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Extraction of Basic Trends of Urban Expansion in China over Past 40 Years from Satellite Images

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Abstract: If urban sprawl is to be avoided in China in the next ten years, it is not only crucial to understand the overall history, current status, and future trends of urban expansion there, but also these differences, and this is presently lacking. In this study, remotely sensed images with approximately 30 m spatial resolution were used to quantitatively assess the spatial and temporal patterns of urban expansion of 60 Chinese cities (1973–2013). Urban-expansion-process curves of the cities studied were drawn using annual expansion area as an indicator. Curve similarity analysis generated four basic process modes of urban expansion in China. These included cities that: 1) peaked around 2004 and then decelerated; 2) peaked around 2010 and then decelerated; 3) showed sustained acceleration, and 4) showed continued deceleration. Four basic process modes represented cities under different levels of development stage. Geographic location was found to be the most related characteristic to urban expansion process. Regional development policies at the national level in each region also showed highly temporal consistency with fluctuation characteristics of urban expansion process. Urban characteristic such as population size and administrative level were not found to be significantly related to urban expansion-process modes. Understanding the basic process-mode categories well is extremely important for future regional-balance planning and development of macroeconomic policies.

Keywords: urban expansion; urbanization; expansion-process mode; long term; urban development stage; curve similarity; urban characteristic

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1 Introduction

Technological, demographic, political, and economic changes during the past century have had substantial impacts on the landscape, and this complex set of factors will continue to drive land-use and land-cover changes in the decades to come. Human modification of the environment is among the most visible, irreversible and rapid of these transformations (Schneider and Woodcock, 2008). On the continuum of anthropogenic activities, urbanization is the most drastic, human-dominated, irreversible form of land use (Seto *et al.*, 2011). Urbanization is a shift of population from rural to urban areas, and it predominantly results in the physical growth of urban areas. Growth of urban areas results in changes in land cover, hydrological systems, biogeochemistry, climate, and biodiversity (Grimm *et al.*, 2008).

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In China, land use and land cover patterns have undergone a fundamental change since 1978 owing to accelerated economic development under economic reform policies (Weng, 2001). In the last four decades, the expansion rate of urban land has been higher than the urban population growth rate in China, suggesting that urban expansion is becoming more of a problem than population increase. Urban growth in this densely populated and rapidly developing country has been at unprecedented rates, which has adversely affected its ecosystem functions and food security at local and global scales (Bolund and Hunhammar, 1999; Wu *et al.*, 2015). Moreover, urban expansion is associated with other problems such as air pollution, traffic jams, inadequate water resources, urban unemployment, inadequate public services, spread of diseases, and challenges in terms of urban planning and management (Batty, 2008; Bloom *et al*., 2008; Wang *et al*., 2012). According to the government′s latest program on urbanization, sprawling cities are among the problems China plans to avoid in the next ten years (The State Council, 2014).

Remote sensing data have played a substantive role in monitoring changes in urban areas (Howarth and Boasson, 1983; Green *et al*., 1994; Herold *et al*., 2003). A large number of studies related to assessment of urban land expansion in China′s cities have been published since the 1990s. The most recently used data source is moderate-spatial-resolution Landsat images, because these continuously record the Earth′s surface and are free to users. The majority of work using these moderate spatial resolution images has been dedicated to analyzing change in urban morphology, amount of urban expansion, of one city (Chen *et al*., 2005; Li *et al.*, 2005; Jiang *et al.*, 2007; Zhang *et al*., 2007; Guneralp and Seto, 2008; Han *et al.*, 2009; Luo and Wei, 2009; Qu *et al.*, 2014) or to studying mega agglomerations (Ouyang, 2005; Tian *et al.*, 2011; Zheng *et al.*, 2012; Liu *et al.*, 2014; Wu *et al.*, 2015). These works monitored the development process of one city or agglomeration well, but comparison of differences in urban expansion among cities is lacking, but exactly this kind of comparison of urban expansion in different regions is critical for a vast country like China. Liao (2013) tried to reveal differences in urban expansion among the eastern, central, and western parts of China based on a single city from each region. Which city should be representative of a region is controversial. Two more comprehensive views on urban expansion came from Wang *et al.* (2012) and Schneider *et al.* (2014). The former group documented growth in 147 of China′s largest cities; however, their study was based on data from only three periods (the 1990s, the 2000s, and 2010); thus their results lacked analysis of the urban-expansion-process. Schneider *et al* (2014). compared the trends in Chinese cities on nine Landsat footprints for seven periods. This work included a uniform and even sampling of coastal and western cities; however, central China, which acts as a link between the eastern and western parts of the country and which has been promoted by the central government since 2004, was not included in their analysis. Comparisons were performed among cities, but the monitoring period was not long enough, making necessary further work on the trends of urban expansion (termed the urban-expansion-process in this study) in China. Overall, compared with the often well-documented urban population trends across China, there is no enough data on how urban land has changed over the past decades on a national scale. Further, there is a lack of understanding in terms of the history of urban expansion across China, as well as the determine factors responsible for the expansion trends.

There were two goals of our study. First was to give a generalized account of the basic urban-expansion-process modes in China from 1973 to 2013. In this study, remotely sensed data were used to develop a quantitative assessment of the spatial and temporal patterns of growth in a sample of 60 Chinese cities. The second goal was to study these basic process modes in relation to some selected urban characteristics (e.g., urban geographical location, urban population, and city administrative levels) in order to identify the major characteristics affecting these basic process modes. Understanding the existing urban-expansion-process modes will become increasingly important for making overall urban spatial layout effective in Chinese New Urbanization Planning of the next five years.

2 Materials and Methods

2.1 Selection of study site

Three important characteristics were used to select the cities studied in this work: 1) region in which the city is located; 2) administrative level; and 3) city size. We first selected all the cities from the primary administrative regions, including four centrally administered municipalities, 28 capitals of provinces and autonomous regions, and two cities from the special administrative regions. Next, we selected 26 other cities from the secondary administrative regions, which represented smaller cities but of greater number. The 60 cities selected for our study were distributed over an expansive region of China (Fig. 1). The population sizes of these cities in 2012 range from 5.70×10^5 to 2.38×10^7 (MOHURD, 2013). We made every effort to include a representative mix of Chinese cities in our study sample.

2.2 Data and processing

Remote sensing images most with a spatial resolution of approximately 30 m were selected as data source for monitoring urban expansion. Although remote sensing data with higher resolution may better meet the requirements of investigation, the time and workload required to process the data and extract urban expansion information would be too great (Zhang Z X *et al.*, 2014). In addition, for early years (from the 1970s to 2000), remote sensing data with higher resolution were always lacking. We collected Landsat Multi Spectral Scanner (MSS) images as the base data for the period from 1973 to 1984. From 1984 to 2011, images obtained through the Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) were employed as the main sources of data. China-Brazil Earth Resources Satellite (CBERS) Charge-coupled Device (CCD) and Huanjing-1 (HJ-1) CCD data were also used to fill in gaps where good quality TM data were not available. Especially in 2008, CBERS CCD data were used as the main data source. In 2011, Landsat 5 suspended its imaging activities; therefore, we obtained Chinese HJ-1 CCD images as the data source for the years of 2011 and 2012. Finally, for 2013, the images collected by a sensor (Operational Land Imager, OLI) of the Landsat Data Continuity Mission (LDCM), were employed as the main source data (Fig. 2). Except for Landsat MSS images used in early period, which had a spatial resolution of 60 m, all the other images have a spatial resolution of approximately 30 m. Specifically, spatial resolution of Landsat TM/ETM+, LDCM OLI, and HJ-1 CCD data are all 30 m. CBERS CCD images

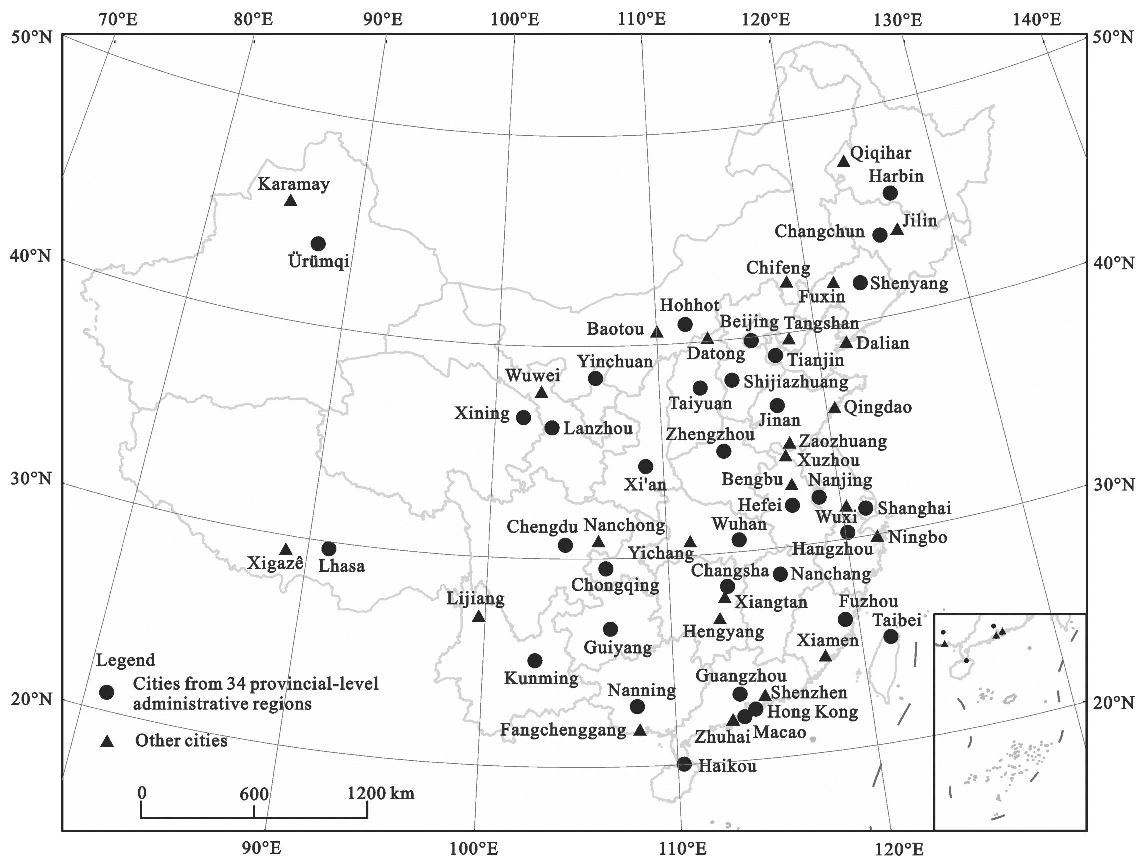

Fig. 1 Spatial distribution of 34 cities from provincial-level administrative regions and 26 other cities assessed in this study

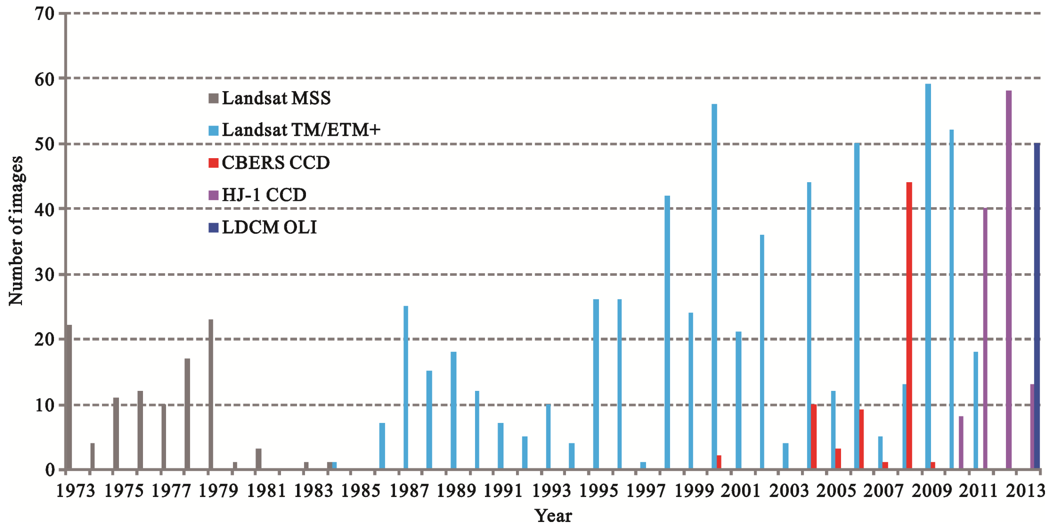

Fig. 2 Visualization of source and number of satellite images used to interpret urban expansion in 60 selected cities from 1973 to 2013. Satellite images used in this study included Landsat Multi Spectral Scanner (MSS), Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+), China-Brazil Earth Resources Satellite (CBERS) Charge-coupled Device (CCD), Huanjing-1 (HJ-1) CCD, and Landsat Data Continuity Mission (LDCM) Operational Land Imager (OLI) images

have a spatial resolution of 19.5 m. These matched well with each other.

For appropriately mapping urban expansion, a series of comparable images of cities are required. To ensure the position of objects located in remote sensing images exactly the same in different years, manual geometric corrections were performed using topographic maps. The accuracy of the geometric corrections, in terms of relative error in position for the same point, did not exceed two pixels.

2.3 Urban land definition

The focus of our mapping was the ′core built-up areas′ where buildings were essentially contiguous, and where municipal utilities and public facilities were available (MOHURD, 1999). The core built-up areas, by this definition, included all artificially constructed elements such as roads, buildings, and parks with vegetation and water. For ′urban-rural transitional areas′, we considered images of built-up areas with a shorter side greater than four pixels as urban areas, excluding those that were only connected by roads (Wang *et al.*, 2012).

2.4 Monitoring of urban expansion process

Although automatic methods for mapping urban areas have existed for a long time (Lorette *et al.*, 2000; Rajput *et al.*, 2014), they are difficult to apply in large urban areas because of the massive amount of adjustments required for the parameters and their low accuracy (Herold *et al.*, 2008). Although human interpretation is time-consuming, it is considered more precise than the automatic method as it can accurately extract dynamic changes that are the most important features in terms of urban expansion. Visual interpretation based on professional knowledge, was employed to determine the urban boundaries (Fig. 3) according to the same set of interpretation criteria introduced in detail by Zhang Z X *et al*. (2014).

2.5 Classification of basic process modes

2.5.1 Expansion process indicator

′Expansion area per year′ was selected to indicate the urban expansion process. Although most of the monitor time intervals were already one year, there were also some missing years for each city. Taking Beijing as an example (Fig. 3b), urban expansion was monitored from 1996 to 1998, but 1997 was missing; urban expansion was monitored from 1992 to 1996, but images for 1993, 1994, and 1995 were missing. Moreover, the years missing were different for each city. In order to make all the cities in the study coincide entirely in time, the area of expansion occurring within two years or more was equally allocated among the years, in order to reproduce usable values for years with no expansion data, according to Equation (1).

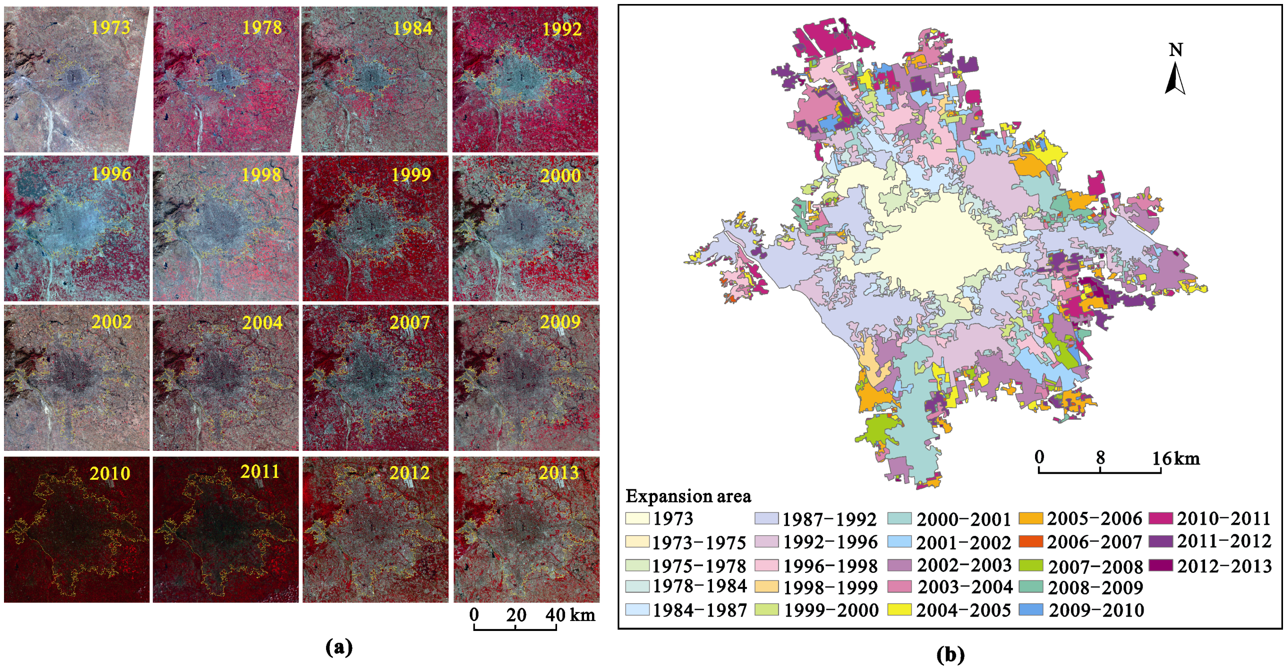

Fig. 3 Urban-expansion-process of Beijing: a sample from 60 cities, showing by satellite images (a) from 1973 to 2013, and complete expansion process (b) from 1973 to 2013

$$EA_{y_{n-1} \to y_n} = \frac{EA_{y_a \to y_b}}{y_b - y_a} \quad (1)$$

where y_a and y_b are the closest monitoring years of a and b, and $y_b - y_a > 1$. The year with null expansion data of one city is y_n, and $y_a < y_n < y_b$, $y_a \le y_{n-1} < y_b$. $EA_{y_a \to y_b}$ is the expansion area from y_a to y_b, whereas $EA_{y_{n-1} \to y_n}$ is the expansion area from y_{n-1} to y_n that lacks urban expansion data. Although the equal allocation method masked the detailed differences in expansion between the two closest monitoring years, the overall expansion area between the two closest monitoring years was exactly based on extracted information.

After allocation, a year-by-year data series of urban expansion areas was built for each city. When a process curve of urban expansion for each city was drawn, we found that some cities showed similar urban expansion processes, but others were quite different. Our aim was to find some basic process modes. We assumed that later studies would need to classify and to compare different process modes, including different numbers of cities. For this reason, we averaged the sum of urban areas of a group of cities in a process mode, by the total number of cities in the same process mode, to get an average expansion area of cities for each year.

2.5.2 Classification of process modes based on curve similarity

The principle used to determine the basic process modes was similarity among the process curves of the 60 cities. Curve similarity is based on the expansion trends of each city, as opposed to the net area expansion in terms of size, because the latter varied significantly between larger and smaller cities. In order to overcome the effects of the original urban size on the expansion area, we normalized the expansion area of each city in different years using the min-max normalization method (Equation (2)).

$$X_i' = (X_i - X_{\min}) / (X_{\max} - X_{\min}) \quad (2)$$

where X_i' is the corresponding normalization value of X_i; X_i is the urban expansion area in year i; and $X_{\min}$ and $X_{\max}$ are the maximum and minimum annual expansion areas of one city from 1973 to 2013. The values of the normalized annual expansion areas ranged from 0 to 1.

There are two commonly used methods for measuring curve similarity (Fasulo, 2001; Yin, 2010): similarity coefficient and distance. Similarity coefficient focuses more on describing the degree of similarity of waveform signals. It is commonly represented by the cosine of the angle between two curves, or the cosine of the angle between the standard deviation of the curves (i.e., correlation coefficient). The distance is a description of the difference in size of the signal. It is the indicator for the varieties of clustering algorithms.

The similarity coefficient was selected as the indicator to determine the basic process modes of urban expansion because it better describes the degree of similarity of a waveform, which is more consistent with the principles used to find the basic process modes of this paper. Pearson correlation coefficient (Equation (2)) was employed although not all the urban expansion areas fully complied with the laws of normal distribution during the study period. This was done because the Pearson correlation coefficient was found to reflect significant annual expansion better (a critical requisite in the analysis of urban expansion) than did the Spearman correlation or Kendall′s rank correlation coefficients.

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \overline{x})^2 \sum_{i=1}^{n}(y_i - \overline{y})^2}} \tag{3}$$

where r_{xy} is Pearson correlation coefficient, $\overline{x}$ and $\overline{y}$ are the means of the variables x and y respectively. x_i and y_i are the ith observation values of variables x and y.

The correlation coefficient between any two cities was calculated based on the normalized annual expansion area of 60 cities from 1973 to 2013. A 60 × 60 correlation coefficient matrix was obtained and it reflects detailed similarity degree between any two cities. For each city, one most similar city was selected by selecting the maximum correlation coefficient (r_{max}) and 60 pairs of city groups were thereby formed (Table 1). This was followed by the merger of the more-related pairs of cities into one group. Grouping was according to the following rules: if A′s most similar city is B, and B′s most similar city is C; A, B, and C will be put to be one group. Further, if C′s most similar city is A or B, this grouping process is finished and we begin a new grouping process from D. If C′s most similar city is D, D will be put in the same group with A, B, and C; and D′s most similar city will be judged. Using this method, 60 pairs of cities were grouped into 13 independent groups of similar cities.

Table 1 Most similar city for each sample city judged by maximum of correlation coefficient

City	r_{max} value	r_{max} city	City	r_{max} value	r_{max} city	City	r_{max} value	r_{max} city
Haikou	0.66	Guangzhou	Tianjin	0.87	Changchun	Chengdu	0.73	Changsha
Zhuhai	0.66	Guangzhou	Fangchenggang	0.93	Changchun	Lanzhou	0.56	Chengdu
Guangzhou	0.67	Jinan	Nanning	0.64	Fangchenggang	Xiangtan	0.56	Chengdu
Chongqing	0.82	Nanjing	Changchun	0.93	Fangchenggang	Nanchong	0.79	Nanchang
Nanjing	0.82	Qingdao	Datong	0.83	Changchun	Wuhan	0.84	Nanchang
Wuxi	0.83	Qingdao	Baotou	0.76	Dalian	Shenyang	0.72	Wuhan
Jinan	0.69	Wuxi	Guiyang	0.88	Dalian	Changsha	0.82	Wuhan
Qingdao	0.83	Wuxi	Dalian	0.88	Guiyang	Nanchang	0.84	Wuhan
Xuzhou	0.69	Hangzhou	Taiyuan	0.63	Shijiazhuang	Xigazê	0.79	Chifeng
Xiamen	0.84	Hangzhou	Macao	0.83	Kunming	Lijiang	0.91	Chifeng
Hangzhou	0.84	Xiamen	Kunming	0.83	Macao	Chifeng	0.91	Lijiang
Tangshan	0.68	Xuzhou	Shijiazhuang	0.77	Kunming	Qiqihar	0.75	Xigazê
Zhengzhou	0.85	Ningbo	Yinchuan	0.81	Harbin	Ürümqi	0.86	Chifeng
Fuxin	0.68	Zhengzhou	Xi′an	0.83	Harbin	Yichang	0.89	Ürümqi
Beijing	0.72	Zhengzhou	Harbin	0.83	Xi′an	Xining	0.91	Bengbu
Shenzhen	0.74	Zhengzhou	Fuzhou	0.79	Hengyang	Shanghai	0.81	Hohhot
Ningbo	0.85	Zhengzhou	Lhasa	0.82	Hengyang	Hohhot	0.85	Xining
Hong Kong	0.38	Taibei	Hengyang	0.82	Lhasa	Jilin	0.85	Xining
Zaozhuang	0.64	Taibei	Wuwei	0.71	Karamay	Hefei	0.88	Xining
Taibei	0.64	Zaozhuang	Karamay	0.71	Wuwei	Bengbu	0.91	Xining

Notes: r_{max} value is maximum Pearson correlation coefficient for each city correlated to 59 other cities. r_{max} city is city showing maximum Pearson correlation coefficient with city that in ′City′ column. Cities in each box are in the same independent group. Thirteen different boxes show 13 independent groups

As mentioned above, curve similarity represented by the Pearson correlation coefficient is sensitive to the year in which significant expansion happens. For practical purposes, urban expansion over a short period is more important than the expansion in a given year. Therefore, it was necessary to merge the 13 groups in terms of periods. The cities were grouped as follows: cities that reached their expansion peak around 2004 (from 2003 to 2006) and then had a lower rate of expansion were termed Mode A. Cities that reached their expansion peak around 2010 (from 2009 to 2011) and then had a lower rate of expansion were termed Mode B. Cities that showed a trend of continuous acceleration of expansion were termed Mode C; and, cities that showed a trend of continued deceleration were termed Mode D. In this manner, four basic types of urban expansion mode were obtained (Fig. 4).

3 Results and Analyses

3.1 Four basic process modes for urban expansion in China

We found that there are four basic process modes for urban expansion in China (Table 2). One peaked around 2004 and then showed deceleration (Fig. 5a). The others peaked around 2010 and then exhibited deceleration (Fig. 5b), sustained acceleration (Fig. 5c), or continued deceleration (Fig. 5d).

3.1.1 Mode A: peaked around 2004 and then decelerated

The 17 cities in this mode underwent fast urban expansion earlier than most other cities in China. By 2004, however, the rate of urban expansion had stopped climbing because these early starters had already attained huge sizes. Urban expansion slowed down significantly from 2007 onward, and cities belonging to this group exhibited stable development. Cities with high expansion rates that peaked around 2004 and then showed decelerated growth, accounted for 28.33% of all the monitored cities. This mode included major municipalities like Beijing and Chongqing; eastern capital cities like Guangzhou, Nanjing and Jinan; and eastern coastal cities like Qingdao, Xiamen and Zhuhai, accounting for 11.76%, 23.53%, and 41.18%, respectively of the total number of cities in this mode. The remaining cities, which are exceptions to the popular trends, accounted for 23.53% of the total number of cities in this mode; including Zhengzhou, a provincial capital in central China; Haikou, a provincial capital on Hainan Island; and resource-based cities such as Fuxin, Tangshan, and Xuzhou in the northeastern and eastern China.

3.1.2 Mode B: peaked around 2010 and then decelerated

The 12 cities exhibiting Mode B also underwent early and fast urban expansion, but the average expansion area was less than for those in Mode A. The rate of urban expansion peaked around 2010 (seven years later than Mode A). From 2011 onward, urban expansion slowed significantly. Cities with high expansion rates that peaked around 2010 and then showed decelerated growth accounted for 20.00% of all the monitored cities. Most Mode B cities are inland provincial capital cities

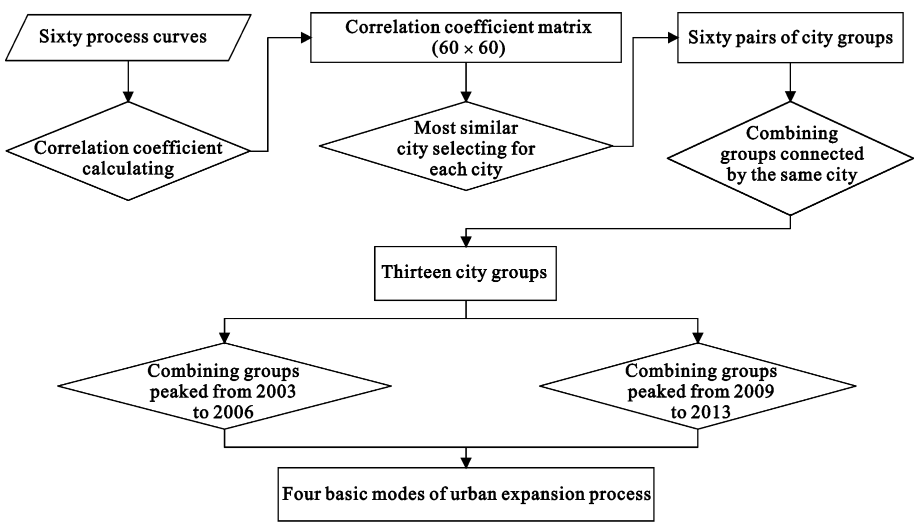

Fig. 4 Flowchart of classification of basic process modes for Chinese urban expansion

Table 2 Results from classification of basic types of urban-expansion-process

Basic process mode	Number of city	City list
Mode A: peaked around 2004 and then decelerated	17	Beijing, Chongqing, Nanjing, Hangzhou, Jinan, Zhengzhou, Guangzhou, Haikou, Tangshan, Fuxin, Wuxi, Xuzhou, Ningbo, Xiamen, Qingdao, Shenzhen, Zhuhai
Mode B: peaked around 2010 and then decelerated	12	Tianjin, Shijiazhuang, Taiyuan, Changchun, Guiyang, Kunming, Nanning, Macao, Datong, Baotou, Dalian, Fangchenggang
Mode C: sustained acceleration	28	Shanghai, Shenyang, Harbin, Nanchang, Hefei, Fuzhou, Wuhan, Changsha, Chengdu, Xi'an, Lanzhou, Xining, Hohhot, Lhasa, Yinchuan, Ürümqi, Chifeng, Jilin, Qiqihar, Bengbu, Yichang, Xiangtan, Hengyang, Nanchong, Lijiang, Xigazê, Wuwei, Karamay
Mode D: continued deceleration	3	Taibei, Hong Kong, Zaozhuang

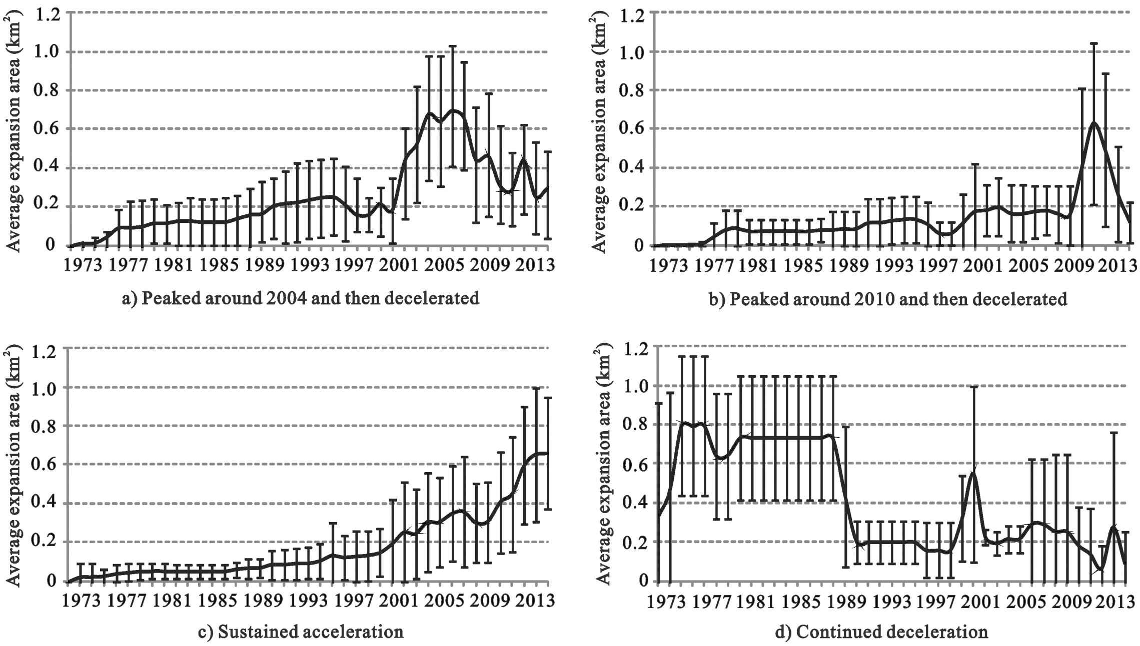

Fig. 5 Results and comparison of four basic process modes for Chinese urban expansion from 1973 to 2013

like Shijiazhuang, Taiyuan, and Guiyang; coastal cities in the northeast or in western regions like Dalian and Fangchenggang. These accounted for 83.33% of the total number of cities in this mode. These cities constituted the core cities subjected to urbanization in the different provinces or regions. The urban development in these cities started later and was slower than the cities in Mode A, but they play important roles within their respective provinces or regions. The remaining cities, two resource cities of Baotou and Datong were exceptions to the popular trends and accounted for 16.67% of the total number of cities in this mode.

3.1.3 Mode C: sustained acceleration

Mode C included the largest number of cities, and accounted for 46.67% of all the cities monitored in this study. Cities belonging to this mode underwent fast urban expansion from the year 2000 onward, later than the cities in Mode A and Mode B. Their urban expansion rates showed sustained growth until 2013 because most of these late beginners (in terms of expansion) were still small and had not reached their expansion peaks earlier. These included central or western provincial capitals like Wuhan, Nanchang, Changsha, Chengdu, Xi′an, Ürümqi, and Lhasa; resource cities like Chifeng, Wuwei, and Hengyang; and small to medium-sized cities, like Nanchong, Bengbu, Yichang, and Lijiang. Shanghai and Fuzhou are exceptions to the popular trends in this mode. Shanghai, as a representative city at the national level and a pioneer in massive urbanization, started early in the 1980s, and showed sustained, rapid development until 2013. Fuzhou, as the core city on the western side of the economic area on the Taiwan Strait also showed sustained growth.

3.1.4 Mode D: continued deceleration

Mode D included the smallest number of cities, and accounted for 5.00% of all the cities monitored in this study. Hong Kong and Taibei in China belong to continued deceleration mode (Mode D). In these cities, the urban expansion rate showed continued deceleration and the total urban area eventually stabilized because they had experienced rapid urbanization in the 1970s and 1980s. After the year 2000, epitaxial expansion occurred rarely; and, Hong Kong and Taibei entered the stable development stage. Some of the inland cities such as Zaozhuang also belong to this mode, but for completely different reasons. As a city with rich non-renewable natural resources, Zaozhuang developed quickly during the early years. However, development eventually slowed owing to exhaustion of its resources.

3.2 Relationship between process modes and urban basic characteristics

The huge differences between the four urban-expansion-process modes confirm that urban development is unbalanced in China. Factors that affect the urban development processes are complex. Such factors include geographical location, population growth, economic conditions, administrative level and policies (Lu and Liu, 2000). The factors are not independent in practice, and a variety of correlations exists among them. The reason for the unbalanced urban development processes are complex. In this study, we selected three basic characteristic (urban population size, urban administrative level, and geographical location) to analyze the relationship between process modes and urban characteristics over a period of nearly 40 years.

Sixty cities were classified into seven urban population size groups based on the criteria of adjustment of city size classification provided by the State Council Information Office (29 October, 2014) on its website (Table 3). Process modes of urban expansion in most urban population size groups showed no obvious consistency. For medium, large, and mega cities, in particular, the cities of any given size did not exhibit any certain expansion process mode (Fig. 6). In contrast, all the small cities belong to the sustained acceleration mode, while 75% of the megacity behemoths peaked around 2004 and then decelerated.

When considering urban administrative level, sixty cities were classified into four levels, municipalities, provincial capitals, special administrative regions, and other cities, besides the above levels. For administrative

Table 3 Criteria for adjustment of city size classification

City size	Type II small cities	Type I small cities	Medium-sized cities	Type II big cities
Population size (10^6)	< 0.2	0.2–0.5	0.5–1.0	1.0–3.0
City size	Type I big cities	Megacities	Megacity behemoths	
Population size (10^6)	3.0–5.0	5.0–10.0	> 10.0	

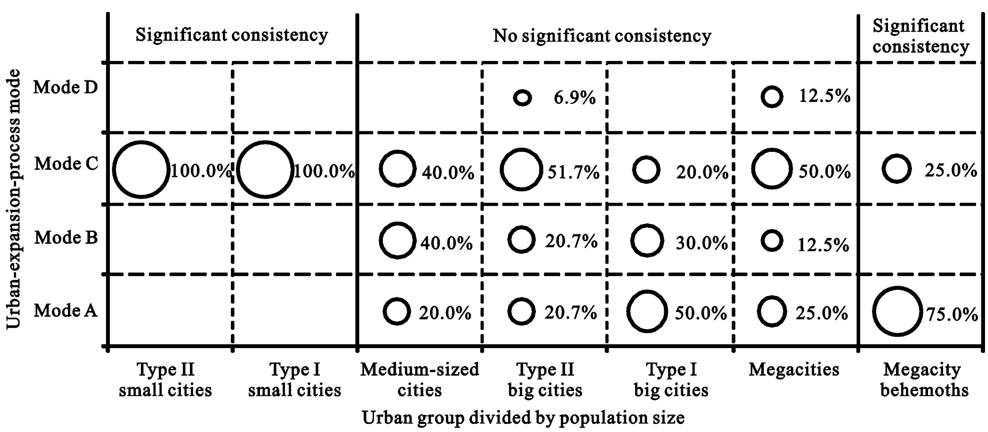

Fig. 6 Consistency checks on cities of certain population sizes and their inclusion in four basic urban-expansion-process modes. Mode A is peaked around 2004 and then decelerated mode; Mode B is peaked around 2010 and then decelerated mode; Mode C is sustained acceleration mode; Mode D is continued deceleration mode. Seven types based on the population size were named accordingly as small cities or big cities which are shown in Table 1. When over 75% of one type of city belonged to a single urban-expansion-process mode, we considered their relationship to be significant

levels also, there was no significant correlation with the expansion modes of the cities (Fig. 7). Fifty percent of the municipalities peaked around 2004 and then decelerated mode, and 53.6% of provincial capitals belonged to the sustained acceleration mode. Two special administrative regions belonged to two different modes respectively. The inclusion rate of each administrative level in the four basic urban-expansion-process modes was not more than 50%.

Geographic location was found to be the characteristic most related to urban-expansion-process. Cities that peaked around 2004 and then decelerated (Mode A) were mainly located in three large urban agglomerations: Beijing-Tianjin-Hebei, Changjiang (Yangtze) River Delta, and Zhujiang (Pearl) River Delta (Fig. 8). These three urban agglomerations can be regarded as the most important centers of Chinese trade, commerce, and

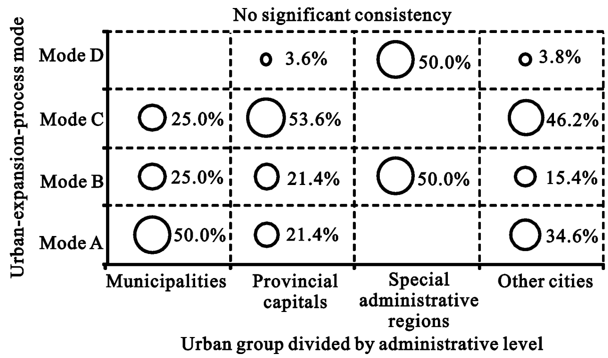

Fig. 7 Consistency checks on cities in certain administrative levels and their inclusion in four basic urban-expansion-process modes. Mode A is peaked around 2004 and then decelerated mode; Mode B is peaked around 2010 and then decelerated mode; Mode C is sustained acceleration mode; Mode D is continued deceleration mode. When over 75% of one type of city belonged to a single urban-expansion-process mode, we considered their relationship significant

Fig. 8 Spatial clusters of cities from different expansion process modes

manufacturing (Haas and Ban, 2014). In addition, core cities in four other urban agglomerations (i.e., Qingdao and Jinan in Shandong Peninsula agglomeration, Zhengzhou in Central China Plain agglomeration , Chongqing in Chengdu-Chongqing Urban Agglomeration, and Xiamen in the western side of the Taiwan Strait agglomeration) also peaked around 2004 and then decelerated; however, non-core cities were not included in this group. The cities in these agglomerations still play a very important role in Chinese economic development, but the area of urban land in these cities is relatively stable now. They have entered into a latent development phase of urbanization. The cities that peaked around 2010 and then decelerated (Mode B) were mainly provincial capitals in the eastern China, parts of central China, and southwest China. They form the transition zone between the east and west. The vast majority of cities from the western China, northeast China, and parts of central China (accounting for approximately half of the land in the country) were found to belong to the sustained acceleration mode (Mode C). This means that epitaxial expansion of urban development is continuing in the region to the left of the blue auxiliary line in Fig. 8. The major cities in Mode D were Hong Kong and Taibei of China on the southeast coast.

4 Discussion

The pace of urbanization has been staggering, and Chinese cities are at different stages of development. The four basic urban-land-expansion-process modes categorized in this paper are reflected by the urban landscape and are highly consistent with the urban-development processes classified using the degree of comprehensive socio-economic development of major urban agglomerations. According to the level of comprehensive socio-economic development (Zhang Xueliang, 2014), five of agglomerations, Beijing-Tianjin-Hebei urban agglomeration, Changjiang River Delta urban agglomeration, and Zhujiang River Delta urban agglomeration, Shandong Peninsula urban agglomeration and Central China Plains urban agglomeration, have been fully developed. Accordingly, the urban land expansion process belongs to process Mode A, which also indicates that core cities in these five urban agglomerations have experienced rapid urbanization and now entered a stable developmental stage.

In China, we determined that population size is not the most important factor affecting the developmental stages of cities. This suggests that the urbanization process in China is somewhat different from the general basic ′S′ urbanization curve. An ′S′ urbanization curve shows changes in the proportion or percentage of people living in cities over time (Mulligan, 2013). It is characterized by an S-shape that can be divided into three stages (Fig. 9). In this sense, urban expansion depends on the urban population size, as well as the total population size. Along with the constantly increasing urban population, the urban population expressed as a percentage of the total population also escalates. When urban population (expressed in percentage of total population) reaches the terminal stage, urban expansion should also stabilize. However, there are some exceptions in China. The most typical case involves the megacity behemoths with populations of more than 2.0×10^7 and urbanization levels greater than 89%, such as Shanghai, still considered on the sustained acceleration list. Such megacity behemoths are still sprawling around a central built-up area. This is bound to affect the comfort of urban lifestyle and lead to environmental problems. The relevant planning departments should focus on the decentralizing urbanization, and on ensuring the livability of cities.

According to our findings, geographical location, an important and stable impact factor for urban development from regional to global-scale (Lu and Liu, 2000; Mertes, 2015), has also proved to be most related to the urban-expansion-process modes in China. On the one hand, the urban geographical location determines the natural conditions (such as climate and terrain) and the

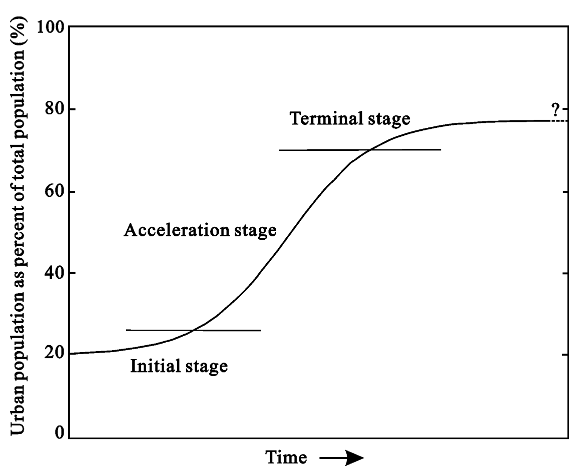

Fig. 9 Urbanization and its stages. Source: Chen (2014)

connections with other regions, which in turn affects the urban economic and urban development. On the other hand, in China, national development policies encouraged regional tendencies during different periods of development over a long time. This is another aspect of the underlying factors that result in urban geographical location playing the most important role in the stage of urban development. It can be said that geographical location affected urban expansion process not only by geographical location itself, but also by the economics and policies affected by geographical location indirectly. The three factors, geographical location, economic, and policies, often tended to be intertwined to play the role in forming the current process modes of urban expansion. China's urbanization has been determined mainly by economic development, while economic development has been achieved mainly due to regional development policies (Kwag, 2013). In the modern history of China, one famous national policy, the Reform and Opening-up Policy implemented from 1978, encouraged some of the coastal areas developed firstly. From the beginning of the program to the year 1999, China pushed development of the eastern provinces or cities along the coasts. These regional policies contributed significantly to the expansion of the urban land in Mode A cities during the early years before 2000. In contrast, many cities in the western or some in the central China in Mode B and Mode C started urban expanding later than that in Mode A. Till to 2000, cities in Mode A had been developed better than the others. At this moment, China entranced World Trade Organization (WTO) in 2001, which facilitate its economic growing significantly (Hopewell, 2015). However, the effects of entrance to WTO on urban development were also varied from regions. The cities with well development base and owning better investment environment (Mode A cities) were facilitated immediately by entrance to WTO. After entrance to WTO in 2001, Mode A cities reached their expansion peak between 2003 and 2006 successively and then maintained stable development trend. Development of most of the cities in Mode B and Mode C reacted to the entrance to WTO less than Mode A cities. Facilitated by development of China's western region policy implemented from 2000 and rise of China's central region policy implemented from 2004, most cities in Mode B and Mode C began expanding fast. Among them, the cities closed to well-developed cities (in Mode A) in north and southwest China (Mode B) developed earlier than that in central China and west China (Mode C), and they reached their expansion peaked between 2009 and 2011 successively. Most of the central cities, western cities, and northeast cities in Mode C were facilitated by continuing national regional policies, such as the development of China's western region policy, the rise of China's central region policy mentioned above, as well as the revitalization of China's northeastern region policy which was initiated in 2003 and further implemented in 2009, and they expanded later and slowly because their development bases were relatively lower. However, the development of some northeastern cities, such as Fuxin, was slow not only in the early years, but also in the recent past. This condition indicates that national policies promote regional urban development only to a certain degree. Meanwhile, the development of the policy also needs to fit with the objective trend in development of each city.

Previous national development strategies in urban development were generally based on four basic geographic units, most of which were involved in the large area development policies. The urban expansion modes promoted in our results are independent of basic geographic units, and give more precise regional differences in patterns of urban expansion over a long period. These are important for the specific implementation and development of macroeconomic policies as they shift in focus from large-area development to small-to-medium-area development.

It is also important to monitor further the process of change in small cities and towns, owing to their large number and thus substantial cumulative contribution, even though they are individually small-scale cities or rural settlements. Small cities or towns are also one of the key battlegrounds for recent urbanization across China. Future studies should consider the process of change in small cities and towns, along with the big cities.

5 Conclusions

The goals of this research were to generalize the basic urban-expansion-process modes in China and to reveal the major urban characteristics related to it. The study was based on a quantitative assessment of the spatial and temporal patterns of growth exhibited by a sample of 60 cities, using remote sensing data spanning 1973–

2013.

We found that there are four basic process modes for urban expansion in China: Mode A cities peaked around 2004 and then decelerated, Mode B cities peaked around 2010 and then decelerated, Mode C cities sustained acceleration, and Mode D cities continued deceleration. These four modes accounted for 28.33%, 20.00%, 46.67%, and 5.00% of the 60 monitored cities, respectively. Considering the number of cities, sustained acceleration (Mode C) is the major mode of Chinese urban land expansion. We also found that geographical location is the urban characteristic most related to the urban-expansion-process. Cities belonging to Cities of Mode A are mainly found in the three largest agglomerations (Beijing-Tianjin-Hebei, Changjiang River Delta, and Zhujiang River Delta) or core cities from Shandong Peninsula urban agglomeration, Central China Plain urban agglomeration, Chengdu-Chongqing urban agglomeration, and the west side of the Taiwan Straits urban agglomeration. Cities of Mode B are distributed in a transition zone from east to west. The vast majority of cities in the western, northeastern, and parts of central China belong to Mode C. Major cities in Mode D include Hong Kong and Taibei on the southeast coast. However, neither urban population size nor administrative level had significant correspondence with urban-expansion-process mode, which shows that the urbanization process in China is somewhat different from the general basic 'S' urbanization curve. The urban expansion mode, derived herein, is independent of basic geographic units; thereby giving more precise regional differences to describe urban expansion over a long period. Because the Chinese government plans to adopt New-type Urbanization in the next five years, it is critical to understand the history, current status, and future trends of Chinese urban expansion at the national scale. Therefore, the basic process-mode categories used to study Chinese urban expansion have been inferred to be extremely important for development of macroeconomic policies.

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