Landscape and Urban Planning 137 (2015) 30–39

Contents lists available at ScienceDirect

Landscape and Urban Planning

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

Research Paper

Multi-order Landscape Expansion Index: Characterizing urban expansion dynamics

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HIGHLIGHTS

- An improved spatial metric is proposed to characterize new urban patches.
- The metric measures the expansion degree of patches using time series data.
- The metric can be used to detect expansive areas and outlying urban clusters.
- The metric helps to characterize the spatial structure of urban expansion dynamics.

ARTICLE INFO

Article history:
Received 24 October 2013
Received in revised form 16 October 2014
Accepted 16 October 2014
Available online 16 January 2015

Keywords:
Multi-order Landscape Expansion Index
Landscape metrics
Urban sprawl
Multi-temporal remote sensing images
Urban clusters

ABSTRACT

Most of the landscape metrics used in urban expansion studies are capable of reflecting the spatial characteristics for individual time points, but are not efficient to capture the integrated information from time series data. A few spatial metrics, for example, Landscape Expansion Index (LEI), are calculated based on two-time-point data. These metrics are insufficient for the analysis of urban expansion dynamics based on multi-temporal data. In this study, we propose an improved spatial metric, Multi-order Landscape Expansion Index (MLEI), to measure the expansion degree of newly grown urban patches by considering their relationships with old patches and their spatial context in the process of urban expansion. A case study is conducted in Wuhan, a fast-growing metropolis in central China, based on remote sensing images from three time points (2000, 2005 and 2010). The MLEI map in 2010 clearly shows the areas that have experienced expansive growth. The greatest difference between MLEI and LEI occurs where outlying clusters are formed gradually through time. Some spatial analysis methods are applied on the MLEI map in 2010 to delineate outlying urban clusters in urban expansion. The map of urban clusters clearly shows the spatial heterogenicity of urban expansion and the most expansive areas in Wuhan. This study suggests that MLEI is capable to capture multi-temporal information, and can be used to characterize the spatial structure of urban expansion dynamics.

1. Introduction

1.1. Characterizing urban expansion using spatial metrics

Since the beginning of the 21st century, half of the global population resided in urban areas (United Nations, 2006). The urbanization rate in China exceeded 50% for the first time in 2012. Urbanization is not only a change in society and economy but also an important geospatial process. Quantitatively characterizing the process is essential for understanding the evolution of cities and prediction of urban growth.

Conventional landscape metrics provide fundamental support for characterization and understanding of the spatial pattern of urban expansion. However, these metrics were mainly computed at single-time-point maps and characterize spatial patterns separately in a time series. Until now, there have been few metrics that integrate the information from multi-temporal maps and directly reflect the properties of landscape dynamics. In recent years, researchers have developed numerous landscape metrics with the help of remote sensing and geographic information system (GIS) techniques, which made it possible to quantify the landscape

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http://dx.doi.org/10.1016/j.landurbplan.2014.10.023
0169-2046/

structures and analyze its dynamics (Forman & Godron, 1986). The landscape metrics are mainly based on size, shape, and arrangement of landscape patches (Matsushita, Xu, & Fukushima, 2006; Riitters et al., 1995; Turner & Gardner, 1991; Turner, O'Neill, Gardner, & Milne, 1989). Landscape metrics have been widely used in various environments; they are also known as spatial metrics (Herold, Couclelis, & Clarke, 2005). These metrics were variously derived from statistical theory, information theory, fractal geometry (Krummel, Gardner, Sugihara, O'neill, & Coleman, 1987; Pielou, 1977; Plotnick, Gardner, & O'Neill, 1993; Turner et al., 1989), and percolation theory (Gardner, O'Neill, & Turner, 1993; Li, Loehle, & Malon, 1996). Landscape metrics have been widely used in characterizing and analyzing various spatial patterns (Bailey & Gatrell, 1995; Csillag & Kabos, 2002; Imbernon & Branthomme, 2001; Liu et al., 2010; Zhang, Zhang, Li, & Cropp, 2006) such as plant communities, animal habitat, soil erosion, land-use and land-cover change (LUCC), urban landscape, and urban sprawl (Angel, Parent, Civco, Blei, & Potere, 2011; Fragkias & Seto, 2009; Herold, Goldstein, & Clarke, 2003). Although these indices can be used in time series analysis with multi-time-point landscape metric values, new indices must be developed to capture the information from multi-temporal data and directly characterize the dynamics of landscape patterns. Urban sprawl is a dynamic process, and characterization of the dynamics of the process is important to gain a better understanding of urban growth.

Many spatial metrics have been used to quantify the patterns of urban expansion. Researchers have also analyzed spatial dynamics using various spatial variables computed on multi-temporal maps (Luck & Wu, 2002). Tsai (2005) divided spatial variables in urban sprawl into three categories: density, diversity, and spatial-structure pattern. Galster et al. (2001) defined several concepts of urban land use patterns, e.g., density, continuity, concentration, clustering, centrality, and proximity. Many studies focus on establishing indices to analyze urban spatial patterns and urban sprawl based on spatial analyses and spatial metrics (Alberti & Waddell, 2000; Batisani & Yarnal, 2009; Feranec, Jaffrain, Soukup, & Hazeu, 2010; Geoghegan, Wainger, & Bockstael, 1997; Hasse, 2004; Herold et al., 2003; Parker, Evans, & Meretsky, 2001; Torrens, 2008). Some researchers developed entropy-based indices to characterize urban sprawl (Batty, 1976; Bhatta, 2009; Bhatta, Saraswati, & Bandyopadhyay, 2010; Li & Yeh, 2004; Sudhira, Ramachandra, & Jagadish, 2004; Yeh & Li, 2001). Jaeger and Schwick (2014) proposed a multidimensional metric to estimate the degree of urban sprawl. Luck and Wu (2002) studied the gradient analysis method for urban land use. Based on quantitative analysis of the spatial patterns, many researchers discussed the types of urban expansion, including infilling, edge-expansion, and outlying or leapfrog (Herold et al., 2003; Wilson, Hurd, Civco, Prisloe, & Arnold, 2003). Many researchers analyzed the dynamics and trends of urban sprawl by comparing landscape metrics from different time periods (Deng, Wang, Hong, & Qi, 2009; Herold et al., 2003). Some new theories on urban growth dynamics were proposed and investigated in case studies, such as the "rank-size rule" (Batty, Bourke, Cormode, & Anderson-Nicholls, 1974; Batty & Shiode, 2003; Nolè, Lasaponara, & Murgante, 2013; Tang, Wang, & Yao, 2006; Zipf, 1949) and oscillatory theory (Dietzel, Herold, Hemphill, & Clarke, 2005; Dietzel, Oguz, Hemphill, Clarke, & Gazulis, 2005; Martellozzo & Clarke, 2011).

1.2. The indices based on boundary-sharing rate in characterizing the process of urban expansion

A set of new spatial metrics to measure the expansion degree of newly grown urban patches was proposed, computed based on the percent of boundary sharing with old patches. Xu et al. (2007) used the ratio between common boundary and patch parameter to define urban growth types. In their study, the common boundary is captured between a new grown patch and its adjoining existing patches. By their definition, the ratio S is an indicator of patch growth types. An infilling expansion type is assigned when the ratio S is larger than 0.5, otherwise an edge-expansion growth is detected. Sun, Wu, Lv, Yao, and Wei (2013) defined an index R based on the same principle and identified three classes of urban growth types: infilling growth, edge-expansion growth, and outlying growth.

The Landscape Expansion Index (LEI) is an analogous spatial metric that is used by Liu et al. (2010) to characterize landscape expansion patterns. They used a buffer around a target patch instead of a one-dimensional boundary in the calculation of the index, which is the primary difference between the S and R indices. The LEI for a newly grown patch is calculated by:

$$\text{LEI} = \frac{A_0}{A_0 + A_v} \times 100\% \tag{1}$$

where A_0 is the area of the intersection between the buffer zone of the new patch and the existing patches (occupied category) and A_v is the area of the intersection between the buffer and the vacant category. An infilling growth patch is defined by an LEI larger than 50 and an edge-expansion growth patch was defined by an LEI smaller than 50 but not equal to zero. The patches with zero LEI were classified as outlying growth. The buffer distance used in computation has an impact on LEI. Liu et al. (2010) argued that the LEI value would be more stable by using a smaller buffer distance, and set the buffer distance equal to 1 m. The buffer distance will be more meaningful if it is set to a value that corresponds to the average size of a type of geographical entity usually used to divide urban blocks such as urban roads.

Although LEI captures the information in two-time-point data to quantify the dynamic change of urban expansion, it cannot capture the information from multi-temporal landscape maps to characterize the dynamics and the structure of continuous urban expansion (Fig. 1).

Fig. 1 illustrates an example of urban expansion. Patch c grew in 2005 and, according to LEI, is outlying growth. The newly grown patches d, e, and f surrounding patches c, e and f are defined as edge-expansion growth, whereas d is an infilling patch. However, patches d, e and f show expansive properties to a large degree because they grew around an outlying patch, compared with the patches that grew around the main built-up area, such as patch h. LEI cannot distinguish d, e, and f from h. Thus, LEI cannot effectively quantify the properties of continuously grown patches in more than three

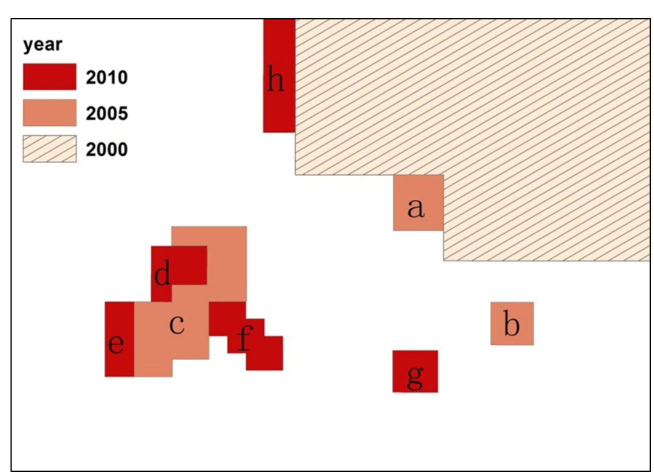

Fig. 1. An example of urban expansion.