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Research Paper

A landscape connectivity model to quantify contributions of heat sources and sinks in urban regions

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ABSTRACT

The effect of landscape configuration on urban temperatures is always an important issue in landscape planning and mitigation of urban heat islands. However, landscape indices used in previous studies did not focus on thermal processes. We proposed a landscape source-sink distance (LSSD) index used to quantify the landscape connectivity and investigate its contribution to variations in land surface temperature (LST) in Beijing. Monthly LST was derived from MODIS remote sensing products in 2002 and 2012. Landscape composition and connectivity was calculated based on QuickBird and IKONOS images. The LSSD of each LST grid was calculated according to the accumulative shortest distance between green-impervious, water-impervious, and green-water types. The contributions of landscape composition and connectivity to variations in LST were assessed using a geographically weighted regression model. Heat sources and sinks were designated as having positive and negative effects on the LST, respectively. Results showed that (1) green spaces served as heat sinks both day and night. Water areas served as daytime heat sinks and nighttime heat sources; (2) the influence of green and water types on daytime LST varied in different months while their influence on nighttime LST was stable seasonally; and (3) a large distance between green and impervious land increased variations in day-night LST while a large distance for water-impervious connectivity might mitigate diurnal variations in LST. This study shows that landscape planners need to rationally use landscape connectivity among different landscape types and should focus on specific time and season for the effective mitigation of urban heating.

1. Introduction

Rapid urbanization and land use change usually lead to significant variations in the thermal environment that are characterized as "urban heat island" (UHI) effects (Chen, Chiu, Su, Wu, & Cheng, 2017; Peng et al., 2012; Stewart, 2011). Generally, UHIs are characterized by variations in air temperature between urban and rural regions (Imhoff, Zhang, Wolfe, & Bounoua, 2010; Zhao, Lee, Smith, & Oleson, 2014). However, in highly urbanized regions, heterogeneous urbanization and land use change create a complex energy balance and microclimate system inside a city (Buyantuyev & Wu, 2010; Jenerette et al., 2016; Song, Du, Feng, & Guo, 2014).

The UHI effect can be assessed by measuring surface air temperature and land surface temperature (LST) (Buyantuyev & Wu, 2010). The LST has been widely used to investigate the urban thermal environment due to the convenience of remoted sensing images (Stewart, 2011). The physical properties and humidity characteristics of different landscape types vary widely and significantly affect the surface energy balance, which in turn affects the urban thermal heterogeneity. The impervious surfaces usually absorb more solar radiation and have greater heat capacity and thermal conductivity. The sensible heat flux is related to the temperature difference between the land surface and the air as well as different landscape patches. The sensible heat is transported by convection, and the air velocity has great influence on it. Urban green spaces and water bodies cannot only reduce the temperature itself but also reduce the ambient air temperature. Therefore, the LST is significantly influenced by the heat exchange between different landscape patches (Adams & Smith, 2014).

The concepts of source and sink have been commonly applied in a broad range of ecological and environmental sciences (Chen, Tian, Fu, & Zhao, 2009). A source is an area of origin for an ecological process while a sink represents the destination of the process. For thermal processes, landscape patches that have higher temperatures are defined as heat sources. In contrast, landscape patches with lower temperatures are designated as heat sinks, which exert cooling effects on the surrounding environment (Chen, Zhao, Yao, & Chen, 2016; Li, Cao, Lang, & Wu, 2017). Understanding the connectivity of sources and sinks in the thermal processes of urban land types is therefore of great interest

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for mitigating the UHI effect in metropolitan regions (Coseo & Larsen, 2014).

A large number of researchers have demonstrated the roles of the cooling effects of green and water types as heat sinks (Ellison et al., 2017; Lee, Mayer, & Chen, 2016). Some research has shown that the mean LST was 6–12 °C higher for impervious surfaces when compared with green spaces in the September morning in Beijing (Kuang et al., 2015), and a 10% increase in green spaces could result in a 0.86 °C decrease in LST (Li, Zhou, Ouyang, Xu, & Zheng, 2012). Similarly, the mean temperature of water bodies was found to be almost 3 °C lower than that of urbanized land in the August morning (Sun & Chen, 2012). However, controversy has persisted over the effects of green and water types on the surrounding thermal environment. For example, a research reported that water bodies can actually increase the temperatures of UHI over some specific length of time (Steeneveld, Koopmans, Heusinkveld, & Theeuwes, 2014).

Two reasons may explain the controversy related to heat sinks and sources of green and water types. Most studies merely focused on UHI effects in some specific time period (Coseo & Larsen, 2014). Given the complex thermal background, green and water types could produce a different amount of latent heat of evapotranspiration and thus result in diverse thermal effects during different times and seasons (Berger et al., 2017; Chen et al., 2017; Hu, Monaghan, Voogt, & Barlage, 2016; Zhou, Zhao, Liu, Zhang, & Zhu, 2014). Moreover, landscape configuration is another contributor to the surface heat flux in addition to landscape composition (Connors, Galletti, & Chow, 2013; Deilami, Kamruzzaman, & Hayes, 2016; Li et al., 2016, 2017). Recent studies have shown that landscape structural complexity was important in maintaining the stability of LST throughout different seasons (Sun, Lü, Chen, Yang, & Chen, 2013). The spatial connectivity of green spaces had important contributions to the variation in LST (Chen, Yao, Sun, & Chen, 2014). Open green spaces can produce cooling effects through the evapotranspiration. On the other hand, they may increase the sky view factor which leads to more sun radiation accepted by the land. The impact of sky view on LST varied during the daytime and nighttime. Therefore, we have two questions that need to be addressed in relation to heat sinks and sources. What are the thermal roles (source *vs.* sink) that green and water types might play during both the day and night and even in different months? In addition, how does landscape connectivity influence mean temperatures in a specific analytical unit?

Landscape metrics have been widely used in linking LST and landscape configuration; however, current metrics have failed to represent ecological processes because they are usually developed based on the geometry of patches and the spatial relationships between patches (Connors et al., 2013). A set of metrics has often been used to describe the configuration of landscapes including size, shape, edge, diversity, and connectivity metrics (Connors et al., 2013; Kong, Yin, James, Hutyra, & He, 2014; Li et al., 2017; Peng, Xie, Liu, & Ma, 2016). These metrics are highly correlated with each other and create serious problems with redundancy and difficulty in interpretation (Song et al., 2014; Uuemaa, Mander, & Marja, 2013). Even though landscape configuration strongly affects and is affected by ecological processes based on the concept of landscape ecology, we should note that not all metrics of landscape configuration are responsible for the thermal processes in a city (Chen et al., 2016). Therefore, constructing landscape metrics in relation to thermal processes would be important to capture the effects of landscape configuration on any variation in LST (Chen et al., 2016).

Physically, the mean LST of a specific region is determined by the heat capacity and exchange among different landscape patches in that region. The spatial connectivity between heat sources and sinks is the essential factor affecting the thermal flows between landscape patches and thus the mean temperature in a region. In this study, a landscape connectivity index of source-sink distance (LSSD) was developed based on the shortest distance between different landscape types. The LSSD was accumulated based on each cell in an analytical unit. We selected the Beijing metropolis as a case study to investigate the dynamics of heat sources and sinks as well as the effects of landscape connectivity. Beijing has experienced massive urban construction and greening since its successful bid for the 2008 Olympic Games in July 2001 (Kuang et al., 2015; Peng et al., 2016; Quan et al., 2014). In order to examine the heat sources and sinks under the changes in landscape composition and connectivity, we used two years of landscape and LST data, that is, data from 2002 and 2012, before and after Beijing's rapid urbanization. This study was conducted to: (1) investigate the roles of heat sources and sinks for green and water types in the day and nighttime and in different months, and (2) quantify the contributions of landscape composition and connectivity to the variations of LST.

2. Methods and materials

2.1. Study area

Beijing, the capital of China, covers an area of approximately 16,800 km^2, and has experienced rapid development in recent decades. The characteristic warm temperature zone of Beijing has a typical continental monsoon climate with four distinct seasons. The coniferous forest mainly consists of *Platycladus orientalis*, *Sabina chinensis*, and *Pinus tabuliformis* in Beijing. They occupied for 23.8% of total greening trees in 2010 (Stewart, 2011; Zheng & Zhang, 2011). The deciduous forest includes *Rhus typhina*, *Populus tomentosa*, *Sophora japonica*, *Ginkgo biloba*, *Robinia pseudoacacia*, etc. The resident population of Beijing reached 20.7 million in 2012 (Wang et al., 2014). Moreover, urban development from 2002 to 2012 was primarily a result of the stimulus provided by urbanization associated with the hosting of the Olympic Games. Rapid urbanization and city expansion resulted in significant urban thermal change characterized by LST (Li et al., 2012). The mean intensity of UHI increased during the period from 1998 to 2011, resulting in 0.4 °C higher temperatures than the mean value from 1984 to 1997 (Fu & Weng, 2016). Researchers have found a temperature gradient of 0.1 °C/km from the city center to the outskirts during the last decade (Sun & Chen, 2017). The pattern of Beijing's development exhibited a typical concentric expansion, generating a ring-shaped pattern from the city center to its outskirts. The urbanization related to the Olympic Games was mostly located inside of the 5th ring-road (Kuang et al., 2015). Our study is targeted on the highly-urbanized region inside of the 5th ring-road of Beijing, which covered an area of 667.28 km^2. This region is relatively flat, with elevations ranging from 20 m to 60 m above sea level.

2.2. Land cover and LST

Two types of high spatial resolution remote sensing images were used to identify land cover types in the Beijing metropolis. First, QuickBird images were acquired on July 5, 2002 with four multispectral bands (2.44 m spatial resolution) and one panchromatic band (0.61 m). Then, IKONOS images were collected on July 29, 2012 with four multi-spectral bands (4 m) and one panchromatic band (1 m). The image classification and change analysis were based on 4-m spatial resolution. The QuickBird images were corrected geometrically to match the IKONOS images based on 40 control points. The spatial error between QuickBird and IKONOS images was less than 2 m (0.5 pixels). Unsupervised classification and decision tree methods were combined to extract the land cover types using ENVI software (Exelis Visual Information Solutions, Inc., Boulder, CO, USA) as described in previous studies (Chen et al., 2016; Sun & Chen, 2017). Three types of land cover were eventually aggregated for this study, including impervious land, green land, and water (Fig. 1). The green land was mainly a mix of forest, grass, and shrubs. The impervious land referred to artificial structures including pavements and built-up areas. The bare lands were omitted because they distributed unevenly and occupied very small areas. Lastly, a standard procedure was applied to assess the classification accuracy by ground-truthing analysis. The overall accuracy of