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Research Paper

How does sprawl differ across cities in China? A multi-scale investigation using nighttime light and census data

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HIGHLIGHTS

- We analyzed urban sprawl for 657 cities of various sizes in China from 1990-2010.
- The annual growth of urban areas was 2.45% greater than that of urban population.
- Small and medium cities in west China had the highest level of urban sprawl.
- Combining nighttime light data and census data can effectively monitor urban sprawl.

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ABSTRACT

Timely and accurate measurement of urban sprawl is indispensable for assessing its environmental and societal impacts. However, few studies have examined urban sprawl in cities across China. In this study, we quantified urban sprawl in different cities across China from 1990 to 2010 by combining the Defense Meteorological Satellite Program's Operational Linescan System (DMSP/OLS) nighttime light images and national census data. We found that the annual growth rate of urban areas was 2.45% greater than that of the urban population in China from 1990 to 2010, indicating an overall trend of urban sprawl. Small and medium cities in west China had the highest level of sprawl over time. We conclude that much more attention should be given to the prevention of excessive urban expansion in small and medium cities in west China.

1. Introduction

Urban sprawl refers to a process of low-density and inefficient urban expansion (Bhatta, Saraswati, & Bandyopadhyay, 2010). A key feature of urban sprawl is that the growth rate of the urban area exceeds that of the urban population (Anthony, 2004; Fulton & Pendall, 2001; Jaeger, Bertiller, Schwick, & Kienast, 2010; Lopez, 2014; Wilson & Chakraborty, 2013). Urban sprawl has led to many environmental problems, including the increased frequency of extreme heat events (Stone, Hess, & Frumkin, 2010), loss of biodiversity (Valiela & Martinetto, 2007), degradation of water quality (Tu, Xia, Clarke, & Frei, 2007), loss of prime farmland (Milesi, Elvidge, Nemani, & Running, 2003), growth of greenhouse gas emissions (Ewing, Pendall, & Chen, 2003), and an increase in land fragmentation (Irwin & Bockstael, 2007).

Urban sprawl has become a common phenomenon around the world because of rapid population growth and global urbanization (Angel, 2012; Clark, Mcchesney, Munroe, & Irwin, 2009; Clifton, Ewing, Knaap, & Song, 2008; Hamidi & Ewing, 2014; Kaza, 2013). The European Environment Agency has reported that the urban area of 24 European cities increased by 78% from 1950 to 2000, whereas the urban population only increased by 33% (EEA, 2006). Fulton and Pendall (2001) found that the amount of urbanized land in 281 metropolitan areas in the United States increased by 47% during the period 1982–1997, whereas the nation's population grew by only 17%. During the last decade, China has witnessed a 46% increase in its urban population, but a 78.5% increase in the area of built-up land (Bai, Shi, & Liu, 2014). Moreover, the trend of rapid urbanization is expected to continue in China in the coming years,

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with the associated risk of further sprawl (Zhao, 2010). According to a recent government forecast, the urban population in China will reach 60% of the total population by 2020 with an annual growth rate of 1% (Bai et al., 2014). Concurrent with such rapid urbanization, the accurate monitoring of the extent of sprawl is necessary to evaluate its impacts on environment and society in China (Zhu, 2005).

Fung (1981) first introduced the term "urban sprawl" into China to describe the nation's urban development. Subsequently, along with the rapid and massive expansion of Chinese cities, urban sprawl has attracted widespread attention from academics and policymakers (Wei & Zhao, 2009). Urban sprawl has been analyzed in many Chinese cities, including Guangzhou (Yu & Ng, 2007), Beijing (Jiang, Liu, Yuan, & Zhang, 2007), Hangzhou (Su, Gu, Yang, Chen, & Zhen, 2010), Shenzhen (Lv et al., 2010), and Wuhan (Zeng, Liu, Stein, & Jiao, 2015).

However, urban sprawl in small and medium cities has received little attention despite the fact that around 80% of China's cities fall into this category. Furthermore, few comparative studies have examined urban sprawl across cities of different sizes in China. This is mainly due to the difficulty of obtaining accurate and timely data for the urban area and population of all cities nationwide. For example, most studies of urban sprawl in China have used data derived from medium-resolution remote sensing images (e.g., Landsat Thematic Mapper (TM)) (Lv et al., 2010; Ma, Gu, Pu, & Ma, 2008; Yeh & Li, 2001), which require very time-consuming data collection processes (He, Liu, Tian, & Ma, 2014; Liu, He, Zhang, Huang, & Yang, 2012; Zhang, He, & Liu, 2014). In addition, urban populations have largely been replaced by nonagricultural populations due to the greater data availability of the latter (Jiang, Deng, & Seto, 2012; Yang, Wu, & Shen, 2013; Yang, He, Zhang, Han, & Du, 2013). However, the nonagricultural population represents only a portion of the urban population because it omits many peasant workers who live and work in cities, but lack registered nonagricultural status (Wang, 2011). For example, the number of peasant workers living in cities nationwide was 245 million in 2013 (Bai et al., 2014). Nonagricultural population data may therefore underestimate the true urban population.

The nighttime stable light (NSL) data collected by the Defense Meteorological Satellite Program's Operational Linescan System (DMSP/OLS) and census data released by the National Bureau of Statistics of China (NBSC) can be used to provide accurate estimates of the urban area and urban population in China, respectively. The NSL data are publicly available from the National Geophysical Data Center, and the data size is more manageable than that of TM images (Zhang et al., 2014). More importantly, such data have been used to monitor urban expansion from the regional to a global scale (Elvidge et al., 1999, 2007; Huang, Yang, Gao, Yang, & Zhao, 2014; Huang et al., 2015; Sutton, 2003; Wei, Liu, Song, Yu, & Xiu, 2014; Yang, He, et al., 2013; Yu et al., 2014; Zhang & Seto, 2011). Based on the NSL data, Liu et al. (2012) and He et al. (2014) investigated urban expansion in China over the last two decades and provided reliable estimates of the urban area across the entire country. The recently released nationwide population census data have provided the latest and most accurate estimate of the urban population. The urban population recorded in the census counts the number of registered nonagricultural people, migrating peasant workers, and foreigners living in cities (Wang & Zhou, 1999). Therefore, the combined use of these two datasets may provide an alternative method for understanding the extent of urban sprawl in China.

The objective of this study was to quantify urban sprawl in cities of various sizes in China from 1990 to 2010, by combining DMSP/OLS NSL and recent census data. First, we quantified the extent of sprawl for 657 cities in China via the urban sprawl index (USI). Then, we compared the USI across cities of different sizes.

2. Data

We collected three types of data: urban area, population census data, and auxiliary data. Urban area data (1990 to 2010) were obtained by combining NSL data, the normalized difference vegetation index (NDVI), and land surface temperature (LST) (He et al., 2014). The data hold an average Kappa of 0.66 and an average overall accuracy of 95.20%, providing reliable information regarding urban expansion in China at a resolution of 1 km (He et al., 2014).

The census data of 657 Chinese cities were obtained by tabulating the urban populations in 1990 and 2010 (Population Census Office under the State Council and National Bureau of Statistics of China, 1992, 2012). Because changes to administrative boundaries can influence the calculation of urban population, we applied the city boundaries in 2010 to both datasets to ensure comparable urban areas and urban populations between 1990 and 2010. For cities with jurisdiction over several municipal districts, county-level cities, and counties, only the municipal districts were merged together to define the extent of the cities. Therefore, the county-level cities were not treated as components of large cities, and their USI values were examined separately.

For the auxiliary data, the administrative boundaries of counties, cities, and provinces were downloaded as Geographical Information System (GIS) files from the National Geomatics Center of China (http://ngcc.sbsm.gov.cn). The spatial scale of the data was 1:4,000,000. Due to the lack of census data for Taiwan, Hong Kong, and Macao, the analysis focused only on mainland China.

3. Methods

3.1. Measuring the extent of urban sprawl

Generally, two types of measure are used to gauge urban sprawl (Lopez, 2014). Some studies have incorporated the multidimensional aspects of sprawl into composite indexes, whereas others have concentrated on a single dimension. Both approaches have advantages and disadvantages. A composite measure provides a more nuanced portrait of urban sprawl, but requires more input data. Moreover, it is difficult to compare such results between different studies (Hamidi & Ewing, 2014; Jaeger et al., 2010). Therefore, composite measures have mainly been used in small-scale studies of one or several cities (Ewing et al., 2003; Frenkel & Ashkenazi, 2008; Galster et al., 2001). Single-dimension measures of sprawl have a limited capacity for identifying the varieties of urban sprawl (Lopez, 2014); however, they are easier to calculate than composite measures and enable comparisons to be made between cities and/or over time. Furthermore, some single-dimension measures (e.g., population density) tend to have a high degree of correlation with composite measures. Therefore, a single-dimensional measure may be adequate for measuring urban sprawl when the large datasets required by composite measures are unavailable (Lopez, 2014). In this study, therefore, the extent of urban sprawl was quantified based on a single measure: the USI (Fulton & Pendall, 2001). The USI considers two primary factors that are closely related to the extent of urban sprawl: the annual growth rate of an urban area and the urban population (Bart, 2010; Bhatta, 2009; EEA, 2006; Frenkel & Ashkenazi, 2008). If the growth in urban area exceeds that of the population during a given period, the pattern of urban development for that city is deemed to be urban sprawl, where a higher value of the USI indicates a larger extent of urban sprawl. The USI is calculated as follows:

$$USI^{i}_{(t_1,t_2)} = UA^{i}_{(t_1,t_2)} - UP^{i}_{(t_1,t_2)} \quad (1)$$

where $USI^{i}_{(t_1,t_2)}$ is the USI of city i from year t_1 to year t_2 (in this study, t_1 and t_2 were 1990 and 2010, respectively). $UA^{i}_{(t_1,t_2)}$ and