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Proximity Expansion Index: An improved approach to characterize evolution process of urban expansion

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ABSTRACT

The spatial relationship of newly grown urban patches to existing urban areas lies at the core of understanding the properties of urban expansion dynamics. Some existing landscape metrics have been used to identify patch expansion types, i.e., infilling, edge-expansion and outlying, capturing the evolution process of urban expansion patterns based on quantifying spatial relationship. However, these existing metrics cannot comprehensively describe the spatial distributions of all new patches relative to old built-up areas, especially for outlying patches, which are the significant elements affecting the urban expansion pattern. We propose a new landscape metric, the Proximity Expansion Index (PEI), to address this problem by incorporating two factors of proximity - distance and boundary sharing rate to old patches. The value of PEI is continuous and has the clear physical meaning for depicting the gradient of the spatial relationship. The landscape expansion types are then redefined by PEI, while the sprawl level of outlying patches is clearly reflected. The variants of PEI are designed as global indices to capture information of the dynamic process of urban expansion from a bottom-up view. We selected Wuhan, a metropolis in central China, as a case area to evaluate PEI based on four periods of remote sensing images (1995, 2000, 2005 and 2010). The results show that the spatial pattern of urban expansion becomes increasingly dispersed, demonstrating that PEI is capable of capturing information of urban expansion evolution. PEI can depict the spatial relationship between new and old patches in a more detailed way by comparing PEI and previous metrics. Using PEI, we can also discover regions of great significance, called outlying seed regions, which have a profound impact on the coalescence of urban morphology.

1. Introduction

1.1. Characterizing urban landscape patterns using spatial metrics

Urban residents reached 54% of the world's population by 2014 and are expected to reach 66% by 2050, which means global urbanization, especially Asian urbanization, will continue to increase at the current level (United Nations, 2014). Urbanization is always accompanied by spatial expansion of urban land, which leads to landscape pattern changes (Alberti & Waddell, 2000; Bailey & Gatrell, 1995; Chen, Yang, Chen, & Li, 2015; Csillag & Kabos, 2002; Wang et al., 2008). It is imperative to depict the spatial pattern evolution caused by urban expansion, to understand the important geospatial process, according to characteristics of landscape pattern change. Different pattern changes in urban expansion create different impacts on urban development (Bhatta, Saraswati, & Bandyopadhyay, 2010; Ewing, Pendall, & Chen, 2002; Jaeger & Schwick, 2014; Wu, Jenerette, Buyantuyev, & Redman, 2011). For example, excessive urban expansion generates a series of extensively debated problems, such as additional infrastructure costs, land fragmentation and waste of land resources (Angel, Sheppard, & Civco, 2005; Ewing, 1997; Irwin & Bockstael, 2007; Redman, 1999; Siedentop & Fina, 2010). We cannot understand the hidden mechanisms without measuring the spatial characteristics of urban expansion. How to describe these characteristics quantitatively and show spatial pattern changes has attracted wide attention (Angel, Parent, Civco, Blei, & Potere, 2011; Deng, Wang, Hong, & Qi, 2009; Jiao, 2015; Kasanko et al., 2006; Laidley, 2016; Luck & Wu, 2002).

A landscape index offers an effective method to describe and understand the characteristics of spatial patterns (Imbernon & Branthomme, 2001; McGarigal & Marks, 1994; Zhang, Zhang, Li, & Cropp, 2006). Traditional landscape indices are mostly derived from statistical theory, information theory and fractal geometry (Krummel,

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Gardner, Sugihara, O'neill, & Coleman, 1987; O'Neill et al., 1988; Plotnick, Gardner, & O'Neill, 1993). Many of them have been widely applied for measuring landscape structures and spatial heterogeneity with landscape composition and configuration (Matsushita, Xu, & Fukushima, 2006; O'Neill et al., 1988; Riitters et al., 1995). Nevertheless, most of the traditional landscape indices only focus on simple comparative analysis and descriptions of the landscape pattern geometrical features, such as the quantifying pattern, without considering the process (Li & Wu, 2004). For example, for a new urban patch, the traditional index of patch characteristics can reflect the number, shape and other information of the patch at a certain time (Forman, 2014; McGarigal & Marks, 1994), but it cannot reflect the dynamic change characteristics of the patch relative to the historical data. Urban expansion is typically a dynamic change process of land use, so the analysis of urban landscape pattern evolution should contain temporal and spatial aspects (Angel et al., 2005; Rossi-hansberg & Wright, 2007).

1.2. Existing spatial indices for depicting the process of urban expansion

In recent years, a number of new approaches have been developed to capture landscape pattern change. For example, local and global spatio-temporal entropy indices, based on two different approaches using either distance ratios or co-occurrences of observed classes, are explored extensions to the spatio-temporal patterns (Leibovici, Claramunt, Le Guyader, & Brosset, 2014). Additionally, the gradient model (GM) approach combined with the patch matrix model (PMM) is capable of enhancing our understanding on how patterns and processes interact and ultimately benefit landscape ecology (Lausch et al., 2015). Moreover, a toolkit of assessment metrics based upon sparse spatio-temporal point process (STPP) observations is routinely applied to any predictive method that generates forecasts for greater insight into the prediction of hotspots (Adepeju, Rosser, & Cheng, 2016).

Urban expansion is a geospatial process with unique characteristics. In the process of urban expansion, there is generally no existing urban zone that “moves” or deurbanizes (Dietzel, Herold, Hemphill, & Clarke, 2005). Changes in urban landscape patterns are mainly affected by the distribution of new urban patches. Therefore, the spatial relationship for new urban patches to existing urban zone lies at the core of understanding the properties of urban expansion dynamics. A few landscape indices satisfy the conditions to analyze the urban dynamic. These metrics mostly use boundary-sharing rates or similar methods to characterize the process of urban expansion. Xu et al. (2007) defined an index S by using the ratio between a common boundary and an existing patch's parameter to study the type and dynamics of urban expansion in Nanjing. In their study, the common boundary is captured between a newly grown patch and its adjoining existing patches. Liu et al. (2010) proposed a Landscape Expansion Index (LEI) that uses the buffer sharing rate to evaluate the expansion character of new urban patches based on two temporal datasets. It is improved by having a buffer around a new patch instead of a one-dimensional boundary in the calculation of the index. Jiao, Mao, and Liu (2015) put forward a multi-order landscape expansion index (MLEI) that applies the boundary sharing rate at multiple points to improve the recognition of the spatial structure of urban expansion. It can be seen that the boundary sharing rate is regarded as a main factor with which to measure the spatial relationship of new urban patches to old patches.

Nevertheless, by calculating the above indices, the values of a newly grown patch that has no shared boundary or buffer overlap with an existing urban patch are treated as 0, which seems to be qualitative for outlying new patches. Because the buffer distance used is generally small, the numbers of new urban patches that are far from old built-up areas may be large, which may have a great impact on the pattern change of the urban landscape in a dramatic expansion process. Therefore, the above methods focus on describing the sprawl level of new urban patches near existing built-up areas while ignoring the dissimilarity of the sprawl degree reflected by outlying newly grown patches. In short, the existing methods cannot quantitatively depict the disparity of distribution of new urban patches in a detailed way and thus cannot express landscape pattern evolution in a comprehensive and accurate manner.

1.3. Aims and objectives

It is necessary to design a new landscape index to fully quantify the spatial relationship between a new urban patch and existing urban patches and accurately capture the evolution process of urban expansion. Effective and comprehensive quantification of the urban pattern evolution process using an improved index is the primary motivation and contribution of this study. This is an important advancement compared to other dynamic metrics based on the boundary-sharing rate that cannot indicate the urban expansion degree in a comprehensive way. The second motivation is to characterize the dynamics of the change in structure of urban landscapes based on the new index, such as identifying outlying seed regions.

This study discusses the definition of the proximity expansion index (PEI), and how to use it to characterize urban expansion patterns and analyze their evolution process through a case study in Wuhan, a fast growing city in China. PEI and its application methods are described in Section 2, and the experimental data are presented in Section 3. The results and discussions are presented in Section 4, while conclusions and future work are summarized in Section 5.

2. Proximity expansion index and its application methods

2.1. Proximity Expansion Index (PEI)

The quantitative description of the spatial relationship between the newly grown patch (new patch) and an existing urban patch (old patch) will provide the basis for the characterization of the evolution process of the urban expansion pattern. Generally, the closer the new patch appears from old patches, the lower the sprawl degree of the new patch is.

To construct an improved index, we list the shortcomings of the original indices. Existing dynamic metrics have widely used the boundary sharing rate (BSR) or its variants to reflect the spatial relationship for depicting landscape pattern changes. The three main dynamic metrics based on BSR, i.e., index S (Xu et al., 2007), landscape expansion index (LEI) (Liu et al., 2010), and multi-order landscape expansion index (MLEI) (Jiao et al., 2015) are presented in Table 1. BSR refers to the proportion of the boundary between the adjacent parts and the new patch. A buffer can be used to calculate the BSR instead of the one-dimensional boundary (metric S can be seen as buffer distance = 0). By calculating these metrics, the value of ‘a’ should be higher than that of ‘b’ because ‘a’ is embedded in the existing patch with a larger area of overlap (Fig. 1). Even if the new patch and the old patch are not connected, the spatial relationship is also affected by BSR. For example, a greater proportion of the boundaries of ‘c’ are close to the old patch, so the expansion degree of ‘c’ should be lower than that of ‘d’. It should be noticed that the distances between these four new patches and the old patch do not exceed buffer distance D.

However, there is a limitation of these existing dynamic metrics using only one buffer for calculating the expansion degree of all new patches. The robustness of these metrics is limited by the choice of buffer distance, and a small buffer distance is typically chosen to generate stable values of the metrics. In actuality, the distribution of new patches is varied. Therefore, when the distance between a new patch and the closest old patch is beyond the buffer distance, the value calculated by these metrics is zero and looks more like qualitative results. For example, ‘e’–‘h’, whose distances to the old patch exceed the buffer distance, are calculated as 0 without discrimination by these indices (Fig. 1). Regardless of how the buffer distance is selected in previous studies, there must be a large number of outlying patches without old