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Analysis of land use/land cover change, population shift, and their effects on spatiotemporal patterns of urban heat islands in metropolitan Shanghai, China

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A B S T R A C T

Using time series Landsat TM/ETM+ imagery and demographic data of Shanghai for 1997 and 2008, the relationship between land use/land cover (LULC) change and population shift and their effects on the spatiotemporal patterns of urban heat islands (UHIs) were quantitatively examined using an integrated approach of remote sensing, geographical information systems (GIS), and statistical analysis. The results showed that this city has experienced unprecedented urban growth and sprawl during the study period. The developed land increased by 219.50%, approximately 72.52% of which was converted from former cropland (24.79%), fallow land (21.21%), forest and shrub (18.97%), bare land (6.62%), and water (0.93%). Furthermore, in combination with the detection of LULC change, an analysis of the spatially differential growth rates for developed land area and population size revealed an urban–suburban–exurban gradient pattern of population shifting, as evidenced by a sharp increase in developed land area within the middle sub-zones at the urban fringe and the exurban sub-zones beyond the outer traffic ring. Consequently, changes in LULC and population shifts resulted in significant variation in the spatiotemporal patterns of the UHIs due to the loss of water bodies and vegetated surfaces. In the foreseeable future, substantial population growth and urban expansion will continue, especially in the rapidly urbanizing suburban and exurban areas, and thus, the extent and magnitude of UHI effects will continue expanding as well. The relationships between land use, the UHI effect, and regional climate change require that the underlying mechanisms, patterns, and processes of land conversion as well as the response of urban climate should be addressed throughout official decision-making processes. Thus, the planners and decision-makers could fully evaluate the environmental consequences of different land development scenarios and therefore improve the scientific basis of future planning and regulations.

Introduction

It is estimated that more than 50% of the global population lives in urban areas, and this percentage will reach 69.6% by 2050 (United Nations, 2010). Currently, urbanization is considered the most important driver of climate change (McCarthy, Best, & Betts, 2010), although the total urban area accounts for only a small proportion of the planetary surface (Grimm, Grove, Pickett, & Redman, 2000; Grũbler, 1994). As addressed in previous studies, intensive and rapid urbanization is an example of human-induced land use/land cover (LULC) change, which has exacerbated the ongoing impacts on the climate system (Jin, Dickinson, & Zhang, 2005). Changes ranging from multi-scale factors such as micro-climatology, biophysical features of underlying surface, urban form and size, and population density played key roles in modifying the local and regional climate (Oke, 1982; Stone, Hess, & Frumkin, 2010). Thus, understanding the influences of urban LULC change on the climate system is of interest in the context of global warming (Trenberth et al., 2007).

Among many useful indices that interpret the relationship between urbanization and climate change, the most well-known and familiar manifestation of urban climate modification is the urban

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heat island (UHI) (Souch & Grimmond, 2006; Yow, 2007), which is closely linked with urban air quality (Han et al., 2009), energy consumption (Kolokotroni, Giannitsaris, & Watkins, 2006), and population health risk (Hattis, Ogneva-Himmelberger, & Ratick, 2012; Johnson, Stanforth, Lulla, & Luber, 2012). In addition to large-scale weather conditions, the UHI is generally regarded as a local- or meso-scale climatic phenomenon associated with human activities (Zhou & Zhang, 1985). To date, to give a spatially continuous view of the UHI induced by human activities, a combination of in-situ data from meteorological station networks and satellite thermal data is beneficial to understand the processes and mechanisms of the UHI associated with land use/land cover (LULC) change (Stathopoulou & Cartalis, 2007). Traditionally, the atmospheric UHI was measured using fine-scale data, in particular the data from meteorological station sites founded by Luke Howard in the 1900s, the early years of meteorology (Zhou & Zhang, 1985). Unfortunately, it is somewhat difficult to recognize spatial patterns of the UHI with in-situ observational data due to their limited spatial coverage and poor spatial resolution (Streutker, 2003). As an alternative, with recent progress in the field of earth observation, satellite-based remote sensing has been a promising approach to monitor patterns of UHIs at meso and large scales, although the temporal resolution of satellite thermal data is less than that of meteorological observation data. This use of satellite thermal data has been possible and practical since it was first used to study UHIs in the 1970s (Rao, 1972). Since then, high spatial resolution satellite thermal data acquired in the daytime have been widely used to detect surface UHIs on meso or large scales when heat island intensities are greatest (Roth, Oke, & Emery, 1989). More recent studies have validated the successful application of various satellite thermal infrared (TIR) data with varying spatial resolutions, including AVHRR (8 km), MODIS (1 km), HJ-1 B (300 m), Landsat TM (120 m), ASTER (90 m), and Landsat ETM+ (60 m), due to their economical low cost, advantageous spatial coverage, and temporal repetition (Aniello, Morgan, Busbey, & Newland, 1995; Chen, Zhao, Li, & Yin, 2006; Dousset & Gourmelon, 2003; Jusuf, Wong, Hagen, Anggoro, & Hong, 2007; Lo & Quattrochi, 2003; Pongrácz, Bartholy, & Dezso, 2010; Yang, Gong, Zhou, Huang, & Wang, 2010; Yue, Liu, Ye, & Wu, 2012; Zhou, Zhou, Ge, & Ding, 2001).

Among these available remotely sensed data, the Landsat TM/ETM+ data have been widely used in many case studies of UHIs worldwide (Srivastava, Majumdar, & Bhattacharya, 2009; Stathopoulou & Cartalis, 2007; Weng, 2001; Xian & Crane, 2006), given the free open-access for data acquisition, the long time span, and the spatial coverage for most of the UHI hotspot areas. Moreover, compared with the coarse resolution TIR data, such as AVHRR and MODIS, the recognition of UHIs based on Landsat TM/ETM+ data can produce persuasive results with much greater accuracy. Previous case studies have provided a wealth of useful information, which has allowed us to rethink the adverse consequences of LULC change and rapid urbanization and to therefore help the decision-makers develop and execute rational land use policies. However, studies using a combination of socio-economic analysis and time series Landsat TM/ETM+ data over a long time span were relatively scarce. This inevitably limited our understanding of the relationship between human activities and the UHI effect. Thus, the fast-growing Shanghai metropolis in China is taken as an example; the purpose of this study is to utilize an enhanced methodology to address the following questions: (1) How do changes in LULC, urban form, and population shift influence the spatiotemporal patterns of the UHI? (2) What are the relationships between the driving forces and the UHI? and (3) What are the implications for official policies on land use zoning and strategies for mitigating UHI effects and adapting to climate change?

Study area

The study area is the Shanghai metropolitan area, located between latitudes 31°32′N and 31°27′N and longitudes 120°52′E and 121°45′E (Fig. 1). This area has a northern subtropical monsoon climate, with an average annual temperature of approximately 15 °C. The high temperatures average 28 °C in the summer and 4 °C in the winter. The average annual precipitation is approximately 1000–1200 mm, with 60% of the rainfall occurring during May and September. Topographically, the area is primarily located on an alluvial terrace of the Yangtze River basin. The elevation of the area ranges between 1 and 103.4 m, with an average of 4 m.

Administratively, the Shanghai metropolitan area consists of seventeen districts, covering a stable terrestrial area of 6450 km^2 (excluding recent tidal land reclamation, the Yangtze river estuary waters, and the Hangzhou bay water area), with a total of 18.18 million residents (Shanghai Municipal Statistics Bureau, 2009). This study focuses on the city of Shanghai proper and its surrounding area, which covers an area of approximately 3999.3 km^2.

To better describe the LULC change patterns, based on our prior knowledge of the land use properties, development intensity, and socio-economic levels of the study area (Li, Zhang, & Kainz, 2012), a total of thirty-two sub-zones was recognized as follows: (1) inner sub-zones within the city proper, enclosed by the inner traffic ring, which are characterized by very dense commercial and residential areas; (2) middle sub-zones at the urban fringe between the inner and outer traffic rings, which are characterized by dense industrial and residential areas; and (3) exurban sub-zones beyond the outer traffic ring, which are characterized by low density to moderate density residential areas, cropland, and natural environment, except for several major industrial parks, such as the Baosteel Corporation in the north and the Wujing chemical industrial park in the south.

Data and methodology

In this study, a working flowchart describing the technical process for the detection of land cover change, the retrieval of land

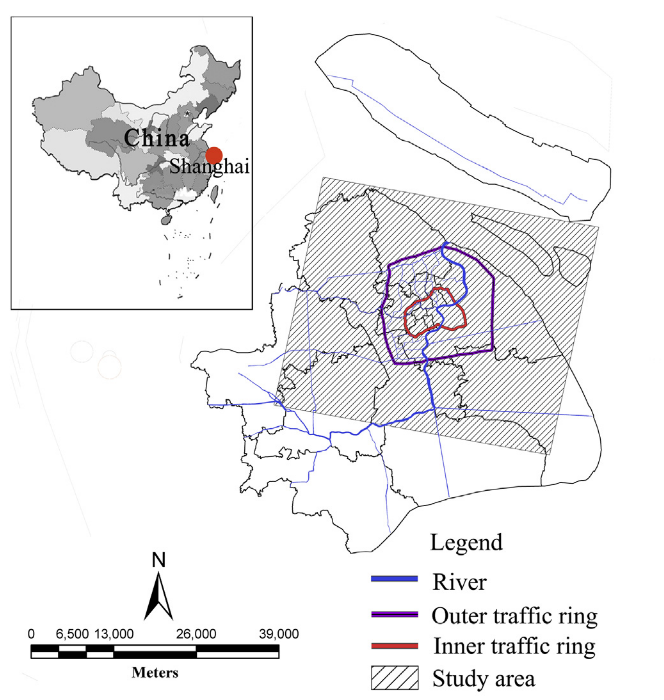

Fig. 1. Location of the study area.