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Research Paper

Urban land density function: A new method to characterize urban expansion

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HIGHLIGHTS

- We observe an Inverse S-shape Rule for the variation of urban land density.
- We propose an inverse S-shaped function to formulate urban land density.
- We derive an established method for concentric partitioning of urban area.
- Useful indicators are derived to characterize urban form and urban sprawl.
- The inverse S-shaped model could be applied to other geographical phenomena.

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ABSTRACT

Density analysis lies at the core of studies on urban expansion; however, many methods in urban land density analysis are arbitrary and suffer from the lack of an established foundation. We observed an "Inverse S-shape Rule" for urban land density that varies outward from an urban center by investigating 28 major cities in China at three time points. We proposed an inverse S-shaped function to formulate urban land density, which fit well for all of the cities in our sample using a nonlinear least squares fitting method. The parameters of the function explicitly describe the basic properties of an urban form. Based on the fitted functions, we derived an established method for the concentric partitioning of urban area and further proposed indicators to measure the urban compactness, urban expansion rate, and degree of urban sprawl. These indicators are practical for characterizing urban form and urban sprawl for either a single city or for multiple cities. A case study on major Chinese cities from 1990 to 2010 reveals that most of the cities expanded rapidly and became less compact and more dispersed during those two decades. However, most of the cities grew faster and showed more sprawl in the second decade compared to the first one. Discussions show that the model is also applicable for non-monocentric cities and possibly can be applied to many other geographical phenomena.

1. Introduction

Cities are dynamic complex systems (Bettencourt & West, 2010), and our understanding of how they evolve is still woefully inadequate (Batty, 2008). A fundamental activity of urban expansion research is the quantitative characterization of city morphology and dynamic growth. The beginning of the 21st century marked a milestone because half of the world's population has resided in cities since then (Fragkias & Seto, 2009). According to United Nations projections, urban population will increase by 1.35 billion by 2030, at which time the urban population in the world will be approximately 5 billion (United Nations, 2012). It is forecasted that global urban land will increase by 1.2 million km^2 by 2030, which will be almost triple the global urban land area circa 2000 (Seto, Guneralp, & Hutyra, 2012). The most significant urbanization in the future is expected to occur in Asia, especially in China and India (Angel, Parent, Civco, Blei, & Potere, 2011; Güneralp & Seto, 2008; Seto et al., 2012; Václavík, Lautenbach, Kuemmerle, & Seppelt, 2013). It is important and urgent to quantitatively characterize and evaluate regional or global urban expansion to support urban growth predictions and related decision making, especially for the areas expected to experience rapid urbanization in the future.

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Many metrics and statistics have been used to characterize urban form and urban sprawl (Arribas-Bel, Nijkamp, & Scholten, 2011; Bhatta, Saraswati, & Bandyopadhyay, 2010; Jat, Garg, & Khare, 2008; Ji, Ma, Twibell, & Underhill, 2006; Liu et al., 2010; Tavernia & Reed, 2009; Wilson, Hurd, Civco, Prisloe, & Arnold, 2003). These metrics, known as landscape metrics, are numerical measurements of the spatial pattern of land-cover at the patch level, class level, and landscape level. Landscape metrics can be generally referred to as spatial metrics because they have been applied to many research fields other than landscape ecology, in particular, urban areas (Herold, Couclelis, & Clarke, 2005; Herold, Goldstein, & Clarke, 2003). Seto and Fragkias (2005) conducted a comparative analysis of four rapidly developing cities in China using landscape metrics, including the edge density, area weighted mean patch fractal dimension, mean urban patch size, and so on. Tsai (2005) classified the metrics describing the urban form into three categories: density, diversity, and the spatial-structure pattern. Schneider and Woodcock (2008) examined the characteristics of the urban form and growth of 25 mid-sized cities across the world using spatial metrics and statistics, such as the built-up area, built-up land density, patch density, and population density. Taubenböck, Wegmann, Roth, Mehl, and Dech (2009) analyzed the spatiotemporal urban types in India by a combination of statistics (e.g., built-up density) and landscape metrics. Angel, Parent, and Civco (2007) presented five attributes of urban spatial structure to describe urban sprawl that were associated with the urban extent, urban population density, suburbanization, and built-up contiguity. In general, the researchers employed spatial metrics (including the built-up density or population density metrics) to characterize urban form and used the variation of the metrics to evaluate the degree of urban sprawl (Li, Li, & Wu, 2013; Xu & Min, 2013). It can be seen that density analyses are basic and important for urban expansion studies from both the studies mentioned above and many others (Bhatta et al., 2010). However, most density metrics used in previous studies were defined arbitrarily. For example, urban land density or built-up land density were defined by a questionable urban extent or based on a subjectively defined concentric partition of a city. A probe of some basic issues of urban land density is necessary to provide a comprehensive theoretical foundation for density analysis in urban studies.

Concentric partitioning of cities was commonly used in studies on urban form and urban sprawl. The variation in spatial metrics or density variables from the city center outward was often discussed (Irwin & Bockstael, 2007). Seto and Fragkias (2005) quantified the spatiotemporal patterns of cities by analyzing the spatial metrics in experientially defined buffer zones, namely, 0–3 km, 3–10 km, and 10–20 km. Taubenböck et al. (2009) analyzed urban structure based on six ring-shaped zones around the main urban center. Schneider and Woodcock (2008) defined the urban core area as a circular area with an urban land density above 50% and divided the remaining landscape into fringe, periphery, and hinterland regions with three 8-km buffers. The buffer zones around the urban center were usually defined by a threshold value for urban land density or given fixed buffer distances that were largely based on the experience of researchers. The researchers found that urban land density generally decreased from the urban center to the outside. Can we identify a universal and explicit rule for the variability of urban land density? Can we quantitatively describe this rule with a reasonable formulation?

Researchers have formulated many functions to describe urban population density, such as the negative exponential function, the Gaussian model, and the inverse power function (Batty & Kim, 1992; Chen & Feng, 2012; Clark, 1951). Until recently, there has been no formulation for urban land density. Compared to an urban population distribution, land use data are much easier to accurately acquire using remote sensing data. This provides a perfect data source to precisely investigate changes in urban land density and makes it possible to accurately formulate the trends of changes in urban land density.

In this study, with 28 major cities at three time points in China as samples, we will illustrate the general trend of urban land density variation from the urban center to the outside and propose a mathematical formulation of the rule. Then, we will investigate the properties of the function and discuss how to use the function to characterize urban form and the dynamics of urban sprawl. In this study, we observed an "Inverse S-shape Rule" for the variation of urban land density. This is the first report of the "Inverse S-shape Rule" for urban land density, and we also introduce new methods to characterize urban form and measure urban sprawl based on the S-shaped urban land density function.

2. Data

2.1. Sample of cities

We examined the urban land density of a total of 28 cities in mainland China in 1990, 2000, and 2010. Most of the cities are provincial capitals or municipalities. Two large cities located in western and southwestern China, Chongqing and Guiyang, were not included in the study due to a lack of available data. These cities are distributed across the Chinese mainland (see Fig. 1). Although most of the cities are capitals or municipalities, they are diverse in scale due to imbalanced regional development. The biggest cities in the sample, such as Shanghai and Beijing, had a population of more than 15 million in 2010 (National Bureau of Statistics of China, 2011), while the smallest cities, such as Haikou and Yinchuan, had a population of 0.37 million and 0.56 million in 1990, respectively (National Bureau of Statistics of China, 1991).

2.2. Image classification

We acquired high quality Landsat TM/ETM+ images for the cities for the years 1990, 2000, and 2010. All of the images are cloud-free (cloud < 10%) and were taken in summer months. Google online maps were used as references to acquire ancillary information, such as administrative information and transportation.

The steps of the image analysis included preprocessing and classification. Preprocessing the images included geometric correction, geographic registration, and resizing. The ETM+ images were resized to 30-meters to be consistent to the others. Image classification was performed using the Maximum Likelihood Classification method in ENVI 4.5. Four classes were extracted for each image, namely, built-up areas, vegetation, water, and other lands. We assessed the accuracy of each classified image with more than 250 independent samples, which were identified by visual interpretation. We revised the results or reclassified the images according to the accuracy assessment results. Finally, the accuracies for all of the results ranged from 85% to 93%.

3. Urban land density function

3.1. Defining urban land and urban extent

There are two problems to be addressed in defining urban land. One is defining what types of land are 'urban'. The other is determining the spatial extent of a city. Urban land in physical terms refers to a complex of impervious surfaces and urban vegetation. Impervious surfaces, including pavement, roofs, and compacted soil, that are closely associated with a built-up environment dominate an urban area. When using remote sensing images, urban land is best defined by impervious surface area (Arnold & Gibbons,