Landscape and Urban Planning 175 (2018) 50–61

Contents lists available at ScienceDirect

Landscape and Urban Planning

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

Research Paper

Spatial scaling of urban impervious surfaces across evolving landscapes: From cities to urban regions

Qun Ma[a], Jianguo Wu[b,a,*], Chunyang He[a,*], Guohua Hu[c]

[a] Center for Human-Environment System Sustainability (CHESS), State Key Laboratory of Earth Surface Processes and Resource Ecology (ESPRE), Faculty of Geographical Science, Beijing Normal University, Beijing 100875, China
[b] School of Life Sciences, School of Sustainability, and Julie Ann Wrigley Global Institute of Sustainability, Arizona State University, Tempe, AZ 85287, USA
[c] Key Lab of Geographic Information Science (Ministry of Education), School of Geographic Sciences, East China Normal University, Shanghai 200241, China

ARTICLE INFO

Keywords:
Urban impervious surfaces
Spatial scaling
Spatial extent
City size
Hierarchical approach
China

ABSTRACT

Urban impervious surfaces (UIS) influence the structure and function of urban systems, and are widely considered a key indicator of urban environmental conditions. However, the amount and pattern of UIS both change with spatial scale, which complicates the computation and interpretation of UIS as an indicator. A better understanding of the spatial scaling relations of UIS is needed to resolve this predicament. Thus, the main objective of this study was to explore how UIS would change with increasing spatial extent and population size across urban hierarchical levels, using data from the three largest urban agglomerations in China. In addition, a comparative analysis of six world metropolitan regions was conducted to test the generality of the UIS scaling relations. Scalograms and standardized major axis regression were used to investigate the scaling relations with respect to spatial extent and city size, respectively. Our major findings include: (1) the total amount of UIS increased, whereas the percentage of UIS decreased, in a staircase-like fashion when the spatial extent of analysis expanded from within a local city to the entire urban agglomeration; (2) the spatial scaling of UIS followed a rather consistent and tight power law function within a local city, but became less consistent and less tight beyond a local city; (3) the scaling relations of the total amount of UIS were more consistent than those of the percentage of UIS, and the total amount of UIS scaled more tightly with urban area than with urban population size. These findings shed new light on the scale dependence of UIS, suggesting that a multiscale approach should be adopted for quantifying UIS and for using it as an urban environmental indicator.

1. Introduction

Urbanization worldwide has converted more and more natural and agricultural lands into urban impervious surfaces (UIS) – i.e., human-made land covers in urban areas through which water cannot penetrate, including rooftops, roads, driveways, sidewalks, and parking lots (Arnold & Gibbons, 1996; Ma, He, & Wu, 2016; Ma, Wu, & He, 2016; Weng, 2012). In 2010, the global total of UIS was about 0.6 million km^2 (or 0.45% of the global land area excluding Antarctica and Greenland), and it has continued to increase rapidly (Liu, He, & Wu, 2016; Liu, He, Zhou, & Wu, 2014; Zhou et al., 2015). For example, the total amount of UIS of mainland China was 10,614.23 km^2 in 1992, and increased to 31,147.63 km^2 in 2009, tripling within 17 years (Ma et al., 2014).

While UIS occupies relatively a small portion of the land area on a regional or global scale, its myriad environmental impacts are disproportionately large (Arnold & Gibbons, 1996; Forman, 2016; Grimm et al., 2008; Luck, Jenerette, Wu, & Grimm, 2001). UIS can change the land surface energy balance, resulting in urban heat islands (Buyantuyev & Wu, 2010; Ma, Wu et al., 2016; Oke, 1982); increase the volume and intensity of urban runoff, leading to urban flooding (Brun & Band, 2000; Weng, 2001); and reduce water quality, degrading aquatic biodiversity and wetland ecosystems (Brabec, 2002; Goetz & Fiske, 2008). Thus, impervious surface coverage is not only a major measure of urbanization itself, but also a key indicator of environmental conditions (Arnold & Gibbons, 1996; Wu, 2014).

Thus, it is important to quantify the amount and spatial distribution of UIS for better understanding urbanization patterns and their environmental consequences. Towards this end, much work has been done during the past few decades based on remote sensing data (Elvidge et al., 2007; Lu, Li, Kuang, & Moran, 2014; Ma et al., 2014; Ma,

---

[*] Corresponding authors at: School of Life Sciences, School of Sustainability, and Julie Ann Wrigley Global Institute of Sustainability, Arizona State University, Tempe, AZ 85287, USA (J. Wu); Center for Human-Environment System Sustainability (CHESS), State Key Laboratory of Earth Surface Processes and Resource Ecology (ESPRE), Faculty of Geographical Science, Beijing Normal University, Beijing 100875, China (C. He).

E-mail addresses: Jingle.Wu@asu.edu (J. Wu), hcy@bnu.edu.cn (C. He).

https://doi.org/10.1016/j.landurbplan.2018.03.010
Received 18 September 2017; Received in revised form 18 January 2018; Accepted 14 March 2018

Wu et al., 2016). However, while we know that urban systems are hierarchically structured, in which large urban regions are composed of smaller sub-regions which in turn comprise individual cities (Batty, 2008; Li, Li, & Wu, 2013; Wu, 1999; Wu & David, 2002), little research has been done to quantify how UIS changes with spatial scale along the hierarchy of administrative levels. Yet, knowing how UIS is structured spatially from the local city to the regional urban agglomeration – i.e., the spatial scaling of UIS – is essential for understanding the patterns and processes of urbanization as well as their environmental impacts on multiple scales.

Quantifying the spatial pattern of UIS necessarily requires a multiscale approach, and scaling relations need to be developed for describing multiscale patterns and making predictions across scales, as numerous studies in ecological and geographical sciences have shown that spatial pattern is scale-dependent (Jelinski & Wu, 1996; Levin, 1992; Liu et al., 2016; Saura, 2004; Shen, Darrel Jenerette, Wu, & Gardner, 2004; Wu, 2004; Wu, Shen, Sun, & Tueller, 2002). Scaling usually refers to the translation of information across spatial and temporal scales or organizational levels, which frequently involves changing grain size, extent, or both (Wiens, 1989; Wu, 1999; Wu, Bruce Jones, Li, & Loucks, 2006). Wu et al. (2002) and Wu (2004) systematically examined the scaling relations of commonly used landscape metrics with respect to changing grain size and extent, and identified three general categories: simple scaling functions (linear or power laws), staircase-like functions, and unpredictable behavior. These findings have consequently been confirmed and amended by several studies (Argañaraz & Entraigas, 2014; Frazier, 2016; Frohn & Hao, 2006; Saura & Castro, 2007; Shen et al., 2004). These scaling relations are informative for understanding the multiscale structural properties of landscapes, and allow for cross-scale predictions when they can be expressed as mathematical functions (Wu, 2004; Wu et al., 2002).

Do such scaling relations exist for UIS when we measure them from a local city to its surrounding urban region and the even greater urban agglomeration? To address this question, we systematically examined the spatial scaling of UIS with respect to changing extent in three major urban megaregions of China, and then we further tested the generality of the UIS scaling relations by conducting similar analyses with several major metropolitan regions around the world. The study was designed to address the following questions: How does UIS change with increasing spatial extent across the administrative levels of urban hierarchy? How do the total amount and percentage of UIS scale differently in space? How does the scaling of UIS in space compare with the scaling of UIS with respect to urban population? Do the scaling relations of UIS derived from Chinese metropolitan regions apply to the world's other metropolitan regions?

2. Methods

2.1. Study area

China, as one of the fastest urbanizing nations around the world, has experienced a rapid and large-scale expansion of UIS, with an annual growth rate of 6.54% since 1992 (Ma et al., 2014). As the urban growth rate continues to accelerate in terms of both urbanized land area and urban human population, a number of urban agglomerations with different levels of economic and social development have emerged across China (Fang, 2011; Fang, 2015; Wu, Xiang, & Zhao, 2014). The three largest national-level urban agglomerations are the Beijing-Tianjin-Hebei (BTH) urban agglomeration, the Yangtze River Delta (YRD) urban agglomeration, and the Pearl River Delta (PRD) urban agglomeration. These three urban agglomerations together account for nearly 40% of the total UIS area, 36% of gross domestic product, and 18% of the total population of China (Ma et al., 2014; State Council of the People's Republic of China, 2014). We chose BTH, YRD, and PRD as the focal sites of our study (Fig. 1) because of their extraordinary environmental and socioeconomic importance, as well as their complete urban hierarchy that extends from the local city to the much broader region of urban agglomeration. In addition, these three urban agglomerations are not only the largest in China, but also have contrasting spatial patterns and urbanization trends due to different population densities and socioeconomic conditions (Kuang, Chi, Lu, & Dou, 2014). All the above characteristics facilitate an in-depth analysis of the spatial scaling of UIS.

We delineated the boundary of each urban agglomeration based on Fang (2011), and derived the demographic and economic data described below from the Department of Urban Surveys of National Bureau of Statistics of China (2011) and the Population Census Office under the State Council and Employment Statistics of National Bureau of Statistics of China (2013). The BTH is located in the North Plain-eastern coastal region of China, with a total land area of 182,000 km^2. In 2010, the total population of this region reached 83.79 million with an urbanization level of 59.95%, and its total GDP exceeded 3776 billion CNY. The YRD lies in the eastern coastal region of China, covering an area of 107,500 km^2. The total population in 2010 was 106.51 million with an urbanization level of 69.75%, and the total GDP was 7591 billion CNY. The PRD is distributed in the southern coastal region of China, covering an area of 54,100 km^2. In 2010, the PRD had 56.13 million people and an urbanization level of 82.72%, and its total GDP exceeded 3700 billion CNY.

Our analysis followed a hierarchical approach to urban studies (Li et al., 2013; Ma, Wu et al., 2016; Wu, 1999; Wu & David, 2002), explicitly considering three administrative levels within each urban agglomeration (Fig. 1): the city proper, the metropolitan region, and the urban agglomeration as a whole. The three levels formed a spatially nested urban landscape hierarchy as each city proper belonged exclusively to a metropolitan region which in turn was part of an urban agglomeration. Specifically, the BTH, YRD, and PRD each contained a megacity (the Beijing metropolitan region, the Shanghai metropolitan region, and the Guangzhou metropolitan region, respectively) whose city proper was chosen as the lowest level of analysis (Fig. 1).

2.2. Data acquisition and processing

The UIS map of China in 2009 with a spatial resolution of 1 × 1 km (Ma et al., 2014) was used in this study. In an earlier study, we developed an improved way of mapping UIS for large regions and quantified the UIS dynamics of China from 1992 to 2009 (Ma et al., 2014). The study utilized four types of remote sensing data to estimate the UIS of China in 2009: the Defense Meteorological Satellite Program's Operational Linescan System (DMSP/OLS) nighttime light (NTL) data (http://ngdc.noaa.gov/eog/dmsp/downloadV4composites.html), the Moderate Resolution Imaging Spectroradiometer (MODIS) 16-day Normalized Difference Vegetation Index (NDVI) composite data (https://ladsweb.nascom.nasa.gov/search/), high-resolution images available on Google Earth, and land use/cover data (http://www.geodata.cn/). The NTL data given in 30-arc-second grids and the annual mean NDVI data derived from the MODIS 16-day 1-km NDVI composite data in 2009 were projected onto an Albers Conical Equal Area Projection and resampled to a pixel size of 1 km based on a nearest neighbor resampling algorithm. The land use/cover data of China for 2010 were used as the reference data for extracting urban areas in 2009. Urban areas in this study refer to places with intensive human activities and extensive human-made land covers that include urban impervious surfaces, parks, and swimming pools/artificial ponds (Potere & Schneider, 2007; Wang et al., 2012). Detailed information on how these urban areas were classified is found in Ma et al. (2014). The accuracy assessment showed that our results of China's UIS had a much higher accuracy than previous estimates using NTL data, with the average root-mean-square error (RMSE) of 0.128, mean absolute error (MAE) of 0.105, systematic error (SE) of −0.008, and correlation coefficient (R) of 0.846 in 2009 (Ma et al., 2014). More details on the acquisition and processing of remote sensing data and estimation of UIS