Postprint: Geographical Detector-Based Analysis of Urban Expansion Characteristics and Spatiotemporal Driving Factors in Urumqi

Authors: Shi Tiange

Date: 2021-06-17T00:00:00+00:00

Abstract

In the new era, the internal and external environment of urban development in China has undergone significant changes, and the characteristics and driving mechanisms of urban expansion have also exhibited new features. Taking Urumqi City as an example, this study describes the characteristics of urban construction land expansion from 1990 to 2018, employs the Geographical Detector method to investigate the spatiotemporal mechanisms of expansion, and focuses on analyzing the new features of expansion after 2010. The results indicate: (1) Urumqi's construction land increased from 84.37 km^2 in 1990 to 361.91 km^2 in 2018, with the urban morphology evolving from a north-south belt pattern to a "T" -shaped structure, and the spatial compactness of urban form gradually decreasing; the urban expansion speed remained stable while the expansion intensity gradually increased. The "core-periphery" structure of urban expansion experienced a spatiotemporal evolution process of "strengthening-weakening-strengthening" . (2) The temporal dimension of urban construction land expansion is primarily influenced by population size, industrial scale, and government propulsion, with population size exerting the greatest effect. Within industrial scale, the secondary industry has a slightly stronger effect than the tertiary industry. After 2010, government propulsion has generated an accelerating effect on urban expansion in Urumqi. (3) In terms of the spatial dimension, transportation and commercial spatial elements are the main factors driving urban spatial expansion. Over time, the spatial dynamics of urban expansion have shifted from being driven by a few key factors to being driven by multiple factors collectively.

Full Text

Urban Expansion and Its Temporal and Spatial Driving Forces of Urumqi Based on the Geodetector Method

SHI Tiange1,2, **SHI Hui**1

1 Xinjiang University of Finance and Economics, Urumqi 830012, Xinjiang, China
2 Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, Xinjiang, China

Abstract

Urban spatial expansion is a classic topic for urban geography, playing an increasingly important role in scientific research and government management. As the internal and external development environments of China's urban areas have changed significantly in the new era, urban expansion and its driving mechanism were also shifted by new factors. This paper, taking Urumqi (a city in northwest China) as an example, described the characteristics of urban construction land expansion and expounded on the spatiotemporal expansion mechanism using the Geodetector method. The results are as follows: (1) Over the past 30 years, the construction land area in Urumqi increased from 84.37 to 361.91 km2. We constructed an urban space compactness index to reflect the rationality of the urban spatial boundary shape. The urban space compactness index gradually decreased over the past 30 years. This indicated that the spatial distribution is more reasonable and more efficient in the process of urban expansion. The urban expansion speed rate is 5.34%, and the urban expansion intensity rate increased from 3.57% to 8.79%. Urban expansion had a "core-periphery" structure, and its core agglomeration extent changed in different periods. (2) Urban expansion is mainly influenced by three factors: population scale, economic scale, and government policy. Population and economic agglomeration have the greatest effect on urban expansion. In economic terms, the secondary sector of the urban economy plays a slightly larger role than that of the tertiary sector on urban expansion. After 2010, new government policies accelerated urban expansion in Urumqi. (3) Transportation and commercial locations were the main spatial driving factors of urban expansion. The effects of single spatial driving factors gradually weakened, whereas the interactive effects of double spatial driving factors gradually strengthened over time. In the future, comprehensive simulations of urban expansion and resource and environmental effects should be further studied for the cities in western China.

Keywords: urban expansion; construction land; temporal and spatial driving forces; geo-detector; Urumqi

Introduction

Numerous scholars have utilized statistical data, remote sensing, and geographic information extraction techniques to study construction land expansion characteristics, influencing factors, and driving forces at multiple scales, including national, provincial, and urban agglomeration levels. Research objects have included central urban areas and municipal jurisdictions, with the former focusing on urban spatial expansion patterns and the latter addressing urban-rural relationships in megacities or semi-urbanized areas, aiming to clarify urban expansion patterns and evolution of urban-rural construction land, optimize spatial layout, and address prominent contradictions in urban development.

Research on construction land expansion mechanisms encompasses economic, institutional, and empirical schools. The economic school examines urban expansion mechanisms from the perspective of the relationship between marginal revenue and marginal cost of urban land. The institutional school explains urban expansion mechanisms through political and institutional arrangements, such as administrative division adjustments and establishment of development zones. The empirical school initially provided qualitative explanations of how economic, social, institutional, population, and other factors influence urban expansion, and later employed spatial regression, geographically weighted regression, and geodetector methods to quantitatively analyze expansion influence mechanisms.

Urumqi, the capital of Xinjiang and the only large city in the region, bears the important mission of constructing the core area of the Silk Road Economic Belt. Previous studies on Urumqi' s urban expansion were conducted earlier and primarily used qualitative analysis. Recent research has adopted quantitative methods but lacks systematic investigation of new mechanisms of urban expansion after 2010. Based on multi-temporal remote sensing data, combined with spatial network analysis and geodetector analysis, this paper systematically examines the urban expansion process and dynamic mechanisms from both temporal and spatial dimensions. Additionally, it advances the spatial identification of urban expansion mechanisms from the regional scale to the intra-urban scale, providing a typical case study of a large western city in China.

Study Area Overview

In 2018, Urumqi had a permanent population of 3.552 million and a GDP of 341.326 billion yuan, accounting for 14.4% of Xinjiang's population and 25.0% of its total economic output. The city governs seven districts (Tianshan, Shayibak, Xinshi (High-tech Zone), Shuimogou, Toutunhe (Economic Development Zone), Dabancheng, Midong) and Urumqi County. In 2007, Miquan City of Changji Prefecture was merged into Urumqi and combined with the original Dongshan District to form Midong District. In 2011, Xinshi District and Toutunhe District merged with national-level industrial parks, implementing a "district-park integration" system. This study takes the central urban area control zone delineated in the 2014 edition of Urumqi' s master plan as the study area. Within this scope, Urumqi County and Dabancheng District have minimal construction land and are therefore not discussed separately.

Analytical Framework

Using high-resolution satellite imagery of Urumqi, we extracted the spatial distribution of built-up areas. To reflect the urban spatial expansion process, we excluded township and rural construction land that was not connected to the urban built-up area. Land on the urban fringe that had been leveled but not yet developed was temporarily excluded from the construction land scope. Using Google historical map imagery, we manually identified urban fringe built-up areas according to adjacency requirements, ultimately obtaining vector data of construction land in Urumqi for five periods. The entire study area was divided into 500 m $\times$ 500 m grids as the basic spatial units for analysis.

There are multiple theoretical schools regarding construction land expansion mechanisms. From the temporal dimension, most scholars agree that population factors, economic factors, and policy institutions significantly influence construction land expansion. Synthesizing these theories, we measured the temporal driving mechanisms of construction land from four aspects: population size, economic level, and government impetus (Table 1). Industry is often the main driving force in the early stages of urban development, while services tend to concentrate in large and medium-sized cities and become the dominant force driving urbanization as the economy develops. Therefore, when selecting economic indicators, we used secondary industry output value and tertiary industry output value to represent the impacts of industry and services, respectively, to examine their relative influence. In selecting government impetus indicators, the fiscal deficit situation is an effective indicator reflecting government stimulation of urban expansion through economic means. After the 2010 Central Xinjiang Work Conference, counterpart assistance to Xinjiang was launched nationwide. Although Urumqi did not have designated supporting provinces or cities, many national-level assistance projects were located in Urumqi, allowing it to enjoy policy dividends. We used a dummy variable D to reflect the impact of assistance policies on Urumqi' s urban expansion, setting it to 0 before 2010 and 1 after 2010.

Drawing on empirical school theory, we examined the spatial mechanisms of urban expansion. Economic cost-benefit elements are the primary factors of urban spatial expansion. We integrated spatial factors affecting economic costs and benefits and supplemented them with natural geographic elements to measure spatial driving factors. For example, distance to urban commercial centers reflects the demand potential of a grid, while distance to railways reflects economic transportation costs. We used distances from grids to various economic and natural point and linear spatial elements as measurement indicators. Hongshan was selected as the city center, the first-level commercial center at Renmin Road and five secondary commercial centers (Youhao Road and Railway Bureau) were selected as point elements, and urban arterial roads and intra-city expressways were selected as major road axis elements.

Research Methods

Construction Land Comprehensive Expansion Index We used expansion rate (UL1), expansion intensity (UL2), and comprehensive expansion index (ULc) to measure the degree of spatial expansion of urban construction land. The formulas are as follows:

$$UL1 = \frac{S_{t2} - S_{t1}}{S_{t1}} \times 100\%$$

$$UL2 = \frac{S_{t2} - S_{t1}}{A_i} \times 100\%$$

$$ULc = \sqrt{UL1 \times UL2}$$

where S_t represents the construction land area in period t ($t = 1, 2$), S_{t1} and S_{t2} represent the construction land areas in the initial and final periods, respectively, and A_i represents the total area of each district/county.

Spatial Morphology Compactness Urban morphology compactness is an indicator reflecting the degree of spatial concentration among internal parts of urban spatial form and is an important concept for reflecting urban morphology. Based on Batty' s compactness formula, we studied Urumqi' s spatial compactness:

$$BCI = \frac{2\sqrt{\pi S}}{P}$$

where BCI is the urban spatial compactness index, S is the urban construction land area (km2), and P is the perimeter of the urban outline (km). The compactness index ranges between 0 and 1, with larger values indicating more compact shapes approaching a circular distribution, and smaller values indicating poorer compactness.

Geodetector The geodetector model, proposed by Wang et al., can analyze driving forces and influencing factors of various phenomena as well as multifactor interactions, and is mainly used to detect spatial heterogeneity of geographic elements. This paper selected the factor detector and interaction detector to study the spatial driving mechanism of urban land expansion.

Factor Detection: This detects the spatial heterogeneity of dependent variable Y and examines the degree to which a factor X explains the spatial differentiation of attribute Y. Here, Y represents changes in construction land, and X represents various spatial driving factors. According to natural breaks in the data, variable X was divided into 5 categories from large to small and converted to a categorical variable. The specific formula is:

$$q = 1 - \frac{1}{N\sigma^2}\sum_{h=1}^{L} N_h \sigma_h^2$$

where q is the detection power index of spatial heterogeneity of the dependent variable; $h = 1, \ldots, L$ represents the stratification (classification or zoning) of the variable or factor; N_h is the number of sample units in the sub-region; N is the number of sample units in the entire region; L is the number of sub-regions; σ^2 is the variance of the dependent variable in the entire region; and σ_h^2 is the variance in the sub-region.

Results and Analysis

Basic Characteristics of Urban Construction Land

From 1990 to 2018, the construction land area in Urumqi' s central urban area increased from 84.37 km2 to 361.91 km2, a 4.3-fold increase with an average annual expansion of 9.91 km2 and an average annual growth rate of 5.34%. Construction land expanded primarily through peripheral extension, focusing on the south, west, and northeast directions. The urban spatial structure evolved from a north-south strip pattern to a "T-shaped"structure [Figure 1: see original paper].

We calculated two urban compactness indices: one based on all construction land in the central urban area (global compactness) and another based only on central construction land closely connected to the original built-up area (core compactness). Urumqi' s spatial morphology compactness index decreased progressively over time, indicating that the city expanded mainly along a few directions constrained by terrain. Core compactness was higher than global compactness, suggesting the existence of numerous construction enclaves [Figure 2: see original paper]. Examples include the Wenquan University Town in Shuimogou District, the High-tech Zone in the northern new district, and newly developed industrial land in the southern district, which are not connected to the existing built-up area, forming a leapfrog expansion pattern.

From 1990 to 2018, the central urban area (Tianshan, Shayibak, Xinshi, Shuimogou districts) expanded faster than the suburbs (Toutunhe, Midong districts). From 1990 to 2000, the suburbs expanded faster than the central area, while after 2000, the central area again expanded faster than the suburbs.

Expansion Characteristics of Urban Construction Land

The expansion of construction land in various districts and counties shows the following characteristics:

First, expansion speed remained stable while expansion intensity gradually increased. The average expansion speed of construction land in Urumqi was 5.34%, while expansion intensity increased from 3.57% to 8.79%, showing a gradually strengthening trend [Figure 3: see original paper].

Second, new urban districts expanded rapidly while central urban areas showed greater expansion intensity. Midong District in northeastern Urumqi had the fastest expansion speed, with an average annual rate of 7.23%. Originally an agricultural county under Changji Prefecture, after being incorporated into Urumqi, Midong vigorously developed industrial parks, significantly increasing logistics and warehousing land and becoming a heavy industrial base for the city. The highest expansion intensity occurred in Xinshi District and Shuimogou District in the central urban area, reaching 23.00% and 16.80%, respectively, both higher than the city average of 8.79%.

Third, urban expansion hotspots shifted from sprawl-type to infill and leapfrog patterns. From 1990 to 2000, new construction land spread around the periphery of existing construction land. For example, the relocation of Urumqi' s municipal government to Nanhu District stimulated surrounding development. From 2000 to 2010, urban expansion began to accelerate, with infill and leapfrog patterns becoming evident, concentrating in Phase II of Xinshi High-tech Development Zone (infill), the Convention and Exhibition District (infill), Midong Industrial Park (sprawl), and the Steel City District (leapfrog). From 2010 to 2018, more infill and leapfrog hotspots emerged, including Phase II of the Economic Development Zone (infill), Jiuding District (leapfrog), Wenquan District (leapfrog), and Cangfanggou District (leapfrog) [Figure 4: see original paper].

Fourth, there were more expansion hotspots in the north than in the south. Using the city center at Hongshan as the boundary, construction land increment in the northern part of the city was significantly higher than in the south over the past 30 years, indicating obvious northward expansion. The northern part of the city is the alluvial plain of the Urumqi River with flat terrain suitable for large-scale contiguous development. The southern part is an intermountain valley of the Tianshan Mountains with undulating terrain and restrictions from upstream water source protection areas, resulting in more scattered and leapfrog expansion. The Urumqi Master Plan (2014-2020) proposed the development direction of "south control, north expansion, west extension, and east advancement," which is consistent with this conclusion.

Fifth, new district development and construction were the main manifestations of expansion hotspots. The concentrated expansion hotspots were large parks and new districts such as Urumqi Economic Development Zone, High-tech Zone, Midong Industrial Park, Steel City Industrial Park, and the southern building materials city and Wenquan University Town. Government-led concentrated development of new districts and parks was the primary means driving urban expansion.

Temporal Influence Mechanism

Using multiple linear regression, we constructed a temporal driving model for Urumqi' s construction land growth. Since correlation coefficients among independent variables were all high, indicating severe multicollinearity, we extracted principal components from independent variables for dimensionality reduction regression. The model passed significance testing:

$$\ln Y = 0.986 \ln X_1 + 0.982 \ln X_2 + 0.990 \ln X_3 + 0.848 \ln X_4 + 0.351 D + 0.502 \ln X_5 + 0.345 \ln X_6 + 0.346 \ln X_7 + 0.298$$

$$R^2 = 0.986, F = 16.486, p < 0.001$$

where Y represents construction land area, X_1-X_8 represent various driving factors, and D represents the dummy variable for assistance policy effects.

The model results yield the following conclusions:

First, population and economic agglomeration are the main drivers of urban expansion. From 1990 to 2018, Urumqi' s share of Xinjiang' s total economic output increased from 21.9% to 25.1%, with enhanced scale agglomeration and a city primacy ratio approaching 2. Population agglomeration led to increased demand for construction land, expanding residential land, public service facilities, and park green space. Population growth also enhanced employment and consumption demand, indirectly stimulating urban economic development and driving urban expansion.

Second, in economic terms, the secondary industry plays a slightly larger role than the tertiary industry, with differences in their influence across time periods. The regression coefficient for secondary industry output value was slightly larger than that for tertiary industry, indicating that industrial drivers remain primary for urban spatial expansion. Based on traditional petrochemical and chemical industries, Urumqi has introduced high-tech industries such as machinery manufacturing and biomedicine, which have become the dominant drivers of recent economic growth. The industrial sector requires large amounts of land for factory construction, promoting urban spatial expansion. The ratio of secondary to tertiary industry in Urumqi showed a pattern of first decreasing, then increasing, and then decreasing again. In the 1990s, Urumqi' s economic development relied mainly on commodity trade-related industries, with the tertiary sector' s share increasing. After 2000, with the national process of heavy industrialization, the secondary sector gradually developed and its share increased. After 2010, the urban economy began industrial upgrading, causing the tertiary sector' s share to rise again. These indicator changes explain why economic driving factors for urban expansion differed across Urumqi' s development stages and why overall secondary industry influence was only slightly higher than tertiary industry.

Third, government influence was smaller than population and economic influences, manifested through increased government debt, urban planning guidance, and assistance policy dividends. The coefficients for government impetus variables X_4 and D were 0.848 and 0.351, respectively, lower than population and economic variables. Government impetus exerted a superimposed effect on economic and population functions, accelerating urban expansion. After 2010, the municipal government shifted from slight surplus to deficit, with the deficit continuing to expand. Through planning and fiscal measures, the government intensified new district and infrastructure construction, driving urban expansion. Under the national context of counterpart assistance to Xinjiang after 2010, central ministries also launched assistance programs, with the Ministry of Construction increasing Urumqi' s annual construction land quotas and sending assistance cadres to oversee new district development. Relying on Shanghai' s assistance to Xinjiang, Urumqi jointly restructured SAIC Xinjiang Automobile Group with SAIC Group to produce passenger vehicles.

Spatial Driving Mechanism

The geodetector method measures spatial heterogeneity from a global perspective. According to its calculation principle, if factor X divides space into 5 categories and the spatial distribution of grids containing Y values shows significant differences, it indicates that Y is concentrated in sub-regions of X, and the classification of X creates heterogeneity in Y. We classified each spatial factor into 5 categories using natural breaks. Since Urumqi' s construction land grids accounted for less than 5% of the total study area, we used a decision threshold of $q = 0.05$ to judge spatial heterogeneity. All spatial factors and construction land growth ratios showed negative correlations that passed significance testing at the $p = 0.05$ level, consistent with theoretical expectations [Figure 5: see original paper]. All factors showed significant q values ($p < 0.05$) across years, indicating that transportation, commercial, and geographic factors influenced construction land expansion. The number of factors exceeding the threshold was 8 in 1990-2000, 9 in 2000-2010, and 7 in 2010-2018, showing that the influence of spatial factors declined and their effects gradually dispersed.

The strongest influences were distance to railway (X_{10}) and distance to urban commercial center (X_6). Distance to urban commercial center reflects benefit factors of construction land expansion—the closer the distance, the greater the development benefit. Distance to railway reflects cost factors—the closer the distance, the lower the transportation costs for industry, logistics, and warehousing. The strong influence of railway and commercial factors reflects Urumqi' s characteristics as a comprehensive trade-oriented city connecting east and west in the Silk Road Economic Belt core area. Over time, the decision power of spatial influencing factors declined.

Interaction Detection results (Table 3) revealed that the interactive effects of construction land expansion spatial factors were stronger than single-factor effects. All two-factor interactions showed enhanced or non-linear enhancement, with no independent or weakening relationships, indicating that interactive decision power exceeded the original independent decision power and better promoted construction land expansion.

The decision power coefficient provides an overall examination of spatial driving effects but lacks detailed information. Further examination of single-factor classification results for construction land growth ratios found that point and axis factor influences conform to the first law of geography—construction land growth ratios decay with increasing distance . Except for the highway factor, the highest construction land proportion for other point-axis factors occurred in Category 1 (closest distance). Among the closest ranges (Category 1), the indicator with the highest distribution ratio was distance to urban centroid (X_8), followed by distance to commercial center (X_6) and distance to railway passenger station (X_3). For geographic factors, high values of construction land expansion for elevation factor concentrated in Category 3. The overall elevation distribution in the study area was 490–1700 m, with construction land concentrated at 600–900 m. The slope factor showed that lower slopes correlated with higher construction land expansion ratios, as flatter land facilitates development.

The number of factors showing non-linear enhancement gradually increased over time, and the decision power of two-factor interactive effects on construction land expansion gradually strengthened, explaining the earlier decline in single-factor decision power. Among them, distance to airport, distance to highway, distance to railway freight station, elevation, and slope achieved better enhancement effects when combined with other factors, with interactive decision power increasing by an average of more than 0.1. The interactive effects of distance to railway passenger station, distance to urban commercial center, and distance to urban centroid with other factors gradually strengthened, with average decision power enhancement levels gradually increasing .

Conclusions

Urban spatial expansion is a classic issue in urban geography. In the new era, China' s urban development internal and external environments have changed significantly, and urban expansion characteristics and driving mechanisms have also shown new features. Based on remote sensing interpretation data and quantitative analysis methods, this paper attempted to explore new factors of urban expansion and explain new characteristics of urban expansion driving mechanisms, reaching the following conclusions:

1. Urumqi' s construction land increased from 84.37 km2 to 361.91 km2, with urban morphology evolving from a north-south strip pattern to a "T-shaped" structure. Urban spatial compactness gradually decreased, with

core compactness higher than global compactness. Urban expansion speed remained stable while expansion intensity gradually strengthened. The "core-periphery" structure of urban expansion experienced a temporal evolution process of "strengthening-weakening-strengthening."

2. In terms of temporal mechanisms, in addition to traditional population and economic factors, government impetus accelerated Urumqi' s urban expansion after 2010. This represents an innovative point distinguishing this study from previous research.

3. In terms of spatial dimensions, transportation and commercial spatial elements were the main factors driving urban spatial expansion. Over time, the spatial dynamics of urban expansion shifted from being driven by a few key factors to being driven by multiple factors.

Discussion

Urban expansion is playing an increasingly prominent role in scientific research and government management. This paper aims to clarify the new characteristics of urban expansion in a typical large western city in recent years to serve future government planning and macro-control. However, it does not discuss the effects of urban expansion or how to select expansion models. Therefore, for western regions, future research should focus on integrated urban spatial expansion simulation and resource-environment effect studies.

In terms of research methods, domestic studies currently 多采用 geodetector to investigate spatial differences in multi-city expansion mechanisms at regional scales, while research on single-city internal mechanisms remains relatively rare. This paper attempts to make breakthroughs in this area. Due to the influence of research scope and spatial unit selection, the conclusion that elevation factors have greater influence than slope factors differs from actual understanding. Future research should improve methodologies to avoid synthetic fallacies in spatial unit selection. Additionally, this paper failed to grid socioeconomic factors to achieve integrated spatiotemporal driving models, which is another limitation.

References

[1] Yao Shimou, Chen Shuang. The trend of urban spatial evolution in the Changjiang River Delta[J]. Acta Geographica Sinica, 1998, 53(Suppl.1): 1-10.

[2] Zhang Li, Shi Xumin. Study on the coordinated development of urban and rural population and construction land in China[J]. Urban Development Studies, 2019, 26(6): 30-36.

[3] Xie Gaodi, Zhang Biao, Lu Chunxia, et al. Rapid expansion of the metropolitan areas and impacts of resources and the environment[J]. Resources Science, 2015, 37(6): 1108-1114.

[4] Wang Xinsheng, Liu Jiyuan, Zhuang Dafang, et al. Spatial temporal changes of urban spatial morphology in China[J]. Acta Geographica Sinica, 2005, 60(3): 392-400.

[5] Zhao Xiaofeng, Liu Mengli, Wang Baiyuan. Spatio-temporal disparity of urban construction land and its impact factors in China based on geodetector[J]. China Land Science, 2018, 32(5): 31-37.

[6] Zhou Runfang, Zhou Liang. Analysis of spatial expansion characteristics of typical Chinese border cities[J]. Science of Surveying and Mapping, 2019, 44(9): 1-8.

[7] Anniwaer Abudureyimu, Alimu Kasimu, Tashigen Jiapaer, et al. Expansion of urban area and its driving forces of Yining City based on remote sense data[J]. Arid Land Geography, 2018, 41(1): 109-118.

[8] Wang Yazhu, Duan Xuejun, Yang Qingke. Spatio-temporal characteristics and driving factors of urban construction land in Jiangsu Province in the last 30 years[J]. Resources and Environment in the Yangtze Basin, 2019, 28(7): 1531-1540.

[9] Chen Jianglong, Gao Jinlong, Wei Yehua, et al. Spatial determinants of urban land expansion in large Chinese cities: A case study of Nanjing City[J]. Scientia Geographica Sinica, 2013, 33(6): 676-684.

[10] Li Jintao, Liu Yansui, Yang Yuanyuan, et al. Spatial-temporal characteristics and driving factors of urban construction land in Beijing-Tianjin-Hebei region during 1985-2015[J]. Geographical Research, 2018, 37(1): 37-52.

[11] Lu Wenlu, Liu Zhifeng, He Chunyang, et al. A new method for detecting urban construction land based on Sentinel-1A synthetic aperture radar data and fully convolutional network[J]. Arid Land Geography, 2020, 43(3): 750-760.

[12] Gao Jinlong, Chen Jianglong, Yuan Feng, et al. Patterns, functions and underlying mechanisms of urban land expansion in Nanjing[J]. Geographical Research, 2014, 33(10): 1892-1907.

[13] Wang Xuewei, Wang Shijun, Song Yang, et al. Space recognition and influence mechanism of urban construction land evolution of Changchun City[J]. Scientia Geographica Sinica, 2015, 35(7): 873-881.

[14] Fang Chuanglin. Strategic thinking and spatial layout for the sustainable development of urban agglomeration in northern slope of Tianshan Mountains[J]. Arid Land Geography, 2019, 42(1): 1-11.

[15] Zhang Tingwei. The urban restructuring of Chinese cities in 1990s and its dynamic mechanism[J]. City Planning Review, 2001, 25(7): 7-14.

[16] Zhang Xinhuan, Yang Degang, Chen Xi. Study on the process and mechanism for urban land expansion in Urumqi in 50 years[J]. Arid Land Geography, 2005, 28(2): 263-269.

[17] Liza Sailike, Zibibula Simayi. Analysis of urban expansion and driving forces based on RS and GIS of Urumqi City[J]. Urban Development Studies, 2013, 20(3): 57-60.

[18] Tan Shaohua, Huang Yuangang, Liu Jianfeng. Study on the mechanism between urban land use growth and policy in China[J]. Urban Development Studies, 2014, 21(4): 24-32.

[19] Wang Jian, Wang Yinghong, Peng Shangui. Incentives for urban land expansion in China[J]. Urban Problems, 2016(1): 7-16.

[20] Long Maoqian, Meng Xiaochen. Urbanization, suburbanization and China's urban spatial expansion[J]. Areal Research and Development, 2015, 34(3): 53-60.

[21] Zhang Yaoyu, Chen Ligen, Song Luyi, et al. Differences in driving force mechanisms in urban land expansion in China[J]. Resources Science, 2016, 38(1): 30-40.

[22] Chen Wanxu, Li Jiangfeng, Xiong Jinhui, et al. Differences in driving force mechanisms in urban land expansion in China based on GWR[J]. Journal of Henan University (Natural Science Edition), 2018, 48(5): 21-29.

[23] Chen Yu, Wang Kaiyong. Influence and mechanism of turning counties (cities) into districts on urban space expansion: Taking Hangzhou as a case study[J]. Geographical Research, 2019, 38(2): 31-44.

[24] Liu Yuping, Zhang Jingxiang. An analysis of government-led transformation of urban spatial structure: Based on an empirical study of Yangzhou[J]. City Planning Review, 2019(6): 20-26.

[25] Wang Z W, Lu C H. Urban land expansion and its driving factors in mountain cities in China during 1990-2015[J]. Journal of Geographical Sciences, 2018, 28(8): 1152-1166.

[26] Batty M. Exploring isovist fields: Space and shape in architectural and urban morphology[J]. Environment and Planning B: Urban Analytics and City Science, 2001, 28(1): 123-150.

[27] Wang J F, Zhang T L, Fu B J. A measure of spatial stratified heterogeneity[J]. Ecological Indicators, 2016, 67: 250-256.

Note: Figure translations are in progress. See original paper for figures.