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Characterizing bi-temporal patterns of land surface temperature using landscape metrics based on sub-pixel classifications from Landsat TM/ETM+

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ABSTRACT

Landscape patterns in a region have different sizes, shapes and spatial arrangements, which contribute to the spatial heterogeneity of the landscape and are linked to the distinct behavior of thermal environments. There is a lack of research generating landscape metrics from discretized percent impervious surface area data (ISA), which can be used as an indicator of urban spatial structure and level of development, and quantitatively characterizing the spatial patterns of landscapes and land surface temperatures (LST). In this study, linear spectral mixture analysis (LSMA) is used to derive sub-pixel ISA. Continuous fractional cover thresholds are used to discretize percent ISA into different categories related to urban land cover patterns. Landscape metrics are calculated based on different ISA categories and used to quantify urban landscape patterns and LST configurations. The characteristics of LST and percent ISA are quantified by landscape metrics such as indices of patch density, aggregation, connectedness, shape and shape complexity. The urban thermal intensity is also analyzed based on percent ISA. The results indicate that landscape metrics are sensitive to the variation of pixel values of fractional ISA, and the integration of LST, LSMA. Landscape metrics provide a quantitative method for describing the spatial distribution and seasonal variation in urban thermal patterns in response to associated urban land cover patterns.

1. Introduction

The urban heat island (UHI) effect is due primarily to the increased use of impervious surface materials, the decrease of vegetation cover and water-permeable surfaces and the emission of heat by human activities (Kato and Yamaguchi, 2005). Its magnitude is exacerbated by global climate change. Land surface temperature (LST) is impacted by surface–atmosphere interactions and energy fluxes between the land surface and the atmosphere (Wan and Dozier, 1996). Past studies measuring LST and heat fluxes have been mainly based on ground observations and digital model simulation (Voogt and Oke, 2003; Weng et al., 2004). Generally, ground observation studies describe detailed seasonal variations of thermal environments, but the number of observations is usually limited due to physical and economic constraints (Voogt and Oke, 2003). Advances in remote sensing have enabled the use of satellite data at various spatial and temporal resolutions for estimating surface temperatures over entire urban regions (Xian and Crane, 2006; Zhang et al., 2009). Thus, satellite remote sensing has been used extensively for a description of thermal patterns and simple correlation analysis of spatially heterogeneous urban land use patterns (Pu et al., 2006; Amiri et al., 2009; Imhoff et al., 2010; Deng and Wu, 2013).

Many previous remote sensing studies of the urban environment have used the Normalized Difference Vegetation Index (NDVI) as a descriptor for urban climate patterns (Lo et al., 1997; Gallo and Owen, 1999; Yuan and Bauer, 2007). However, NDVI measurements are subject to seasonal variations due to vegetation phenological cycles. Furthermore, the relationship between NDVI and LST is known to be non-linear (Price, 1990; Owen et al., 1998; Chen et al., 2006). Therefore, NDVI alone is considered insufficient for quantitatively studying urban environments. Impervious surfaces are defined as any impenetrable material, such as rooftops, roads, parking lots and other man-made surfaces that prevent infiltration of water into the soil (Arnold and Gibbons, 1996).

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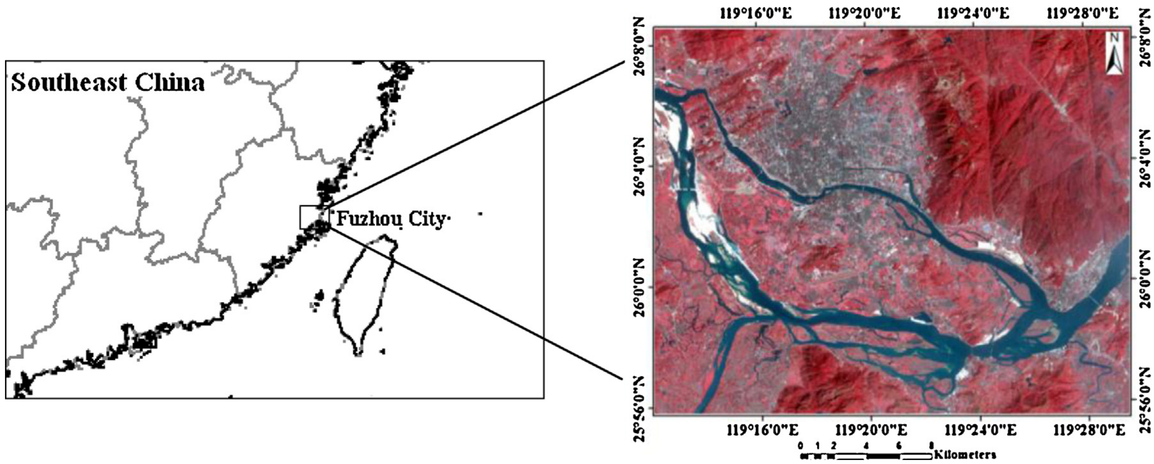

Fig. 1. Location of the study area showing the Landsat 7 ETM+ image.

Impervious surface areas (ISA) are stable and not affected by seasonal changes, and are therefore an important parameter for the analysis of LST and urban thermal patterns (Lu and Weng, 2006; Zhou et al., 2014). At the scale of 20–50 m it is common in many cities to have mixed pixels that are only partially covered by ISA. Due to this mixed pixel problem, in many cities traditional per-pixel classifiers cannot effectively handle the complex fine-scale urban landscape patterns. A solution is to use percent ISA rather than a crisp classification to characterize urban land cover patterns (Lu and Weng, 2006; Frazier and Wang, 2011). The vegetation–impervious–soil (VIS) model assumes that the spectral signature of land cover in urban environments is a linear combination of vegetation, impervious surfaces, and soil when water surfaces can be ignored (Ridd, 1995). The VIS model is an effective way of coping with the mixed-pixel problem (Smith et al., 1990; Rashed, 2008; Michishita et al., 2012). Continuous percent ISA information on a scale from 0% to 100% also reveals central business districts (CBD) and urban residential areas with varying densities and patterns, rural developed centers and relatively undeveloped areas (Zhang et al., 2009). For the purpose of developing effective climate change adaptation strategies in urban environments it is important to analyze the relationship between LST and percent ISA in urban environments as an alternative approach to traditional land cover based methods.

Landscape/land use/land cover patches in a region have different sizes, shapes and spatial arrangements. These contribute to the spatial heterogeneity of the landscape, and have significant effects on urban thermal environments (Zhang et al., 2013a,b; Liu and Weng, 2008; Maimaitiyiming et al., 2014). To understand the dynamics of patterns and processes and their interactions in the landscape, methods for accurately quantifying the spatial landscape patterns and their seasonal changes are required. A series of landscape metrics have been developed to characterize spatial landscape patterns and their impacts on the environment (Frazier and Wang, 2011; Liu and Weng, 2008; Riitters et al., 1995; Gustafson, 1998; Yue et al., 2007). When applied to the study of urban LST patterns, these landscape metrics have often been calculated based on 'hard', binary classifications of ISA and other land cover categories (Liu and Weng, 2008; Li et al., 2011).

However, in the published literature such landscape metrics have not yet been calculated from percent ISA, i.e., a 'soft' classification of ISA, to our knowledge. This may be because these metrics cannot be computed directly for percent ISA. This paper has tested a new method for discretizing sub-pixel ISA data at gradually increasing thresholds using two different approaches: the range approach and the threshold continuum approach. Based on converting continuous ISA fractions to discrete ISA classes by these two methods, landscape metrics can be calculated for each discrete ISA class. This provides the advantage that sub-pixel information on percent ISA provides more realistic descriptions of urban landscape structure than 'hard' land cover classifications. In addition to the absolute fraction of ISA, the effects of different spatial patterns of percent ISA on the magnitude of urban LST is quantified here with landscape metrics including the indices of patchiness, edge length, fractal dimension and texture. Since these metrics are sensitive to the variations of the sub-pixel ISA values, we can analyze quantitatively how different spatial patterns of different percent ISA zones contribute to the overall urban thermal characteristics and patterns in a city. The results of this analysis of micrometeorological seasonal variability will provide valuable information for the validation of predicted climatic change at the local scale.

2. Study area and data

The study area is Fuzhou City, located on the southeast coast of China (Fig. 1). Like many other Chinese cities, the population of Fuzhou is rapidly increasing (from 5.2 million in 1989 to 6.5 million in 2001) leading to increased urban expansion. Compared with the warmer summer climate, the weather in Fuzhou in spring, autumn and winter is relatively similar. Therefore, two images were selected to quantify the effects of the two major climatic seasons: A Landsat 5 TM image (acquired on June 15, 1989) and a Landsat 7 ETM+ image (acquired on March 4, 2001). Landsat bands 1–5 and 7 images have a spatial resolution of 30 m, and the thermal infrared band (band 6) has 120 m spatial resolution for TM and 60 m for ETM+.

An IKONOS image acquired on 29 October 2000 with 4 m spatial resolution and aerial photographs acquired on 20 May 1988 with 2 m spatial resolution were used to validate the retrievals of ISA from Landsat data. All images were reprojected to the Universal Transverse Mercator (UTM) projection, based on the geocoded high resolution IKONOS image and aerial photograph. The RMSE of the georectification was <0.3 pixels (<9 m).

We used the radiative transfer equation to retrieve LST from the Landsat data. This method has three steps (Zhang et al., 2009; Yuan and Bauer, 2007): The first step is to convert the digital numbers of the bands to top-of-atmosphere (TOA) radiance (Schroeder et al., 2006), and then to further convert TOA radiance of visible and near-infrared bands to surface reflectance by applying an atmospheric correction. Step 2 is to convert TOA radiance of the thermal band to surface-leaving radiance using the atmospheric correction tool MODTRAN 4.1 to remove the effects of the atmosphere (Berk et al.,