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Research Paper

A new approach for urban-rural fringe identification: Integrating impervious surface area and spatial continuous wavelet transform

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ABSTRACT

Urban-rural fringe is the frontier of urban expansion and the most dynamic area in urban region. Identifying the urban-rural fringe accurately is of great significance, as it helps to measure the extent of urbanization and its environmental effects from the urban-rural contrast perspective. However, traditional studies with spatial discrete data and threshold methods make it difficult to identify its boundary objectively and accurately. To solve this problem, a new approach was proposed in this study, integrating the spatial continuous data of impervious surface area (ISA) and the method of spatial continuous wavelet transform (SCWT). Taking Beijing City, one of the largest city in China, as a case, this study identified the boundary of urban-rural fringe, which extended mainly in the southwestern and northeastern direction, with the area increased by 18.75% between 2009 and 2014. The accuracy of the identification result was verified by spatial differentiation characteristics of nighttime light and normalized difference vegetation index. Meanwhile, when compared with the subjective threshold method, it showed that SCWT could identify the fringe more accurately. And the ISA based identification result was more consistent with the actual spatial patterns of urban development in Beijing City than land use degree index based one, which showed the remotely sensed spatial continuous data performed more effectively well on identifying the urban-rural fringe. The proposed approach can identify the urban-rural fringe directly from remote sensing images, which is of great significance to quickly urbanization monitoring and thus sustainable urban planning and management.

1. Introduction

With the rapid pace of global urbanization, urban regions have been experiencing a dramatic growth (Han, Hayashi, Cao, & Imura, 2009). The global built-up areas have increased from 0.60 to 0.87 million km^2 during 2000–2010 (Dou, Liu, He, & Yue, 2017). Located in the transition zone between urban and rural areas (Pryor, 1968), urban-rural fringe is the frontier of urban expansion, with intensive land use change, uneven economic development and complex population composition (Sharp & Clark, 2008). Although urban-rural fringe is characterized by high heterogeneity and development vitality (Cash, 2014; Vizzari & Sigura, 2015), the urban problems are also particularly prominent in this region, making it need more attention in urban management. Therefore, identifying the boundary of the urban-rural fringe accurately is crucial for monitoring urban expansion and mapping out specific development policy to avoid, mitigate or solve social and environmental problems along with urbanization process (Berling & Wu, 2004; Dennis & James, 2017).

The study of the urban-rural fringe can be traced back to the 19th century, when Herbert Louis recognized the long-term significance of physical limitations on urban growth (Whitehand, 1988). In the 1990s, concerns about the protection of open space made researches on the urban-rural fringe extremely topical (Friedberger, 2000). Early studies of the urban-rural fringe focused on the discussion of related concepts and regional social issues, due to the interdisciplinary nature of the research and limitations of data acquisition (Pryor, 1968). With the development of geographic information technology and mathematical methods, the attention of researchers turned gradually from qualitative description to quantitative analysis (Antrop, 2004). For example, Sharp and Clark (2008) identified urban-rural fringe in Ohio using a threshold-based classification method through the commuting distances to the state's largest urbanized area. Wang, Li, Feng, and Fang (2009) took basic information from Landsat TM images and defined the urban fringe in Beijing City using the theories of Shannon entropy and land use degree index. Peng, Zhao, et al. (2016) proposed a new model, combining wavelet transform and kernel density estimation, to identify the urban-rural fringe based on land use data.

In the recognition of spatial development patterns, land surface

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information based on remote sensing images have gradually replaced statistical indicators such as economic activity and population density. Compared with statistical indicators which is restricted by administrative statistical units, land surface information can display spatial differences more detailed. Moreover, the application of remote sensing images can also avoid the difficulty in acquisition of timely statistical data. However, current studies still utilize spatial discrete data, rather than spatial continuous data, ignoring the details of spatial pattern. Although the methods for identifying the urban-rural fringe are evolving and becoming more diverse, the majority of these approaches is based on an artificial threshold with high subjectivity, lacking objective mathematical methods (Peng, Zhao, et al., 2016).

In this study, a new approach was proposed to identify the urban-rural fringe combining impervious surface area (ISA) and spatial continuous wavelet transform (SCWT). This approach is based on the assumption that land use in urban-rural fringe is more heterogeneous than that in urban and rural areas. The range of urban-rural fringe can be drawn by identifying the region with high variation rate of land use in transects. Therefore, in the proposed approach, with ISA representing the land surface, SCWT is used to detect the locations where the change rates of ISA exceed a certain threshold, which are called mutation points (Peng, Zhao, et al., 2016). As a spatial continuous data directly extracted from remote sensing images, ISA can quantitatively reveal urbanization patterns in the view of urban-rural gradient, providing a timely data source for urban-rural fringe identification. Moreover, the application of SCWT can identify the urban-rural fringe by the spatial pattern of ISA objectively and precisely, and thus solve the subjective problem in traditional methods.

As the political, economic and cultural center of China, Beijing City is one of the most intensely and rapidly urbanizing areas and has entered an integration process of city suburbanization and suburb urbanization (Li, Zhou, & Ouyang, 2013; Wang, Ma, & Zhao, 2014). In this process, various social and environmental problems have occurred, especially in urban-rural fringe. It is essential to identify urban-rural fringe accurately for problem analysis and corresponding specific policy making. Therefore, taking Beijing City as a case study, this study mainly aimed to develop a new approach for urban-rural fringe identification, and to examine its efficiency by comparison with traditional ones using spatial discrete data or threshold method.

2. Methodology

The new approach mainly uses remotely sensed ISA data and SCWT method to identify the urban-rural fringe, including three steps. Firstly, ISA index is extracted from Landsat TM image using V-I-S model, to characterize land use patterns in the study area; secondly, SCWT is applied to detect mutation points along the urban-rural gradient; and thirdly, the boundary of urban-rural fringe is identified by linking the most adjacent mutation points in turn. Meanwhile, the identification result is verified by comparison with spatial patterns of nighttime light and NDVI, and the results using traditional data source and methods.

2.1. Study area and data sources

Located in the northwest of North China plain (39°28′-41°05′N, 115°25′-117°30′E), Beijing City is made up of 16 administrative districts (Fig. 1), and borders the Yanshan Mountains and the Inner Mongolia Plateau in the north, the Huang-Huai-Hai Plain in the south, Taihang Mountains in the west, and the Songliao Plain in the northeast. The total area of Beijing City is over $1.6 \times 10^4\,\mathrm{km}^2$, with a transverse distance of approximately 160 km from east to west and 176 km from north to south.

Beijing City has experienced a great expansion since reform and opening up. In the early 1990s, construction land was concentrated within the second ring road around Beijing City, as well as partly between the second and third ring roads (Peng, Shen, et al., 2016). After 20 years of development, the city center of Beijing City has expanded to near the fifth ring road. The expansion has crossed the two greenbelts that were established by the government, gradually eroding and extending to the outer rural areas (Zhang, Meng, Wang, & Xu, 2014). Beijing City is faced with various problems such as land use and social issues caused by rapid urbanization. Separating the urban and rural areas, and thus identifying the boundary of urban-rural fringe accurately and timely is of great significance to monitor urbanization process, and to quantify its environmental effects in the urban-rural contrast perspective.

The data used for the analysis and the corresponding sources are listed in Table 1. All the data were collected for 2009 or 2014. However, as DMSP-OLS nighttime light has stopped production by 2013, we used the data in 2013 to present the nighttime light in 2014. Moreover, land use types to calculate land use degree index were obtained by supervised classification with the overall classification accuracy of 0.8433 after validated by 134 sample points in a higher resolution SPOT image data (2.5 m).

2.2. ISA extraction based on the V-I-S model

Impervious surface is mainly composed of construction lands such as buildings, asphalt roads and parking lots (Liu, Wang, Li, & Peng, 2013). It is one of main land cover types in cities (Lu & Weng, 2006; Kuang et al., 2016), and the increasing proportion of impervious surface is an obvious characteristics of urbanization in a region (Kuang, Chi, Lu, & Dou, 2014; Song, Sexton, Huang, Channan, & Townshend, 2016). Impervious surface area (ISA) refers to the area ratio of impervious surface per unit area, which is a comprehensive measure of urban land use intensity and is calculated as follows:

$$\mathrm{ISA} = S_{IS}/S_t \tag{1}$$

where ISA is the index of impervious surface area, S_{IS} is the area of impervious surface in one 30 * 30 pixel, and S_t is the total area of the pixel.

In this study, the V-I-S model is used to extract ISA (Ridd, 1995), which mainly includes three steps. The first step was data preprocessing, including radiation correction, noise masking, and repair of bad pixels, followed by improving the accuracy of pure components through normalized reflectance processing. In the second step, three endmembers, such as the dark surface endmember, the vegetation endmember, and substrate endmember were selected after the minimum noise fraction (MNF) transformation and pixel purity index (PPI) adopted from the linear spectral mixture model (LSMM) in ENVI 5.0. As water and vegetation shade might be misclassified in extracting ISA, they were considered to be eliminated. In this study, the water mask was extracted by new water index (NWI), which mixed band 7 in TM images. The vegetation shade was extracted by normalized difference umbra index (NDUI), which mixed the saturation and lightness. And it was found that the conditions of NDVI > 0.1 and NDUI > 0.4 could effectively eliminate the vegetation shading (Peng, Liu, et al., 2016). Finally, the extraction result of ISA was compared with high resolution image data, and was validated by R-Squared and mean relative error.

$$\mathrm{MRE} = \sum_{i=1}^{n}\left(\frac{|x_i - y_i|}{y_i}\right)/n \qquad \mathrm{i}= 1,2\ldots\mathrm{m} \tag{2}$$

where MRE represents the mean relative error; x_i and y_i represent the proportion of impervious surfaces from TM images and high-resolution images, respectively; and n represents the number of samples.

2.3. Mutation detection based on spatial continuous wavelet transform

The continuous wavelet transform (CWT) is an effective signal processing tool and can decompose a signal vector ($\mathrm{f}(t)$) into multi-scale wavelet coefficients by the inner product with a basic wavelet function