



Identifying the urban-rural fringe using wavelet transform and kernel density estimation: A case study in Beijing City, China



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ABSTRACT

The urban-rural fringe, known as the region located between the urban and rural areas, is the frontier of urban expansion against rural reservations. Identifying this particular region precisely, which was usually simplified by researchers, is the most important prerequisite in studies related to urban-rural patterns. In this study, we proposed a new model, combining wavelet transform and kernel density estimation, to identify the urban-rural fringe based on land use data. After testing the model using Beijing City as a case study, it is proved that the model is able to delineate the boundaries of urban-rural fringe precisely with respect to different landscape patterns at different regions (central urban area, urban-rural fringe area, and outer rural area). Furthermore, due to the advantage of the self-adaptive-bandwidth kernel density estimation, the model can also distinguish some of the satellite towns from the central urban area and outer rural area with the boundaries of urban-rural fringe.

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1. Introduction

Urbanization, known as the engine of modernization and economic development, has become the major outcome of globalization all over the world. Due to the rapid pace of urbanization, expanding cities have brought various kinds of ecological and environmental problems to the world, which has correspondingly limited the sustainable development of these cities (He et al., 2014). Therefore, protecting ecological and environmental system from the impact of urbanization has become an important global strategy and has stimulated large amount of studies (Li et al., 2012, 2013a, 2014). For instance, researchers have studied the effects of urbanization on the land cover change (Lambin and Meyfroidt, 2010; Zhou et al., 2014), dynamic of vegetation's ability to fix carbon and release oxygen (He et al., 2016; Zhang et al., 2012), as well as on water resources management (Mouri et al., 2012), and on the urban heat island effect (Li et al., 2011). However, most of these studies were conducted based on comparing urban areas with rural areas. Furthermore, due to urban-rural difference, the spatial-temporal changes and its driving forces differ from each other (Li et al., 2013b; Zhang et al., 2008; Zhou et al., 2011). Therefore,

precisely delineating the boundary between urban areas and rural areas, and thereby being able to help distinguish the urban regions from rural areas, is the first and most important step of these urbanization related studies (He et al., 2013; Zhou et al., 2014). The urban-rural fringe area separates the central urban area and the outer rural area with its inner and outer boundaries, respectively, and provides an effective way to characterize and understand the spatial structure and correlations between urban and rural regions (Peng et al., 2014).

The urban-rural fringe, first noted by European researchers in the 1900s, is the transitional region located between urban areas and rural areas. As a region that is witnessing the transformation of rural area to urban area, urban-rural fringe has attracted large amounts of studies due to its special characteristics, which are apparently different from those of both urban and rural areas (Vizzari and Sigura, 2015). Furthermore, the studies that originally focused on describing the urban and rural areas have now evolved into examinations of specific problems with quantitative studies based on mathematical analysis (Antrop, 2004; Buhaug and Urdal, 2013; Pryor, 1968). In consideration of identifying this special region, a widely held assumption in most of the quantitative studies has been that the spatial patterns of some social or economic factors can be applied effectively. In these studies, land use, population structure, gross domestic product (GDP) distribution or some other

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compound factors were usually selected as the identification factors. Among these factors, land use, which can directly reflect the expansion of a city (Schippers et al., 2015), is regarded as the most intuitionistic factor for identifying the urban-rural fringe areas, where land use types are affected by both urban and rural areas and mutate frequently.

When considering the methods of identification, reclassification is regarded as the most intuitionistic method in identifying the urban-rural fringe area. Usually, this kind of method can be applied by reclassifying an index-map using a threshold or clustering algorithm, such as Self-Organizing Feature Map or K-means algorithm (Gao et al., 2014; Wang et al., 2011). For instance, Imhoff et al. (2010) divided the area between the urban and rural regions into five classes using a threshold-based classification based on impervious surface maps. However, the precision of studies using such an approach is frequently affected by the noises (i.e., uncertainties) in the index map, often resulting in low-resolution results or inaccurate identification of urban-rural fringe areas. In addition, defining a threshold for an identification scheme is somewhat subjective. The other kind of identification method is to detect and map the mutation points of an index map. For instance, Zhang et al. (1999) delineated the urban-rural fringe based on the mutation points that were identified on a land use ratio map. Qian et al. (2007) recognized the urban-rural fringe in Jingzhou City, China, based on the mutation points identified on a land use entropy map. However, delineating the urban-rural fringe area based on the detection of mutation points is usually compromised by two main problems. Firstly, most of these studies map the mutation points visually, which may result in inaccurate results. Secondly, delineating the boundaries based on the identified mutation points is usually fulfilled merely by directly drawing straight lines between neighboring mutation points that were detected, which is regarded to be another subjective practice that may result in inaccuracies.

In order to solve the problems described above, we developed a new model to identify the urban-rural fringe, and tested the model using Beijing City, the capital of China, as a case study based on land use data derived from Landsat 8 OLI/TIRS images captured in 2014. The model combines a land use degree index (LUDI) evaluation model with the methods of Spatial Continuous Wavelet Transform (SCWT) and Kernel Density Estimation (KDE). By using the SCWT, mutation points of the LUDI map are detected and mapped precisely and automatically, which reflects the spatial patterns of the mutation in the land use directly (Li et al., 2008). By applying the KDE method in the urban-rural fringe identification, a density surface is constructed based on the detected mutation points, which can reflect the spatial patterns of the mutation points and indicate the frequency of mutation in land use types, and thus can be set as the distinguishing characteristic of the urban-rural fringe. In detail, the method calculates a density value for each pixel based on the total number of neighboring mutation points and delineates the urban-rural fringe area by slicing the density surface according to the appropriate threshold determined by the landscape metrics. Furthermore, we validated the accuracy of the results by comparing the location of the identified regions with current road network map and spatial patterns of central urban area and satellite towns, and by calculating and validating such landscape metrics as Shannon's Diversity Index (SHDI) and the index of Percentage of Landscape (PLAND).

It is regarded as one of the novel contributions of the new model that it transfers the spatial patterns of mutation points to the density surface effectively, making the mutation points usable for researchers to delineate the boundaries of the urban-rural fringe objectively. In order to discuss the advantage of KDE method over conventional mutation points detection methods in mapping urban-rural fringe, we compared the urban-rural fringe area

identified with the mutation points map, and it was proved that the KDE could eliminate some of the incorrect mutation points effectively. Furthermore, it is proved that the modified self-adaptive bandwidth KDE, applied in the model, can delineate the boundaries of central urban, outer rural areas and even, the satellite towns effectively than the fixed-bandwidth KDE.

2. Methodology

The new model mainly uses the methods of SCWT and KDE to identify the urban-rural fringe area based on the land use patterns of the study area, which change from the downtown to the outer area. The model uses a remotely sensed image as the input data and identifies the urban-rural fringe with three sections. Section I, is data preparation, including interpretation of the remotely sensed images and evaluation of land use intensity based on LUDI model; Section II, is urban-rural fringe identification, including two parts: SCWT-based mutation points detection and mapping, and self-adaptive-bandwidth-KDE-based density surface construction; and Section III, is result mapping, including slicing the density surface based on the statistical curves of perimeter-area ratio (including statistics of area-weighted mean and range of the index). An overview of the model is portrayed schematically in Fig. 1.

2.1. Study area and data source

Beijing City, the selected study area (Fig. 2), locates in the north of the North China Plain, at 39°28'N–41°05'N and 115°25'E–117°30'E. The city covers a total terrestrial area of 16,411 km², stretching approximately 160 km from west to east and approximately 176 km from north to south, with 16 subordinate districts. Mountainous area, locating at the northern and western part of the city and possessing large amount of vegetation, occupied 62% of Beijing City, and the remaining 38% is occupied by plain area, which possesses the main urban area and has been well developed. The total population of Beijing City is nearly 22 million (as of 2014) and is mainly distributed in the plain regions where the main urban area is located. As the capital of the People's Republic of China, Beijing City has become the political and cultural communication center of the country and the most intense area of urbanization in China.

In recent years, Beijing City has experienced rapid growth and achieved lots of economic success (with GDP of approximately 2.1 trillion yuan in 2014). Correspondingly, the city also witnessed an expansion of urban area at tremendous speed, especially through conventional urban sprawling, resulting in a sharp increase in proportion of constructed areas (Wang et al., 2014). As monitored by the government, the central urban area has expanded from the second ring road to near the fifth ring road, and now is comprised of an area more than double that in the 1980s (Qian et al., 2015). This expansion has crossed the two greenbelts that were established by the government, and currently is threatening the outer rural areas (Zhang et al., 2014; Zhao, 2013). During this expansion, more than ten satellite towns were gradually established and they are also expanding and approaching the central urban area. And this made the urban-rural fringe of Beijing City more and more complex with rapid and substantial changes over the years. Therefore, precise identification of urban-rural fringe is essential for researchers to study spatial patterns, both in central urban area and satellite towns, and the social, economic, or ecological effects of urbanization in Beijing City. Besides, the characteristics described above, expanding with the pace of building new ring roads, makes the city an ideal case study area for identifying the urban-rural fringe based on detection of mutation points.

In this study, we used Landsat 8 images as the source of base

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