Chin. Geogra. Sci. 2015 Vol. 25 No. 2 pp. 250–262
doi: 10.1007/s11769-014-0687-0

Springer Science Press
www.springerlink.com/content/1002-0063

Characteristics and Driving Forces of Spatial Expansion of Oasis Cities and Towns in Hexi Corridor, Gansu Province, China

LIU Hailong, SHI Peiji, TONG Huali, ZHU Guofeng, LIU Haimeng, ZHANG Xuebin, WEI Wei, WANG Xinmin

(*College of Geography and Environmental Science*, *Northwest Normal University*, *Lanzhou* 730070, *China*)

Abstract: This paper presents an integrated study of urban spatial expansion in the Hexi Corridor, Gansu Province, China based on TM, ETM remote sensing data in 1987, 1990, 1995, 2000, 2006 and 2011. The study explores the characteristics of urban spatial expansion and dynamic mechanism by using expansion speed index, expansion intensity index, compact index, fractal dimension, and extended flexibility index. We built the index system of influencing factors of urban spatial expansion by using the grey incidence model. The results showed that urban spatial expansion rate in the Hexi Corridor has been on the upward trend since 1987. Expansion intensity showed an obvious upward trend, however, the upward trend varied in different urban areas. In addition, the urban structure was loose relatively, but the urban compactness was more obvious. The urban spatial form tended to be simple, and the urban land use tended to become more intensive. Urban spatial expansion experienced several stages: padding internally, external expansion and padding internally. The main driving factors of urban spatial expansion are not the urban water resources and the oasis scale, but one or several factors such as economy, traffic, population, resource and national policy.

Keywords: spatial expansion; driving forces; oasis cities and towns; Hexi Corridor; China

Citation: Liu Hailong, Shi Peiji, Tong Huali, Zhu Guofeng, Liu Haimeng, Zhang Xuebin, Wei Wei, Wang Xinmin, 2015. Characteristics and driving forces of spatial expansion of oasis cities and towns in Hexi Corridor, Gansu Province, China. *Chinese Geographical Science*, 25(2): 250–262. doi: 10.1007/s11769-014-0687-0

1 Introduction

The direct consequence of urbanization is urban spatial expansion which linked to the study of pattern-structure-process-mechanism in geography. The progress and pattern are vital characteristics of regional urbanization and urban regionalization (Ma *et al*., 2008). There are some underlying factors motivating the urban spatial expansion, which are nature, society, economy and culture (Huang *et al*., 2008). Researches on the progress, pattern, and mechanism have become the effective measure to identify the urban development phases and rules (Che *et al*., 2011). With the restructuring of the global economic integration and the influence of the knowledge economy, the internal mechanism of urban spatial structure has become more complex. In recent years, along with the rapid advance of the urbanization process in China, urban space has expanded sharply. Under the influence of internal and external factors, some different expanding characteristics have emerged gradually. In such cases, it is necessary and meaningful to study the urban spatial expansion.

From the 1910s, geographers began to focus on urban space research. In recent years, some different countries and regions focused on the research of the scale, speed and pattern of typical urban spatial expansion, and the relationships between urban expansion and nature protection, demographic changes, and economic develop-

Received date: 2013-08-30; accepted date: 2013-12-27

Foundation item: Under the auspices of National Natural Science Foundation of China (No. 41271133, 41261104), National Social Science Foundation of China (No. 12CTJ001)

Corresponding author: SHI Peiji. E-mail: Shipj@nwnu.edu.cn

ment, the researchers summarized regional difference, background and reasons of urban spatial expansion (Kline *et al*., 2001; Weber and Puissant, 2003; Sato and Yamamoto, 2005; Mique-Àngel and Ivan, 2011). They simulated and predicted the urban space growth through the perspectives of people, environment, economy, resources and the distribution of enterprise (Hassea and Lathrop, 2003; Martin and Sunley, 2006; Eric *et al*., 2012). They used the methods of mathematical statistics, remote sensing, GIS, computer simulation model, combining investigation and quantitative and qualitative analysis. The urban space has been studied in China since the 1980s. In recent years, the studies focused on the scale, speed, direction of spatial expansion, space variation characteristics, process of urban spatial extension (Zhang *et al*., 2006; Wang *et al*., 2008; Zhu and Feng, 2010; Zhao *et al*., 2011). Many comparative studies about the urban spatial expansion in different economic development stages were carried out (Zhang *et al*., 2012), different urban space development pattern and driving mechanism were summarized (Liu and Shen, 2006; Liao *et al*., 2007; Wu *et al*., 2008; Shi *et al*., 2009), and the urban spatial expansion were simulated and predicted by using the methods of the cellular automata model, genetic algorithm, neural network and system dynamics models (Li and Ye, 1999; He *et al*., 2006; Yang and Li, 2007; Qiu and Chen, 2008; Kuang *et al*., 2011). The study area mainly concentrated on the economically developed areas and the typical undeveloped areas, while the central and western regions in China have not been studied deeply, especially in terms of the progress, pattern, and mechanism of urban spatial expansion.

Oasis is the main region of human activities in the arid area, and the contradiction between human and ecological environment is obvious in the oasis area. Since the 1990s, the contradictions have been more and more severe with the resources exploitation and urban space growth in the oasis area of Hexi Corridor Gansu Province, China. In addition, this region met new development opportunities because of new national policies, such as 'Western Development Strategy', the construction of national spatial development pattern and the reconstruction of the Lanzhou-Xinjiang Economic Belt. However, the research of spatial expansion in oasis cities and towns mainly focused on the characteristics, urban land expansion, mechanism, pattern evolution and variation rules in recent years (Zhang *et al*., 2005; Zhang *et al*., 2006; Dong *et al*., 2006; Liu *et al*., 2011; Shi *et al*., 2012), there is not enough integrated study about urban expansion and its driving mechanism. It was necessary to study the progress, pattern, characteristics and mechanism of urban spatial expansion in the Hexi Corridor.

In this study, we studied 20 units, including 19 county-level administrative regions and one prefecture-level city (Jiayuguan City) in the Hexi Corridor. The characteristics of the urban spatial expansion were analyzed in this study by expansion speed index, expansion intensity index, compact index, fractal dimension and extended flexibility index, which were based on remote sensing data. We built the index system of influential factors, including economy, transportation, population, resources and other natural and social economic factors, and then we analyzed the driving factors of urban spatial expansion by using the grey incidence model, which can scientifically provide the theoretical basis for oasis cities and towns and urban development in arid areas.

2 Study Area and Data Sources

2.1 Study area

The Hexi Corridor, a very important route connecting the west and east of Northwest China since ancient times, lies in Gansu Province and on the west of the Huanghe (Yellow) River in China. It is a long natural corridor, and the distance from north to south is 40–100 km and from east to west is about 1120 km. It starts at Wushao Mountain in the east, and ends at Yumenguan in the west (Fig. 1). This region has a typical temperate desert climate: dry with very little precipitation, plenty of sunshine and fragile ecological environments. There are 19 county-level administrative regions (Jinchuan District, Liangzhou District, Ganzhou District, Suzhou District, Yongchang County, Minqin County, Gulang County, Tibetan Autonomous County of Tianzhu, Linze County, Shandan County, Minle County, Gaotai County, Yugur Autonomous County of Sunan, Jinta County, Yumen City, Dunhuang City, Guazhou County, Mongolian Autonomous County of Subei and Kazak Autonomous County of Aksay) and one prefecture-level city (Jiayuguan City). The total area is about 2.76×10^5 km^2, which account for 60.4% of the area of Gansu Province. Total population in 2011 was 4.82×10^6, which ac-

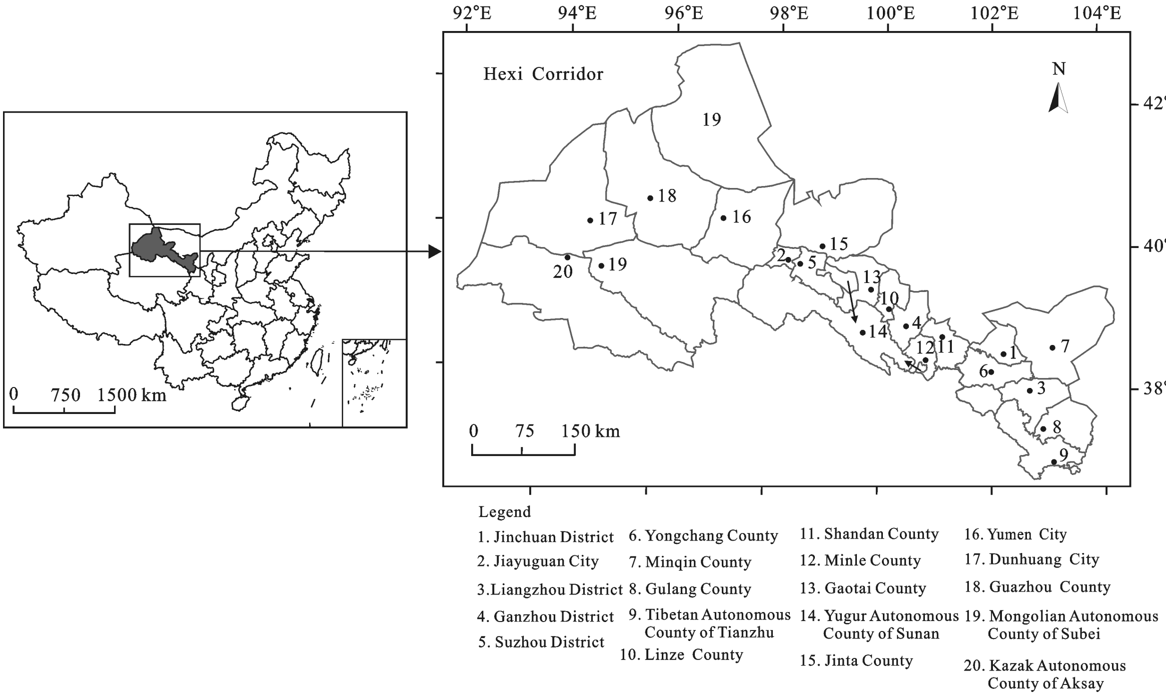

Fig. 1 Location of study area

counted for 18.81% of that in Gansu Province. GDP reached 1.4791×10^{11} yuan (RMB) in 2011, accounting for 29.46% of the total economy in Gansu Province (Gansu Bureau of Statistics, 2012).

2.2 Data sources

The remote sensing data were obtained from the United States Geological Survey (USGS) website (http://glovis.usgs/Imgviewer) and scientific data service platform in Computer Network Information Center, Chinese Academy of Sciences (http://datemirror.csdb.cn), which include Landsat TM images (30 × 30 m) of the Hexi Corridor in July of 1987, August of 1990, July of 1995, July of 2006 and August of 2011 and Land ETM images (15 × 15 m) in July of 2000. Based on the topographic map (1∶100 000) of the study area, we used cubic polynomial model for geometric correction, and errors were kept within one pixel. By adopting the combination of visual interpretation and supervised classification method, we extracted the urban built-up area from 1987 to 2011(Fig. 2).

The accuracy of the extracted urban built-up area was verified based on the data in *Gansu Province Development Yearbook 2012* (Gansu Bureau of Statistics, 2012). The verification result showed Jinchuan District was 98.40% which was the highest, Suzhou District, Jiayuguan City, Ganzhou and Liangzhou districts were 90.54%, 85.48%, 79.77%, and 74.98% respectively. However, there were a large number of housing estates around the central area of Ganzhou and Liangzhou districts, which were also calculated in the urban built-up area in the statistical data. So the data used in the paper extracted from the remote-sensing image were more accurate, it could reflect the actual urban expansion more truthfully and met the needs of our research. The socioeconomic data were obtained from *Statistical Yearbook 1988*; *1991*; *1996*; *2001*; *2007*; *2012* (Gansu Bureau of Statistics, 1988; 1991; 1996; 2001; 2007; 2012). Traffic data were obtained from a document compiled by the Gansu provincial traffic network diagram (1∶1000 000) and Gansu Provincial Highway Mileage Atlas in 2012. We overlaid the traffic data and administrative region boundaries for digital maps using GIS (Feng *et al*., 2009). Water resources data were provided by 'Environmental & Ecological Science Data Center for West of China, National Natural Science Foundation of China' (http://westdc.westgis.ac.cn), which included the concurrent data of the ecological security evaluation in the Hexi Corridor and landscape planning research project. Besides, the water resources data in 2006 and 2011 were obtained from the Annual Report of Water Resources in Gansu Province.

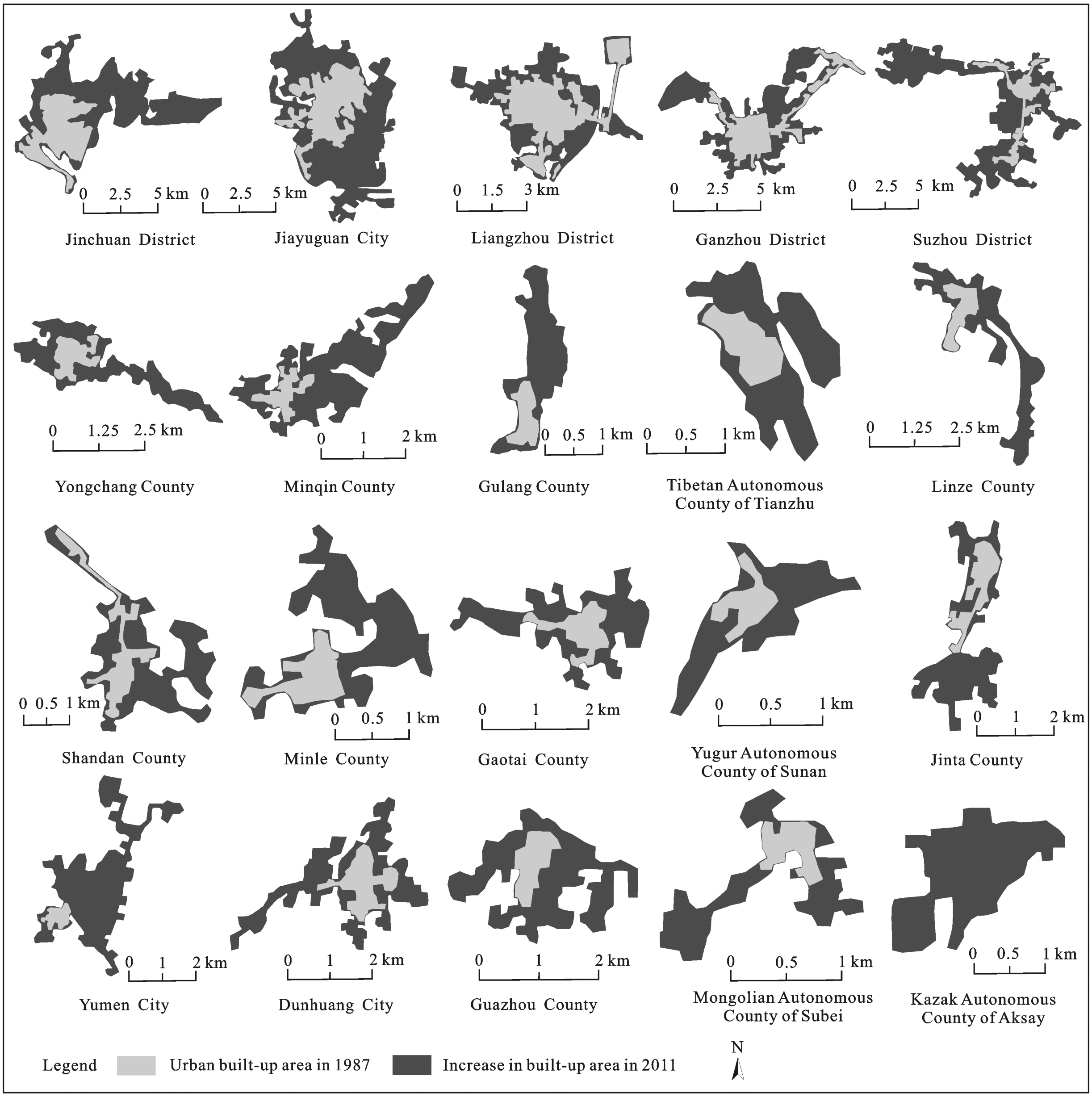

Fig. 2 Urban spatial expansion in Hexi Corridor (1987–2011). Because there was a relocation in Kazak Autonomous County of Aksay in 1995, the built-up area is not labeled

3 Methodology

3.1 Characteristics of urban spatial expansion

There are a number of indexes reflecting urban space expansion characteristics currently. Based on the researches of predecessors, considering the complement and the availability of different indexes, expansion speed index is used to reflect the overall changes of urban land, and expansion intensity can reflect the average annual urban expansion speed and boost the comparability of the expansion velocity during different periods (Chu *et al*., 2006). Besides, compact index can reflect the spatial agglomeration degree; fractal dimension of urban land shows the complexity and irregularity degree of the urban boundary; extended flexibility index can reflect whether urban land is intensive or not. In the paper, we used the above indicators synthetically to reflect the spatial pattern and structure characteristics of urban space expansion (Zhang *et al*., 2006).

3.1.1 Expansion speed index and expansion intensity index

Expansion speed index M_{ue} and expansion intensity index I_{ue} were normally used to analyze and describe the expansion of different urban lands, and compared the strength, speed and trend of the extension during different periods (Chu *et al*., 2006; Che *et al*., 2011). The formula is as follows:

$$M_{ue} = \frac{\Delta U_i}{\Delta t \times ULA_i} \times 100\% \quad (1)$$

$$I_{ue} = \frac{\Delta U_i \times 100}{TLA \times \Delta t} \quad (2)$$

where ΔU_i is the scale of urban land expansion for period i; Δt is the time span; ULA_i is the urban built-up area in the beginning of period i; TLA is the territorial area of the study region.

3.1.2 Compact index

Compact index was a parameter to reflect the object shape that could display the characteristics of urban land expansion. The perimeter of the plaques was compared with the circumference equaling to the area of the plaques (Wang *et al*., 2008). In general, it can be expressed as follows:

$$C_{ij} = \frac{2\sqrt{\pi A_{ij}}}{P_{ij}} \quad (3)$$

where C_{ij} is the compact index of town i in the year j; A_{ij} is the urban built-up area of town i in the year j; P_{ij} is the perimeter of the urban built-up area of town i in the year j. C_{ij} values are between 0–1. If the value is larger, the urban compactness is larger. whose compact index is 1. Larger compact index means lower transportation fee, and the improvement of utilization efficiency of urban infrastructure (Liu *et al*., 2011).

3.1.3 Fractal dimension

Fractal dimension of urban land shows the complexity and irregularity degree of the urban built-up area boundary (Wang *et al*., 2012). The formula is as follows:

$$D_{ij} = \frac{2\ln\left(\frac{1}{4}P_{ij}\right)}{\ln A_{ij}} \quad (4)$$

where D_{ij} is the fractal dimension of urban land of town i in the year j; A_{ij} is the urban built-up area of town i in the year j; P_{ij} is the perimeter of the urban built-up area of town i in the year j. The values of fractal dimension are between 1–2, and the bigger of fractal dimension, the more complex of urban form. When $D_{ij} < 1.5$, urban morphology tended to be simple; when $D_{ij} = 1.5$, the urban form was not stable because of the Brownian movement; when $D_{ij} > 1.5$, urban form was complicated. Fractal dimension can reflect the internal urban expansion ability with the compact index.

3.1.4 Extended flexibility index

Referring to the concept of elasticity in economics, we use extended flexibility index to discuss the coordinating relations between urban expansion speed and the population increase speed, and to reflect the rationality of urban expansion (Wang *et al*., 2008). Its formula is as follows:

$$R_{ij} = \frac{\Delta A_{ij}}{\Delta Pop_{ij}} \quad (5)$$

where R_{ij} is the extended flexibility index of town i in the time j; ΔA_{ij} is the average annual growth rate of urban built-up area of town i in the time j; ΔPop_{ij} is the average annual growth rate of non-agricultural population of town i in the time j. Related studies show that the reasonable extended flexibility index of towns in China is 1.12 (Chu, 2007; Zheng *et al*., 2009).

3.2 Driving forces of urban spatial expansion

Urban spatial expansion resulted from the inherent adaptability factors and external driving factors. The inherent adaptability factors included climate, topography, hydrology, vegetation and the external driving factors included resources, economic, population and traffic location. To represent the driving factors of urban spatial expansion in quantification, we chose the urban built-up area as an independent variable, and put the nature, society and economy as the dependent variable. Then an indicator system on driving factors was built up (Table 1) (Deakin *et al*., 2002; He *et al*., 2002; Tan *et al*., 2003; Liu *et al*., 2011; Cai *et al*., 2012). We used the grey incidence method to analyze the driving forces except some qualitative driving forces, like policy.

Economic and population factors were divided into gross and component (Table 1). We dealt with each economic factor on the basis of the constant in 1987 to eliminate the influence of different period. Non-agricultural population mainly expresses the relationship between population urbanization and land urbanization. Urban water resources refer to the part of annual runoff for urban water supply deducted the water cost by eco-

Table 1 Indicator system on driving factors of urban spatial expansion

Index level	Driving factor
Economic factor	GDP
	Added value of agriculture
	Added value of industry and construction industry
	Added value of commercial and service industry
Traffic factor	Accessibility index
Population factor	Total population
	Non-agricultural population
Natural factor	Urban water resources
	Oasis area

logic and agriculture at a specific ratio. Although groundwater in this region also accounts for a certain proportion, we do not consider the influence of groundwater in the paper. Oasis area reflected the relations between the heart of oasis and the urban spatial expansion. The traffic factors had an important influence on urban development in the Hexi Corridor. An accessibility index displayed the relations between traffic and urban spatial expansion. Policy factor was discussed qualitatively. The urban spactial expansion is influenced by the categories of industrial parks which is one of the important driving factors. However, considering many industrial parks, such as Huangyang industrial park and Gaotai industrial park, are far from or located within urban area, which makes it difficult to extract the area of these industrial parks, we just applied the area to do qualitative analysis.

3.2.1 Grey incidence analysis

The grey system theory was originated from Deng Julong in China in the early 1980s (Deng, 1985). The basic idea of grey incidence analysis was to determine the similarity degree according to the geometrical shape of different sequences. When the curve was closer, the corresponding sequences had greater correlation. The main feature was that we do not have to consider the sample capacity and the regularity of samples. The calculated results only related to the change rate relative to the starting point rather than concrete numerical value (Liu *et al*., 2010). Therefore, this paper studied the main driving factors of urban spatial expansion in 1987–2011 by using the relative degree of incidence with the initial value of the standardized data. The calculation steps go as follows (Liu *et al*., 2010; Xu and Liu, 2012; Liu *et al*., 2013):

(1) Reference sequence and compared sequence

Put the time series of the urban area as the reference sequence, $X_{i0}(k)$; put the influencing factors as the compared sequence, $X_{ij}(k)$. The formula is as follows:

$$X_{i0}(k)=\left\{X_{i0}(1),X_{i0}(2),\ldots,X_{i0}(n)\right\} \quad (6)$$

$$X_{ij}(k)=\left\{X_{ij}(1),X_{ij}(2),\ldots,X_{ij}(n)\right\} \quad (7)$$

where $X_{i0}(k)$ is the urban built-up area of town i in the year k; $X_{ij}(k)$ is the element j affecting urban spatial expansion of town i in the year k; i is the number of towns in the study region, i = 1, 2, …, p; j is the number of compared sequence, the number of elements influencing urban spatial expansion, j = 1, 2, …, m; k is the year.

(2) Standardization processing of indexes

Using the initial value method, each column data were divided by the first data in the column, then a set of fixed sequence could be obtained based on the development speed. $X'_{i0}(k)$ is the new reference sequence, and $X'_{ij}(k)$ is the new compared sequence, the formula is as follows:

$$X'_{i0}(k)=\frac{X_{i0}(k)}{X_{i0}(1)},\qquad X'_{ij}(k)=\frac{X_{ij}(k)}{X_{ij}(1)} \quad (8)$$

(3) Calculation of the absolute difference between reference sequence and compared sequence

$X''_{ij}(k)$ is the absolute difference between reference sequence and compared sequence, from the equations (6), (7) and (8), the following equation can be obtained:

$$X''_{ij}(k)=\left|X'_{ij}(k)-X'_{i0}(k)\right| \quad (9)$$

(4) The accumulative difference between reference sequence and compared sequence. $|s'_{i0}|$ is the accumulative value of the reference sequence after dealing with the absolute difference. $|s'_{ij}|$ is the accumulative value of the compared sequence after dealing with the absolute difference. By calculating $|s'_{i0}|$, $|s'_{ij}|$, $|s'_{ij}–s'_{i0}|$ through the Equation (10), (11), (12), the following equations can be obtained:

$$\left|s'_{i0}\right|=\left|\sum_{k=2}^{n-1}X''_{i0}(k)+\frac{1}{2}X''_{i0}(n)\right| \quad (10)$$

$$\left|s'_{ij}\right|=\left|\sum_{k=2}^{n-1}X''_{ij}(k)+\frac{1}{2}X''_{ij}(n)\right| \quad (11)$$

$$\left|s'_{ij}-s'_{i0}\right|= \left|\sum_{k=2}^{n-1}(X''_{ij}(k)-X''_{i0}(k))+\frac{1}{2}(X''_{ij}(n)-X''_{ij}(n))\right| \quad (12)$$

(5) Calculation of the relative degree of incidence

r_{i0j} is the relative degree of incidence. In general, the expression goes as follows:

$$r_{i0j} = \frac{1+|s'_{i0}|+|s'_{ij}|}{1+|s'_{i0}|+|s'_{ij}|+|s'_{ij}-s'_{i0}|} \quad (13)$$

3.2.2 Traffic accessibility index

Traffic accessibility index was built based on the traffic density and convenience degree (Feng *et al.*, 2009). Traffic density is the ratio of total road length and the land area; convenience degree is the distance between urban center and highway, railway, airport, *etc* (Table 2).

We eliminate the influence of dimension by normalized processing, endowing with corresponding weight of each indicator, then we can get the traffic density and convenience degree in each district and county in the study area. On this basis, the accessibility index is the half of the sum of traffic density and convenience degree.

$$TD=0.25R_h+0.25R_n+0.25R_r+0.125R_p+0.125R_c \quad (14)$$

$$SL=0.25D_a+0.25D_r+0.25D_h+0.125D_n+0.125D_p \quad (15)$$

$$TAI=1/2(TD+SL) \quad (16)$$

where *TAI*, *TD*, *SL* are the traffic accessibility index, traffic density and convenience degree respectively; R_h, R_n, R_r, R_p and R_c are high-speed road density, the national road density, the railway density, provincial road density and the county road density, respectively; D_a, D_r, D_h, D_n and D_p is the distance from the built-up area to airport, railway station, entry of the high-speed road, the national road and provincial road respectively. Accessibility index value is between 0 and 1, when it become closer to 1, that is to say, the degree of accessibility become larger (Feng *et al.*, 2009).

4 Results

4.1 Characteristics of urban spatial expansion

4.1.1 Expansion speed index and expansion intensity index

From Fig. 3, it can be seen that the expansion speed of the built-up area for Liangzhou District, Ganzhou District, Linze County, Yugur Autonomous County of Sunan, Yumen City and Guazhou County increased gradually in 1987–2000, and there was relocation in 1995 in Kazak Autonomous County of Aksay. The expansion speed of other 14 units all slowed down in the same period. Influenced by 'Western Development Strategy', the urban expansion speed of most studied regions reached the highest in 2000–2006, and had a little fall back in 2006–2011. The urban expansion speed of other studied regions reached the highest in 2006–2011. The urban expansion in Yumen City and Suzhou District showed a dramatic high speed after 2000 because Yumen City moved to Yumen Town and Yumen Oilfield Administration Bureau moved to Suzhou District. The expansion speed of the oasis cities and towns in the Hexi Corridor in 1987–1995, 1995–2000 and 2000–2006 was 5.43%, 4.43% and 10.54% respectively. According to Che (2011), in the Changjiang (Yangtze) River Delta, the urban expansion speed was 3.2%, 5.80% and 15.85% respectively in the corresponding periods. Comparatively speaking, the urban expansion speed of the Hexi Corridor slowed down after 1995. In overall terms, influenced by own conditions and regional development strategy, the urban expansion speed in the Hexi Corridor

Table 2 Indicators of accessibility index

Destination layer	Criterion layer	Indicator layer
Traffic accessibility index	Traffic density	High-speed road density
		National road density
		Railway density
		Provincial road density
		County road density
	Convenience degree	Distance away from airport
		Distance away from railway station
		Distance away from entrance of high-speed road
		Distance away from national road
		Distance away from provincial road

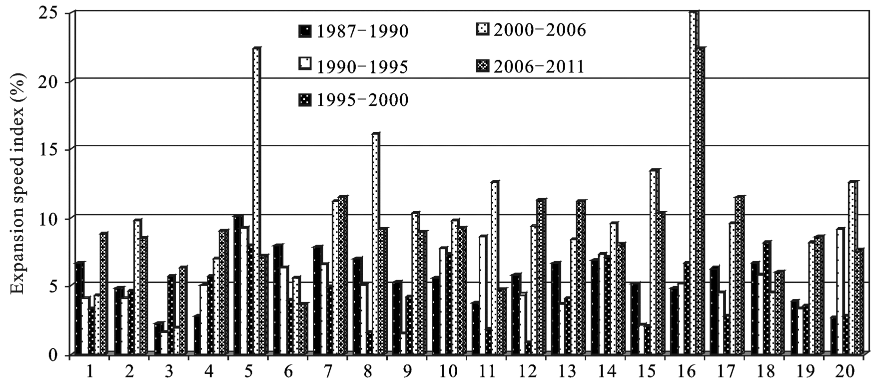

Fig. 3 Expansion speed index of oasis cities and towns in Hexi Corridor (1987–2011). 1, Jinchuan District; 2, Jiayuguan City; 3, Liangzhou District; 4, Ganzhou District; 5, Suzhou District; 6, Yongchang County; 7, Minqin County; 8, Gulang County; 9, Tibetan Autonomous County of Tianzhu; 10, Linze County; 11, Shandan County; 12, Minle County; 13, Gaotai County; 14, Yugur Autonomous County of Sunan; 15, Jinta County; 16, Yumen City; 17, Dunhuang City; 18, Guazhou County; 19, Mongolian Autonomous County of Subei; 20, Kazak Autonomous County of Aksay

declined slowly first and then rise up fast in 1987–2011. On the whole, it presented a trend of increasing, but had a further widening gap with the eastern region of China.

The expansion intensity of the oasis cities and towns in the Hexi Corridor had the similar trends and characteristics (Fig. 4 and Fig. 5). During 1987–2011, the urban expansion intensity showed an increase trend, except Suzhou District, Yongchang County and Shandan County showed a decline trend because extension speed decreased dramatically during 2006–2011. The expansion intensities of cities or districts (Jinchuan District, Jiayuguan City, Liangzhou District, Ganzhou District, Suzhou District) were higher than those of counties, but Linze County, Shandan County, Minle County and Gaotai County had higher expansion intensities than Liangzhou and Ganzhou districts in 2000–2011, and Linze County had the highest ones in all periods. Suzhou District showed the abnormal trend in 2000–2006 because Yumen Oilfield Administration Bureau moved in. The expansion intensity of Jinchuan District, Jiayuguan City, Suzhou District, Ganzhou and Liangzhou districts were above 0.01. The average values of the expansion intensity in the study area were 0.004, 0.006 and 0.014 in 1987–1995, 1995–2000 and 2000–2006 respectively. During the same periods, the expansion intensity of Changjiang River Delta was 0.07, 0.08 and 0.46 (Che *et al*., 2011). Thus it can be seen the land use scale is relatively small because there is a large area of gobi and desert and mountain in the oasis cities

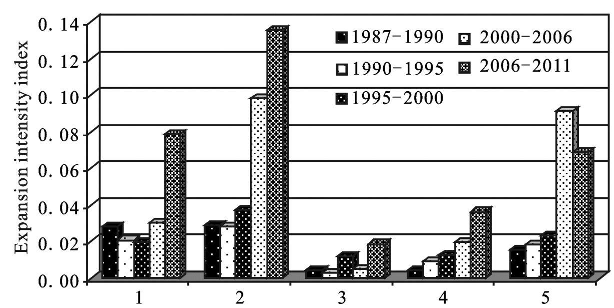

Fig. 4 Expansion intensity index of prefecture-level cities in Hexi Corridor (1987–2011). The codes are the same with Fig. 3

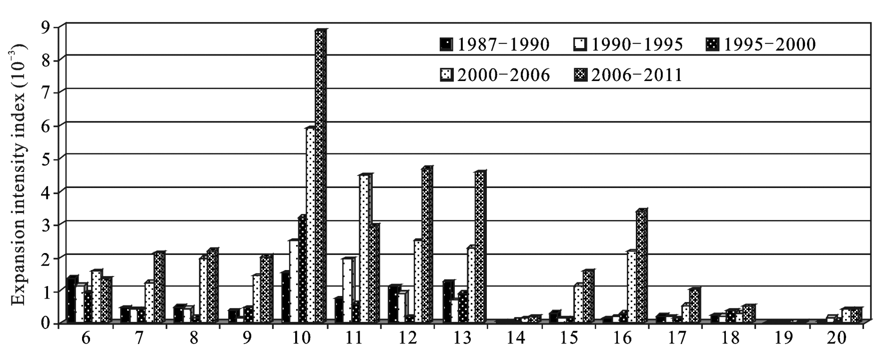

Fig. 5 Expansion intensity index of oasis cities and towns in Hexi Corridor (1987–2011). The codes are the same with Fig. 3

and towns administrative area. Overall, the expansion intensity of the oasis cities and towns were small in arid regions.

4.1.2 Compact index

As shown in Fig. 6, because the oasis cities and towns were mainly distributed on the plains of Hexi Corridor, the urban spatial expansion had less restricted factors, and the urban space layout was relatively loose. The compact degree of the oasis cities and towns were smaller overall, and the biggest compact degree was 0.577. The compact degree showed a decreasing trend about in 2000 except Jinchuan District, Jiayuguan City, Yugur Autonomous County of Sunan and Kazak Autonomous County of Aksay, which mainly related to industrial layout and urban expansion stage. Urban expansion was mainly based on expansion outward, and internal filling was complementary. Compared with the prefecture-level cities (except the mineral resource cities), county towns had more compact urban space form.

4.1.3 Fractal dimension

Figure 7 showed the fractal dimension change of oasis cities and towns in the Hexi Corridor in 1987–2011. The fractal dimension of all oasis cities and towns were less than 1.5, and urban space form tends to be simple, which corresponded with the small scale of oasis cities and towns. Overall, the fractal dimension showed a decline trend except Yongchang County, Yugur Autonomous County of Sunan and Mongolian Autonomous County of Subei, and the style of internal filling expansion is the main style of urban spatial expansion. The evolution of urban land use trends obviously intensified. The urban boundary in larger land use scale was more complicated, which result in that the fractal dimension of the prefecture-level cities were bigger than that of the county towns. Some counties, with outward expansion as the main, showed a rising trend of urban expansion in 1995–2000, which identifies with the study conclusions of compact on the whole. Therefore, urban spatial expansion in the Hexi Corridor in 1987–2011 experienced several stages—padding internally, external expansion and padding internally.

4.1.4 Extended flexibility index

The extended flexibility index of oasis cities and towns in the Hexi Corridor during 1987–2011 was shown in

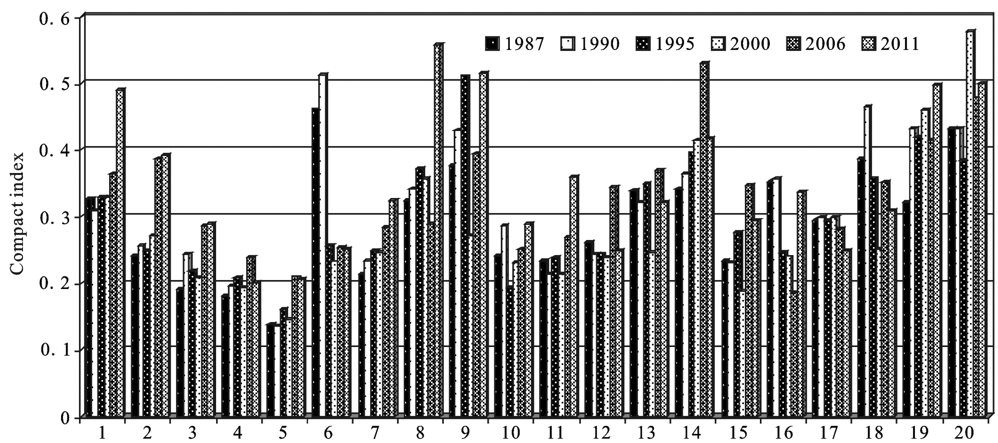

Fig. 6 Compact index of oasis cities and towns in Hexi Corridor (1987–2011). The codes are the same with Fig. 3

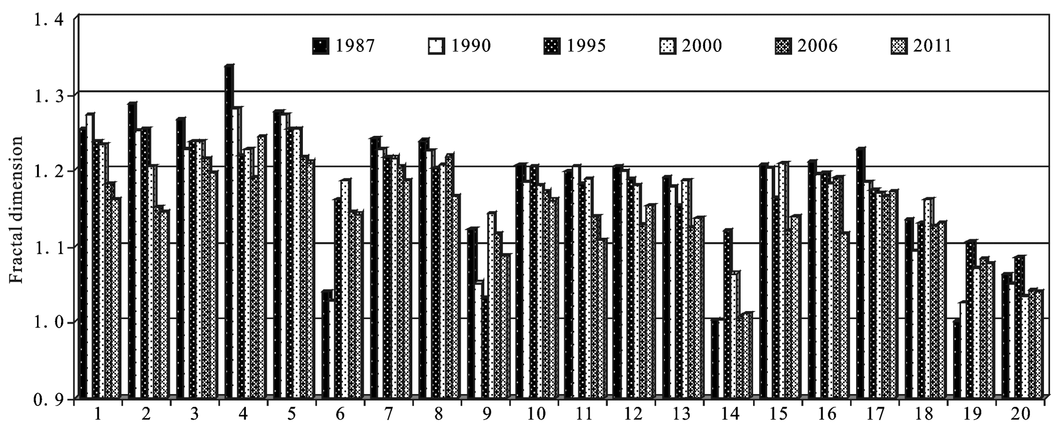

Fig. 7 Fractal dimension of oasis cities and towns in Hexi Corridor (1987–2011). The codes are the same with Fig. 3

Fig. 8. Generally speaking, the flexibility index of urban expansion was large, which was not reasonable. The average flexibility index during 2006–2011 was 2.39, and it was 4.38 in Dunhuang City, this was far from the ideal value (1.12). Only Gulang County and Kazak Autonomous County of Aksay were close to the ideal value during 2006–2011. As the rationality of the urban construction land expansion increased, the extended flexibility index declined gradually during 1987–1995 except Gaotai County and Kazak Autonomous County of Aksay. Meanwhile, the speed of population growth was relatively faster than the growth of urban spatial expansion. The extended flexibility index of oasis cities and towns increased gradually during 1995–2006 which means the speed of urban land expansion was higher than the growth of urban population and the reasonable urban infrastructure expansion declined significantly. However, urbanization developed faster, and urban population increased rapidly after 2006. The extended flexibility index of most of the towns decreased which reflected the reasonable urban infrastructure expansion increased except Jinchuan District, Minle County, Gaotai County, Yugur Autonomous County of Sunan and Jinta County. Thus it can be seen that the scale of urban land use in the Hexi Corridor was large generally, and there was a serious waste of land resources in the urban development. Therefore, it was essential to implement the intensive urban land use mode.

4.2 Driving forces of urban spatial expansion

The driving forces of urban spatial expansion were analyzed quantificationally in this study by using the grey incidence model (Table 3). As shown in the results, the relative degree of incidence between urban expansion and economic factors and non-agricultural population was pervasively high. The economic factor was the main driving factor of the spatial expansion of oasis cities and towns. For the type of agriculture oasis cities and towns, the agriculture was their first driving force; for the resource-based cities and towns, like Jinchuan District, Jiayuguan City, the industry and construction industry were the main factor of the urban spatial expansion; for Suzhou District, the rapid development of new energy industry in recent years made industry as one of its main economic factors. Dunhuang City was a famous tourist city and Suzhou District was a developed business city, the commercial and service industry were their main economic factors.The relative degree of incidence between non-agricultural population and urban spatial expansion was higher generally. The increase of non-agricultural population directly promoted the urban residential, commercial, industrial, transportation and other related industry development, thus promoting the urban construction land expansion. Population urbanization and land urbanization promoted mutually, and the demand for urban space of non-agricultural population were the direct cause for oasis cities and towns to expand (Liu *et al*., 2011).

The relative degree of incidence between traffic accessibility index, total population, urban water resources, oasis area and urban expansion was low, whereas the urban expansion in Jinchuan District, Liangzhou District and Yongchang County were affected by transportation. For population factors, the relative degree of incidence between total population and urban spatial expansion was lower generally, except Jinchuan District,

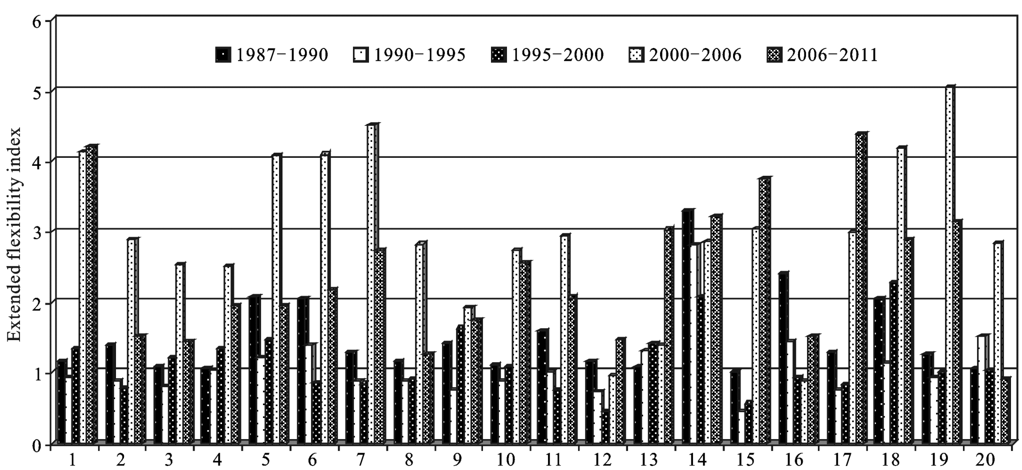

Fig. 8 Extended flexibility index of oasis cities and towns in Hexi Corridor (1987–2011). The codes are the same with Fig. 3

Jiayuguan City and Liangzhou District. The total population was not the main factor in the oasis cities and towns. There was not much relation between urban water resources and urban spatial expansion, which indicated that urban water resources were not the main driving force, although the urban location and layout in arid region were decided by the water resources. The relative degree of incidence between oasis area and urban expansion was also small, and even though oasis carries the mass production and living activities of human being in arid areas, the driving action for urban expansion was confined.

As remote ethnic minority autonomous counties, the urban expansion of Yugur Autonomous County of Sunan, Mongolian Autonomous County of Subei and Kazak Autonomous County of Aksay were lack of obvious driving forces except the commercial and service industry and non-agricultural population. The main driving force of these counties was the national and local policies. Besides, Yumen City also was influenced by policy and financial support because of the resources exhaustion, although Yumen City showed the characteristic of the commercial and service industry as the main driving force. Different types of industrial parks had some influence on the space expansion in the study area, especially after 2000. Owing to actualizing of the ′Western Development Strategy′, special advantageous industries were supported, the number of industry parks was increased, and the scale was expanded rapidly, which exerted a great effect on the expansion speed, intensity and direction in some oasis cities and towns (e.g., Suzhou District, Yumen City, Linze County, Shandan County).

Generally, although the urban location and layout in the Hexi Corridor were influenced by the spatial distribution of water resources, the main driving force of urban spatial expansion in arid region was neither urban water resources nor the oasis scale since 1987. The important driving forces were economy, traffic, resources, population and national policy, and other factors.

Table 3 Relative degree of incidence between urban expansion and driving factors in Hexi Corridor (1987–2011)

Cities and Towns	GDP	Added value of agriculture industry	Added value of industry and construction industry	Added value of commercial and service industry	Traffic accessibility index	Total population	Non-agricultural population	Urban water resources	Oasis area
Jinchuan District	0.745	0.656	0.831	0.733	0.805	0.762	0.795	0.629	0.630
Jiayuguan City	0.756	0.624	0.796	0.686	0.674	0.798	0.871	0.572	0.523
Liangzhou District	0.704	0.727	0.643	0.677	0.852	0.762	0.948	0.642	0.657
Ganzhou District	0.715	0.800	0.621	0.654	0.696	0.644	0.896	0.559	0.612
Suzhou District	0.931	0.728	0.862	0.861	0.581	0.558	0.705	0.528	0.559
Yongchang County	0.650	0.759	0.657	0.633	0.751	0.592	0.710	0.598	0.563
Minqin County	0.884	0.910	0.590	0.734	0.629	0.562	0.775	0.629	0.588
Gulang County	0.686	0.921	0.583	0.594	0.624	0.595	0.781	0.644	0.569
Tibetan Autonomous County of Tianzhu	0.727	0.708	0.618	0.612	0.667	0.574	0.731	0.542	0.581
Linze County	0.796	0.968	0.671	0.744	0.643	0.582	0.883	0.544	0.618
Shandan County	0.705	0.817	0.735	0.601	0.728	0.692	0.716	0.555	0.576
Minle County	0.775	0.995	0.627	0.655	0.665	0.608	0.885	0.558	0.553
Gaotai County	0.870	0.911	0.674	0.702	0.672	0.584	0.848	0.538	0.623
Yugur Autonomous County of Sunan	0.699	0.689	0.538	0.835	0.627	0.547	0.611	0.544	0.621
Jinta County	0.661	0.777	0.655	0.605	0.664	0.657	0.941	0.573	0.616
Yumen City	0.785	0.698	0.762	0.979	0.548	0.514	0.521	0.527	0.537
Dunhuang City	0.722	0.775	0.703	0.817	0.653	0.677	0.738	0.567	0.594
Guazhou County	0.765	0.834	0.731	0.696	0.641	0.613	0.665	0.565	0.582
Mongolian Autonomous County of Subei	0.553	0.678	0.536	0.662	0.710	0.711	0.794	0.645	0.617
Kazak Autonomous County of Aksay	0.679	0.711	0.675	0.601	0.664	0.614	0.764	0.579	0.607

5 Conclusions and Suggestions

This paper analyzed the space expansion characteristics and driving forces of 20 units in the Hexi Corridor during 1987–2011 by using remote sensing, GIS, related index model and grey incidence model. The results showed that: 1) Expansion speed of the oasis cities and towns in the Hexi Corridor showed a feature of 'decline slowly first and then rising fast' during 1987–2011. Overall, it showed a trend of increasing, but has a widening gap with the eastern region of China. Expansion intensity of the oasis cities and towns tended to upward obviously, however, the scope was small and there was big difference between different oasis cities and towns. The distribution of urban space was relatively loose. But the compact tendency was apparent. The urban space form was simple, and the trend of urban land use evolution was intensifying. Urban spatial expansion experienced several stages: padding internally, external expansion and padding internally, which was not reasonable, and resulted in larger scale of land use. 2) Since 1987, the main driving forces of urban spatial expansion were neither the urban available water resources nor the oasis scale, which was the capacity of production and living activities in arid areas, but one or several factors of economy, traffic, resources, population and national policy in a particular situation.

Therefore, based on the above research conclusions, there are some suggestions for reasonable urban extension as follows: first, during the urban spatial planning, the urban form compact should be taken into account to improve the utilization efficiency of infrastructure; second, the urban land use should be intensive so that the land use efficiency will be improved correspondingly; third, the development of special competitive industries should be accelerated and the capacity of industrial concentration should be enhanced to promote economic development; fourth, the construction of urban transportation should be accelerated to improve the urban traffic density and then promote urban space expansion.

References

Cai Yuanbin, Zhang Hao, Pan Wenbin *et al.*, 2012. Urban expansion and its influencing factors in natural wetland distribution area in Fuzhou City, China. *Chinese Geographical Science*, 22(5): 568–577. doi: 10.1007/s11769-012-0564-7

Che Qianjin, Duan Xuejun, Guo Yao *et al.*, 2011. Urban spatial expansion process, pattern and mechanism in Yangtze River Delta. *Acta Geographica Sinica*, 66(4): 446–456. (in Chinese)

Chu Jinlong, 2007. *Quantitative Analysis and Research of Urban Space Morphology*. Nanjing: Southeast University Press, 63–64. (in Chinese)

Chu Jinlong, Ma Xiaodong, Gao Shu *et al.*, 2006. Spatio-temporal characteristics of urbanization area growth in Nantong City, Jiangsu Province. *Journal of Natural Resources*, 21(1): 55–63. (in Chinese)

Deakin M, Curwell S, Lombardi P, 2002. Sustainable urban development: The framework and directory of assessment methods. *Journal of Environment Assessment Policy and Management*, 4(2): 171–197. doi: 10.1016/S1464-3332(02)00097-8

Deng Julong, 1985. *Grey System*: *Society and Economy*. Beijing: National Defence Industry Press. (in Chinese)

Dong Wen, Zhang Xiaolei, Wang Bin *et al.*, 2006. The research of intensity of urban land use growth and differentiation characteristics in Urumqi city. *Science in China Series D*, 36(S2): 148–156. (in Chinese)

Eric de Noronha Vaz, Peter Nijkampc, Marco Painhoa *et al.*, 2012. A multi-scenario forecast of urban change: A study on urban growth in the Algarve. *Landscape and Urban Planning*, 104: 201–211. doi: 10.2139/ssrn.1940371

Feng Zhiming, Liu Dong, Yang Yanzhao, 2009. Evaluation of transportation ability of China: From county to province level. *Geographical Research*, 28(2): 419–429. (in Chinese)

Gansu Bureau of Statistics, 1988. *Gansu Yearbook 1988*. Beijing: China Statistics Press. (in Chinese)

Gansu Bureau of Statistics, 1991. *Gansu Yearbook 1991*. Beijing: China Statistics Press. (in Chinese)

Gansu Bureau of Statistics, 1996. *Gansu Yearbook 1996*. Beijing: China Statistics Press. (in Chinese)

Gansu Bureau of Statistics, 2001. *Gansu Yearbook 2001*. Beijing: China Statistics Press. (in Chinese)

Gansu Bureau of Statistics, 2007. *Gansu Yearbook 2007*. Beijing: China Statistics Press. (in Chinese)

Gansu Bureau of Statistics, 2012. *Gansu Development Yearbook 2012*. Beijing: China Statistics Press. (in Chinese)

Hassea J E, Lathrop R G, 2003. Land resource impact indicators of urban sprawl. *Applied Geography*, 23 (2–3): 159–175. doi: 10.1016/j.apgeog.2003.08.002

He Chunyang, Norio Okada, Zhang Qiaofeng *et al.*, 2006. Modeling urban expansion scenarios by coupling cellular automata model and system dynamic model in Beijing, China. *Applied Geography*, 26: 323–345. doi: 10.1016/j.apgeog.2006.09.006

He Chunyang, Shi Peijun, Chen Jin *et al.*, 2002. Process and mechanism of urbanization in Beijing area. *Acta Geographica Sinica*, 57(3): 363–371. (in Chinese)

Huang S L, Wang S H, William W B, 2008. Sprawl in Taipei's peri-urban zone: Responses to spatial planning and implications for adapting global environmental change. *Landscape and Urban Planning*, 90: 20–32. doi: 10.1016/j.landurbplan.2008.10.010

Kline J D, Moses A, Alig R J, 2001. Integrating urbanization into landscape-level ecological assessments. *Ecosystems*, (4): 3–18. doi: 10.1007/s100210000056

Kuang Wenhui, Liu Jiyuan, Shao Quanqin *et al.*, 2011. Dynamic urban growth model at regional scale and its application. *Acta Geographica Sinica*, 66(2): 178–188. (in Chinese)

Liao Heping, Peng Zheng, Hong Huikun, 2007. Research on dynamic mechanism and model of urban spatial expansion since the establishment of Chongqing Municipality. *Geographical Research*, 26(6): 1137–1146. (in Chinese)

Liu Lina, Qu Jiansheng, Zeng Jingjing *et al.*, 2013. Application of gray relational analysis method in the influencing factor analysis of China's rural household carbon emissions. *Ecology and Enviromental Sciences*, 22(3): 498–505. (in Chinese)

Liu Shuhua, Shen Yufang, 2006. A probe into the urban sprawl model and its drive mechanism in Shanghai. *Economic Geography*, 26(3): 487–491. (in Chinese)

Liu Sifeng, Dang Yaoguo, Fang Zhigeng *et al*., 2010. *Grey System Theory and Application* (*5th edition*). Beijing: Science Press, 63–96. (in Chinese)

Liu Yaxuan, Zhang Xiaolei, Lei Jun *et al.*, 2011. Spatial expansion and driving forces of oasis cities in Xinjiang, China. *Journal of Desert Research*, 31(4): 1015–1021. (in Chinese)

Li Xia, Ye Jiaan, 1999. Constrained cellular automata for modelling sustainable urban forms. *Acta Geographica Sinica*, 54(4): 159–166. (in Chinese)

Ma Xiaodong, Zhu Chuangeng, Ma Ronghua *et al.*, 2008. Urban spatial growth and its evolution in Suzhou, Jiangsu Province, China. *Acta Geographica Sinica*, 63(4): 405–416. (in Chinese)

Martin R, Sunley P, 2006. Path dependence and regional economic evolution. *Journal of Economic Geography*, (6): 395–473. doi: 10.1093/jeg/lbl012

Miquel-Àngel Garcia-López, Ivan Muñiz, 2011. Urban spatial structure, agglomeration economies,and economic growth in Barcelona: An intra-metropolitan perspective. *Papers in Regional Science*, 91(4): 1–20. doi: 10.1111/j.1435-5957.2011.00409.x

Qiu Bingwen, Chen Chongcheng, 2008. Land use change simulation model based on MCDM and CA and its application. *Acta Geographica Sinica*, 63(2): 165–174. (in Chinese)

Sato Yasuhiro, Yamamoto Kazuhiro, 2005. Population concentration, urbanization, and demographic transition. *Journal of Urban Economics*, 58: 45–61. doi: 10.1016/j.jue.2005.01.004

Shi Longyu, Shao Guofan, Cui Shenghui *et al.*, 2009. Urban three-dimensional expansion and its driving forces: A case study of Shanghai, China. *Chinese Geographical Science*, 19(4): 291–298. doi: 10.1007/s11769-009-0291-x

Shi Peiji, Wang Zujing, Li Wei, 2012. Urban spatial expansion process and pattern in Shiyang River Basin. *Scientia Geographica Sinica*, 32(7): 840–845. (in Chinese)

Tan Yongzhong, Wu Cifang, Ye Zhixuan *et al.*, 2003. The indicator system and method to assess the sustainability of urban land use. *China Soft Science Magazine*, 3: 139–143. (in Chinese)

Wang Houjun, Li Xiaoyu, Zhang Zulu *et al.*, 2008. Analysis on urban spatial expansion process in Shenyang city in 1979–2006. *Chinese Journal of Applied Ecology*, 19(12): 2673–2679. (in Chinese)

Wang Shijun, Wang Ruoju, Wang Yongchao *et al.*, 2012. Analyzing Daqing's urban spatial form evolution: Basing on the technology of RS and GIS. *Economic Geography*, 32(6): 67–73. (in Chinese)

Weber C, Puissant A, 2003. Urbanization pressure and modeling of urban growth: Example of the tunis metropolitan area. *Remote Sensing of Environment*, 28(3): 341–352. doi: 10.1016/S0034-4257(03)00077-4

Wu Zhengzheng, Song Jinping, Wang Xiaoxia, 2008. On urbanization process and spatial expansion in the urban fringe of Beijing: A case study of Daxing District. *Geographical Research*, 27(2): 285–293. (in Chinese)

Xu Hui, Liu Jun, 2012. Grey relational analysis of innovation capability measurement of regional technology in Guangdong Province. *Scientia Geographica Sinica*, 32(9): 1075–1080. (in Chinese)

Yang Qingsheng, Li Xia, 2007. Integration of multi-agent systems with cellular automata for simulating urban land expansion. *Scientia Geographica Sinica*, 27(4): 542–548. (in Chinese)

Zhang Jinqian, Deng Nanrong, Wei Suqiong *et al.*, 2012. Comparative study of urban spatial expansion between regions with different economic development phases: A case study of Fuzhou and Taipei. *Journal of Natural Resources*, 27(2): 177–186. (in Chinese)

Zhang Xinhuan, Yang Degang, Chen Xi *et al.*, 2005. Study on the process and mechanism for urban land expansion in Urumqi in 50 years. *Arid Land Geography*, 28(2): 263–269. (in Chinese)

Zhang Yufang, Yang Degang, Zhang Xiaolei, 2006. Spatial-temporal changes of urban spatial morphology at the northern slope of the Tianshan Mountains. *Progress in Geography*, 25(6): 138–147. (in Chinese)

Zhao Jingzhu, Song Yu, Shi Longyu *et al.*, 2011. Study on the compactness assessment model of urban spatial form. *Acta Ecologica Sinica*, 31(21): 6338–6343. (in Chinese)

Zheng Wei, Liang Jinshe, Zhang Hua, 2009. Comprehensive analysis of urban compactness of provincial capital cities in China. *China Land Science*, 23(4): 11–17. (in Chinese)

Zhu Haoran, Feng Jian, 2010. Urban spatial expansion in less developed region of China: A case study of Nanchong. *Geographical Research*, 29(1): 43–56. (in Chinese)