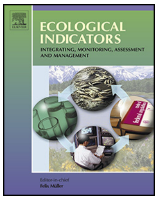
Ecological Indicators 69 (2016) 828–835

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind



Application of a new integrated landscape index to predict potential urban heat islands

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ARTICLE INFO

Article history:
Received 20 January 2016
Received in revised form 6 April 2016
Accepted 24 May 2016

Keywords:
Landscape pattern
LST
Location weighted landscape index
LWLI
Urbanization

ABSTRACT

Studies on the interactions between urban landscape patterns and land surface temperatures are the key to urban heat island (UHI) mitigation. However, the landscape pattern indices used in previous studies were inconsistent in type and number. Furthermore, few studies combined the composition and configuration indices into one integrated indicator. The description of landscape pattern is thus a great yet rewarding challenge. In this study, we used the integrated location weighted landscape index (LWLI) proposed by Chen et al. (2009) and revised it to indicate potential UHIs. Fifty-six circular landscape samples along four transects were created and the LWLI was derived based on the theory of the GINI index. The LWLI considers the type, composition and configuration of different land covers inside a landscape, where configuration is treated as location weights. The potential UHI was represented by the land surface temperature (LST) of each circle landscape center. The correlation analysis results showed that the LWLI was significantly positively correlated with summer potential UHIs, with a Pearson R equaling 0.736, and barely correlated with winter potential UHI. Moreover, the LWLI was slightly more strongly correlated with potential UHI than composition alone. These correlations weakened as the landscapes grew larger. The linear regression results further revealed that the LWLI explained about 53% of the summer potential UHI, which was slightly better than composition alone (49%). This indicated that the LWLI was as effective in predicting the potential UHI as the combination of several pattern indicators, echoing Tobler's first law of geography, which states that “all things are related, but nearby things are more related than distant things.” This study also leaves room for improvement of the index by integrating more environmental/ecological parameters as weights, and for further application of the index in other fields.

1. Introduction

Global urbanization often leads to the deterioration of the urban climates, causing urban heat islands (UHIs). Originally, and still most commonly, the term UHI refers to the phenomenon that more urbanized areas have a higher air temperature than their surrounding suburban areas. With the development of thermal infrared remote sensing in the last few decades, UHI can also refer to surface UHI; namely, the difference in land surface temperature (LST) at the urban canopy layer or the urban boundary layer (Buyantuyev and Wu, 2010; Saaroni et al., 2000; Voogt, 2002). The LST is the mean radiative skin temperature, determined by air temperature and long-wave radiation between the surface and the atmosphere (Nichol et al., 2009; Weng, 2009). Unlike air temperature, LST has a higher spatial resolution and relates more closely to surface land use or landscape pattern, which can easily be derived from remote sensing data (Imhoff et al., 2010; Voogt and Oke, 2003; Weng, 2009). Thus, surface UHI and its associated data source, LST, have been increasingly used in the study of urban climate in recent decades (EPA, 2009; Li et al., 2013; Mirzaei and Haghighat, 2010). Previous studies have shown that both air and surface UHIs are associated with heat waves (Changnon et al., 1996; Fischer et al., 2007), disease (Liu and Weng, 2009) and pose a health risk to more than 50% of the world's population (Frumkin and McMichael, 2008; Wu, 2010). Hence, sustainable urbanization is urgently needed to

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http://dx.doi.org/10.1016/j.ecolind.2016.05.045
1470-160X/

mitigate the effects of UHIs and improve urban living conditions (Opdam et al., 2009; Wu, 2010).

For this purpose, a large body of research (Chen et al., 2014; Connors et al., 2013; Li et al., 2011; Weng et al., 2007; Zhou et al., 2011) has focused on the relationship between surface UHIs and landscape patterns using landscape indices based on the concept of landscape ecology; that is, the theory that landscape patterns strongly affect and are affected by ecological processes (Turner, 1989). Composition and configuration, as two aspects of landscape patterns, were both tested (Chen et al., 2014; Connors et al., 2013; Zhou et al., 2011), with the conclusion that composition is more effective than configuration in influencing LSTs or surface urban heat islands (SUHIs) (Chen et al., 2014; Li et al., 2012; Zhou et al., 2011).

However, there has been less consistency in the type and number of landscape indices used in previous studies (Chen et al., 2014). Usually, a set of metrics rather than an integrated metric was needed to describe the landscape pattern. The percentage of a certain class in the whole landscape (PLAND) as a composition metric is a prerequisite and is the most used (Chen et al., 2014; Connors et al., 2013; Zhou et al., 2011), whereas several other configuration metrics were also needed, including shape metrics, edge metrics and isolation metrics. For instance, the perimeter-area ratio (PARA), shape index (SI) and fraction index (FRAC) are used to describe shape while the gyration index (GYRATE), total edge (TE), edge density (ED) and so on are used to describe the edge (McGarigal et al., 2012). One or several shape, edge and diversity metrics were always added to PLAND to indicate SUHIs.

Numerous metrics (Baker and Cai, 1992; McGarigal and Marks, 1994; McGarigal et al., 2002, 2009; O'neill et al., 1988) have been proposed and used to describe landscape patterns, and landscape composition and configuration have been addressed. These metrics are not only used in UHI-landscape pattern analysis, but also in many other fields such as water quality and biodiversity (Schindler et al., 2013; Uuemaa et al., 2013). Nonetheless, these metrics face serious problems with redundancy and difficulty in interpretation (Cushman et al., 2008; Kupfer, 2012; Uuemaa et al., 2013). Chen et al. (2014) showed that landscape metrics exhibit high redundancy in indicating LSTs, and that proportion is the most important factor affecting LSTs.

Recently, there have been some appreciable efforts to create indicators linking landscape patterns to ecological function (Chen et al., 2009; Ku'ulei et al., 2012). This is a good sign and a necessary trend, especially when combined with spatial analysis (Kupfer, 2012). Ku'ulei et al. (2012) considered the classes and composition of a landscape, whereas Chen et al. (2009) also considered landscape configuration, and constructed an integrated landscape index they named the location-weighted landscape index (LWLI). The theoretical basis of the LWLI, is "source-sink" landscape theory (Chen et al., 2008, 2009) and Tobler's first law of geography (1970), which states that "all things are related, but nearby things are more related than distant things." "Source-sink" landscape theory (Chen et al., 2008) classifies the attribute class within a landscape as "source," "sink" or "flow," according to its contribution to the targeted ecological process. The construction of the LWLI falls within the frameworks of the Lorenz Curve and the GINI index (Chen et al., 2009; Gastwirth, 1972). One trial, in which the LWLI and "source-sink" landscape theory were used to assess the effects of landscape type and configuration on nutrient losses in a watershed (Chen et al., 2009) proved to be both efficient and effective.

In this study, we used the LWLI to describe landscape patterns in urban areas to examine its performance in predicting UHIs. Tobler's first law of geography implies that the LST of a landscape center would be more affected by the nearer landscape, and urban areas tend to form a heat center with more "hot" land acting as a heat "source" located around the center. Consequently, the hypothesis is that the LWLI describing the distribution of "source" and "sink" land cover around a landscape center might be correlated with the center LST. The subsequent analysis focused on testing this hypothesis to find the seasonal performances of the LWLI in indicating the center LST in different scales of landscape. The index is meant to be useful in describing the landscape structure around an urban center, and is helpful in predicting the potential of a UHI effect for an urban planning graph.

2. Methodology

2.1. Study area and sample landscapes

We took Beijing (39.9°N,116. 3°E), China as the case study area. Beijing has a monsoon-influenced humid continental climate characterized by hot-humid summers, due to the East Asian monsoon, and cold-windy-dry winters, due to the Siberian anticyclone. The highest average daytime temperature in January is around 1 °C, whereas in July the highest average daytime temperature is higher than 30 °C. Although the average UHI's summer daytime air intensity in the 1970s was only about 1 °C, and has only increased 0.31 °C every ten years since then (Yu et al., 2005), the surface UHI analysis shows a higher UHI intensity, ranging from 5 to 10 °C (Wang et al., 2007).

The city spreads out in five concentric ring roads, which go from the Second Ring Road around the urban center to the Sixth Ring Road in the suburbs, as shown in Fig. 1. The region within the Fifth Ring Road was used as the study area because it is the main metropolitan area.

Four transects were created and points were assigned on them at 1 km intervals. This resulted in 56 sample points, as shown in Fig. 1. Round sample landscapes were created based on these points by the Buffer Analysis Tool in the ArcGIS^{TM} software. Four radii—500, 1000, 1500 and 2000 m—were used to derive the round buffers representing different scales of circular landscapes.

2.2. Materials

2.2.1. Land cover map

Six swaths of QuickBird (QB) images were used to obtain land cover data. The central parts of the study area (~75%) were covered by two QB images taken on July 5, 2002. The other parts were covered by four QB images, with the two eastern images taken on April 24, 2002 and the two western images taken on April 1, 2002.

Unsupervised classification and the decision tree method were combined to obtain the land cover map, as detailed in Chen et al. (2014). Four types of land cover were considered for land use classification: vegetation, water, bare soil and built up areas or impervious surfaces (ISs). The vegetation in the metropolis was mainly a mix of grass, shrubs and trees. ISs included buildings and impervious roads. Bare soil was generally bare land. "Water" referred to rivers and lakes.

The overall accuracy was 85.2% (31674/37174 pixels), with a Kappa coefficient of 0.79. The mapping resulted in a pattern of land cover with 931.0 ha (1.4%) of water, 26882.5 ha (40.3%) of vegetation and 38915.3 ha (50.3%) of built up surface, plus bare soil (8.0%), as shown in Fig. 2.

Please note that 4.16% of the central parts of the QB images are clouds. We used the land cover date mapping from the IKONOS images on July 9, 2012 to replace the cloud area. The cloudy parts were mostly located in the already urbanized area, where less land cover was changing. Moreover, we used the transect samples, which cover only small sections of the clouds. The error from cloud effects was thus negligible.