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Origin, spatial pattern, and evolution of urban system: Testing a hypothesis of “urban tree”

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A B S T R A C T

The origin, spatial pattern, and evolution of urban system have been hot research issues in the field of urban system. In this study, the theory of “urban tree (UT)” was proposed to address these issues. The spatial pattern of urban system can be expressed by the phrase UT and the growth of the UT reflects the origin, spatial pattern, and evolution of urban system. Analysis of the UT growth can reveal the evolutionary mechanisms of the urban system. We present an UT resistance model to determine spatial extension in the evolutionary processes of urban system. The Thiessen polygon method and spatial remapping were used to construct the UT. Data collected in 1995, 2000, 2005 and 2010 from cities in the Huai River Basin were used to construct the UT model to analyze the origin, spatial pattern, and evolution of urban system in this region. Xuzhou City was the UT “tree root” and the UT growth the followed four paths. Growth of cities on the nodes of these paths promoted the evolution of urban system. The UT theory expresses the spatial pattern and evolution of urban system in an intuitive way and helps to explain the origin and evolution mechanisms of urban system. Empirical research supported the UT theory. Because of the operational and visual expression, this theory has broad application prospects in the urban system research.

1. Introduction

The origin, spatial pattern, and evolution of urban systems are an important manifestation of human social development processes on spatial scale (Catalan, Sauri, & Serra, 2008), which reflects the change of human social spatial structure, and reveals the spatial patterns of the overall behavior of human society. These changes and their patterns are the foundation for the research of sustainable development of the human society (Alnsour, 2016).

Urban system originates from the growth of a single city. Population, industrial, and investment growth are the main driving forces of urban formation and growth (Ahmed & Ahmed, 2012; Lin, Wang, Wang, & Wang, 2015; Lu, Wu, Shen, & Wang, 2013; Mondal, Das, & Dolui, 2015). The cellular automata model (Gonzalez, Aguilera-Benavente, & Gomez-Delgado, 2015; Santé, García, Miranda, & Crecente, 2010; Stevens, Gicevic, & Rothley, 2007), support vector machine (Rienow & Goetzke, 2015), self-organizing structure model (Arribas-bell, Nijkamp, Scholten, 2011), gravity model (Gu & Pang, 2008; Vaz & Nijkamp, 2015), class-size model of city hierarchies (Chen, 2002) and systematic dynamics (Shen et al., 2007) have been used to describe spatial expansion of cities. Urban growth is also influenced by the scale of urban space, traffic network, and complexity of the terrain (Ayazli, Kilic, Lauf, Demir, & Kleinschmit, 2015; Thapa & Murayama, 2011). Some authors believe that gradient is the decisive factor of urban spatial growth (Zhang, Su, Xiao, Jiang, & Wu, 2013). Changes in the size of a city can be analyzed using remote sensing images (Herold, Goldstein, & Clarke, 2003) according to the relationship between urban scale and intensive use of land (Hui, Wu, Deng, & Zheng, 2015), with night light intensity as an effective indicator of urban scale (Gibson, Boe-Gibson, & Stichbury, 2015). A mechanism for the origin and growth of the city has been proposed (Bettencourt, Lobo, & West, 2008) but modeling the spatial and temporal dynamics of urban origin and evolution remains difficult (Hamidi & Ewing, 2014; Murcio & Rodriguez-Romo, 2011). A comprehensive framework

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for dynamic modeling of urban space can simplify the model (Irwin, Jayaprakash, & Munroe, 2009) while calculate spatial scenarios of urban growth and mapping of urban space expansion (Hayek, Jaeger, Schwick, Jarne, & Schuler, 2011) can enhance the utility of the research for urban growth. As individual cities grow, the interactions between cities increase (Wu, Zhang, Jin, & Deng, 2009). Therefore, city groups of specific scales form in particular regions.

The evolution of urban system mainly includes changes in two aspects: land use pattern and system structure. City spatial structure in the narrow sense refers to the topological connection joined geographically with the land scale (boundary) and its position. This is usually shown as a grid pattern and is termed spatial pattern (Qin, Zhang, & Jiao, 2006). City spatial structure typically refers to all of the networks constructed within the urban area, including the transportation (Zhou & Hu, 2002), urban economic chain (Sun, Tang, & Tang, 2015), and information networks (Yao, Chen, Zhu, & Chen, 2001). The evolution of urban spatial structure is usually studied by remote sensing techniques or spatial land use change models (Krehl, Siedentop, Taubenböck, & Wurm, 2016; Van de Voorde et al, 2016), the (population or economic indicators) modeling method and graph theory analysis. The generalized equilibrium model (Berliant & Wang, 2008), logical model (Ikeda, Akamatsu, & Kono, 2012) and gravity model (Wang, Deng, Su, & Song, 2014) have been widely applied in this field. Since the evolution of spatial structure of urban system is closely related to population and economic factors (Chadchan & Shankar, 2012; Dong et al., 2014), population and economic indicators are often used to describe the urban system growth and decline (Filion, 2010; Li, Huang, & Wang, 1998). The urban system is a system with ability of self organization, and the structure change can be described by the center of mass and the weighted average value (Park, 2011). Based on graph theory, large scale analysis has demonstrated that the structure of urban system becomes increasingly effective and stable with increased complexity, and more favorable to the sustainable development of the urban system (Marull, Font, & Boix, 2015).

The evolution of the inner structure of urban system includes the evolution of its grouping system (Fujita, Krugman, & Mori, 1999) and changes in the inter-city material and energy flow (Zhang et al., 2015, 2016), with changes in land use, urban population, urban density, and urban grade being the main characteristics of this evolution (Gallo & Chasco, 2008; Jaeger & Schwick, 2014; Li, Zhang, & Liang, 2010; Poelmans & Rompaey, 2009). Threshold analysis is commonly used to measure this evolution (Garcia, Garmestani, & Karunanithi, 2011). Urban density in the urban system of developing countries is more compact and dense than that of developed countries (Huang, Lu, & Sellers, 2007).

The models and methods listed above are used to study the evolution of urban system from the perspective of the origin mechanism and spatial pattern. They identified major factors contributing to the evolution of urban system, discussed the pathways of material, energy and information exchange, and provided indices for measuring agglomeration evolution. These studies provide a theoretical foundation for understanding the origin and evolution of urban system but there remains a need for a unified theory that expresses the urban system spatial patterns on a temporal scale. We established a theory about spatial and temporal growth characteristics of urban system termed "the theory of urban tree (UT theory)". Our goal was to explain the origin of urban system based on temporal and spatial evolution and use this to reconstruct the timelines of spatial patterns of regional urban system. The following scientific questions are studied: (1) What is the best method for communicating the spatial structure of urban system? (2) How is an urban system originated? (3) How does the spatial pattern of urban system evolve?

We therefore developed the UT concept, and constructed the UT model. We propose: (1) The urban system is a spatial self-organization system and the evolution process of urban system can be reconstructed by using the UT model. The structure and evolution of urban system in different periods can be visualized by the UT growth. (2) The urban system has spatial pattern similar to a tree, and the evolution process is similar to the growth of a tree. We explain the UT growth mechanism, and describe the UT growth process using the resistance model and graph theory. The UT at different time periods in the Huai River Basin was sampled as an empirical study to analyze its evolution process and evolution mechanism. The results confirmed our hypothesis of UT growth. This study provides a new theoretical explanation and research method for the origin and evolution of urban system.

2. Theory and method

2.1. Basic hypothesis of UT growth

2.1.1. The UT

Within a specific geographic area, cities can be divided into different types according to population size (city level) and the time of origin: Cities with the largest scale and earliest time of origin are grouped as first tier cities; second tier cities have smaller scales and were formed after first tier cities; and so on. Each city in the region is considered as a node of the UT. Based on the type of cities, nodes are divided into level one, two, three nodes, and so on. The connection between the nodes is defined as a "trunk". The first city in the level one node will be selected as "root". The connection between any two level one nodes is called level one branch (trunk), and the connection between a level one and a level two node is called level two branch, connection between a level two and a level three node is called level three branch, and so on. An UT can be formed using the above method to connect all the cities in a region.

2.1.2. Growth mechanism of UT

A city is a concentrated residence with largest human population within a defined time period in a region. The origin of population centers starts from the location with resource advantages (natural, human, or both) in the region within a certain period of time, and provides the foundation of regional social development. City size is related to the size of the regional resources and the degree of optimal utilization of regional resources. Regional resource advantage determines the condition of city development and the optimization of regional resources will continue to increase the scale of the city. With the development of society, the ability of human to use the resources continuously improves and the urban scale will also continue to increase.

Many smaller regional resource advantage centers usually form within large regional area and these develop into cities of various scales over different time periods. Material, energy, and information exchange occurs among cities, based on which we define an urban system. An urban system, within a defined region, is therefore a combination of multiple cities closely involved with each other by exchange of material, energy and information.

The growth of urban system has three levels. The first level is the growth of individual cities. The second level focuses on the growth of inter-city communication within the urban system. The third level is the overall growth of the urban system. We focused on the second level of growth, the formation of inter-city communication within urban system.

We theorize that the exchange of material, energy, and information among cities develops fastest along paths of least resistance. Therefore, the direction with minimum resistance forms a fast communication path. We use urban population size and GDP