (LPI) and contagion index (CONTAG) values may intensify UHI effects (Connors et al., 2013; Li et al., 2011; Li et al., 2014). At the same time, some indicators, which can be used to classify land use types by setting different threshold values and qualitatively describing land use conditions, have also been taken into account with the development of numerous satellite products and remote sensing images (Sun et al., 2012). For instance, the normalized difference vegetation index (NDVI) and normalized difference water index (NDWI) were both negative indexes for UHI effect, while the normalized difference built-up index (NDBI) exhibited the opposite trend.

However, urban LST is not only related directly to land cover characteristics, but also to urban form (Yang and Li, 2015). Quantitative evaluation of the influence of urban form on LST is necessary to study the mitigation of the UHI effect (Kuang et al., 2015). The direct relationship between urban form and LST has been explored in several empirical studies, which found that a city's area, scale, and geometry can dramatically affect the range and intensity of the UHI effect. Nevertheless, conflicting conclusions from these studies mean that the relationship between urban form and LST remains under debate. For example, sky view factor (SVF) (Chun and Guldmann, 2014), which was considered to be one of the most important factors in explaining the UHI effect, had varying influence on UHI across different study areas. In addition, some studies have argued that the LST tends to be much cooler where there is low building density (Guo et al., 2016) and high floor area ratio (FAR) (Giridharan et al., 2005), another indicator describing urban form, whereas others argued that low-density residential development patterns contribute more heat than higher density habitations (Jr and Rodgers, 2001). Obviously, more study is needed on the influence of urban form on the UHI effect. This paper selected SVF, building density, and FAR, all of which quantify urban form, to study their influence on the UHI effect.

2.2. Analysis units review

Quantitative analyses of the UHI effect and its factors of influence are typically carried out over temporal (Arnfield, 2003) and spatial units. In particular, the use of different analytical units in the evaluation of the UHI effect would result in inconsistent conclusions (Chun and Guldmann, 2014; Li et al., 2011). In order to explore the impact of population factors on the UHI effect, some studies adopted the census block as analysis unit (Huang et al., 2011). In fact, the most commonly used unit for UHI effects research has been a gridded unit, primarily because LST data is derived from remotely-sensed raster-based imagery for its advantages of long sequential and wide coverage, and spatially-explicit temperature data can help clarify the hotspot maps. The use of raster data is often confronted with the problem of selecting the appropriate spatial resolution. Changes in spatial resolution will lead to variation in observed UHI effects and overlying surface structure, which may

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