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Linking potential heat source and sink to urban heat island: Heterogeneous effects of landscape pattern on land surface temperature

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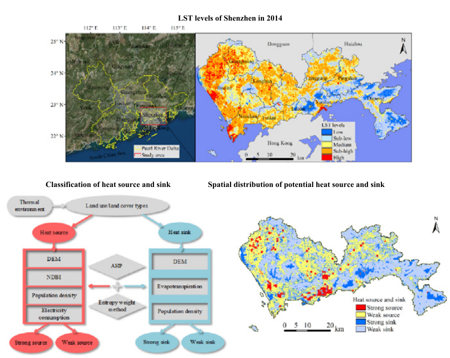
HIGHLIGHTS

- We identified potential heat source and sink by natural and socio-economic factors.
- Heterogeneous effects of landscape pattern on LST were investigated.
- Compositions of heat source and sink landscape have fundamental effects on LST.
- Effects of patch shape and spatial arrangement vary across different regions.
- It offers implications for mitigating UHI by designing and transforming landscape.

GRAPHICAL ABSTRACT



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ABSTRACT

Rapid urbanization has significantly contributed to the development of urban heat island (UHI). Regulating landscape composition and configuration would help mitigate the UHI in megacities. Taking Shenzhen, China, as a case study area, we defined heat source and heat sink and identified strong and weak sources as well as strong and weak sinks according to the natural and socioeconomic factors influencing land surface temperature (LST). Thus, the potential thermal contributions of heat source and heat sink patches were differentiated. Then, the heterogeneous effects of landscape pattern on LST were examined by using semiparametric geographically weighted regression (SGWR) models. The results showed that landscape composition has more significant effects on thermal environment than configuration. For a strong source, the percentage of patches has a positive impact on LST. Additionally, when mosaicked with some heat sink, even a small improvement in the degree of dispersion of a strong source helps to alleviate UHI. For a weak source, the percentage and density of patches have positive impacts on LST. For a strong sink, the percentage, density, and degree of aggregation of patches have negative impacts on LST. The effects of edge density and patch shape complexity vary spatially with the fragmentation of a strong sink. Similarly, the impacts of a weak sink are mainly exerted via the characteristics of percent, density, and shape complexity of patches.

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1. Introduction

Rapid urbanization over the past several decades (Seto et al., 2010; United Nations, 2012) has led to land use/cover change (LUCC), especially the transition from natural landscapes to impervious surfaces (Deng and Wu, 2013; Song et al., 2014). This process has been accompanied by a series of ecological and environmental problems, one of which is the urban heat island (UHI) effect. Currently, the relationship between landscape pattern and UHI is a widespread concern (Chen et al., 2014; Coseo and Larsen, 2014; Du et al., 2016b; Li et al., 2011; Peng et al., 2016). Based on a division of the land surface into clear land use/land cover (LULC) types, a large number of studies have found that construction land and bare land make the greatest contribution to UHI, whereas other LULC types, including forest and water, are beneficial for mitigating UHI (Amiri et al., 2009; Song et al., 2014). In addition, the effects of landscape composition and configuration on land surface temperature (LST) have been investigated (Zhou et al., 2014; Asgarian et al., 2015). However, both natural conditions and socioeconomic factors exert certain effects on LST pattern (Buyantuyev and Wu, 2010; Jenerette et al., 2007; Kuang et al., 2015). The studies based on traditional LULC classification mentioned above failed to exclude impacts of other factors from the landscape pattern, which increased the uncertainties of analyzing the relationship between landscape pattern and UHI.

To investigate the thermal effects of landscape composition and configuration more accurately, we introduced the concepts of source and sink, which are commonly applied in studies on air pollution (Lal, 2000), the carbon cycle (Canadell et al., 2007), and other topics. A source is the origin of a process, while a sink refers to the disappearance of the process (Chen et al., 2008). For the thermal environment, the LULC types that generally produce UHI are defined as heat source, which plays an important role in contributing heat to the adjacent environment. Contrarily, the LULC types beneficial for mitigating UHI are defined as heat sink, which exerts cooling effects on the adjacent environment. In addition, with consideration of the natural and socioeconomic factors influencing LST, heat sources are classified as potential strong heat source or potential weak heat source (hereafter referred to as strong source and weak source, respectively), and heat sinks are classified as potential strong heat sink or potential weak heat sink (hereafter referred to as strong sink and weak sink, respectively). Theoretically, a strong source has a stronger potential for increasing LST than a weak source, while a strong sink has a stronger potential for lowering LST than a weak sink. The purpose of the classification is to differentiate the potential contributions of heat source and heat sink patches to the thermal environment and exclude the impacts of other factors when exploring the relationship between landscape pattern and UHI. Additionally, it is helpful to combine landscape pattern with ecological process (Chen et al., 2008). It can be assumed, under this land surface classification framework, that the LST difference is mainly caused by various landscape compositions, shapes, and spatial arrangements. Thus, the investigation of the thermal effects of heat source and heat sink can provide guidance for landscape planning and design intended to mitigate UHI.

The various biophysical conditions in an urban ecosystem generally lead to heterogeneity of how and to what extent the landscape pattern affects the thermal environment. However, heterogeneity has not been considered sufficiently by common methods, including correlation analysis (Guo et al., 2015), ordinary least squares (Connors et al., 2013; Zhou et al., 2014), and spatial lag and spatial error models (Song et al., 2014). Geographically weighted regression (GWR), proposed by Fotheringham et al. (1996), embeds spatial heterogeneity into local parameter estimation. Additionally, Nakaya et al. (2009) further expanded the GWR model to a semiparametric GWR model (SGWR), which allows simultaneous global and local parameter estimation. This model is suitable for investigating the heterogeneous effects of landscape pattern on UHI (Buyantuyev and Wu, 2010; Su et al., 2012).

Taking Shenzhen, China, as a case study area and using Landsat-8 OLI/TIRS images, we analyzed the urban thermal environment in the megacity and developed SGWR models to explore the relationship between landscape pattern and LST. The specific objectives were to (1) investigate how to identify potential heat source and heat sink in order to exclude the impacts of natural and socioeconomic factors when analyzing the relationship between landscape pattern and LST; (2) analyze how landscape composition, shape, and spatial arrangement affect the heat effects exerted by heat source and heat sink patches; and (3) examine whether the effects of landscape pattern on LST are heterogeneous. The results from this study can support decision making in land-use planning and management and provide a methodology reference for study of the thermal environment based on landscape pattern.

2. Data and methodology

2.1. Study area

Shenzhen, a major central city in southern Guangdong Province, China, is located on the east coast of the Pearl River Delta (22°27′″”–22°52′ N; 113°46′–114°37′ E) (Appendix A, Fig. A.1) and has an area of 1952.84 km^2. The city has a subtropical monsoon climate with hot and rainy summers and mild and humid winters. The area has an annual average temperature of about 22.4 °C, an annual precipitation of 1948 mm, and a terrain trend of higher terrain in the southeast and lower terrain in the northwest. Since China's Reform and Opening beginning in 1978, Shenzhen has had rapid urbanization. Such a dramatic LUCC process inevitably brings an UHI.

2.2. Land use/land cover

Two Landsat-8 OLI/TIRS images were acquired on October 15, 2014 (path 122/row 44) and October 8, 2014 (path 121/row 44) to cover the entire area of Shenzhen, respectively, under highly clear atmospheric conditions. The pre-processing for each image included radiometric correction, atmospheric correction, and geometrical distortions correction. With reference to Google Earth, supervised classification and man-computer interactive interpretation were utilized in ENVI 5.1, and the final LULC included cultivated land, forest, grassland, construction land, water bodies, and bare land (Fig. A.1). According to the classification accuracy test, the Kappa coefficients of the two images were 0.909 and 0.900, respectively, which satisfied the needs of the study.

2.3. LST retrieval and classification

The thermal infrared band of Landsat 8 OLI/TIRS (band 10) was used to derive LST in ENVI 5.1. First, the digital number (DN) was converted into top-of-atmosphere (TOA) radiance. Second, the brightness temperature corresponding to each pixel was derived. Lastly, brightness temperature was modified to LST via the emissivity of different land covers, to reflect the difference of temperature among various cover types on the real land surface. Additional details can be found in the studies by Xiao et al. (2007), USGS (2013), and Estoque and Murayama (2015).

After the retrieval of LST, to eliminate systematic error caused by different time or atmospheric conditions, we used the LST retrieved from the image (path122/row44), which could cover most areas of Shenzhen, as reference and adjusted the LST retrieved from the other image based on the invariant object method. On this basis, the LST was standardized in ArcGIS 10.1 according to the data range, and the density slice method was applied to divide the LST into five levels (Appendix A, Table A.1). In addition, the LST data were resampled to 30 m to match the LULC data.