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Urban Expansion of China from the 1970s to 2020 Based on Remote Sensing Technology

LIU Fang, ZHANG Zengxiang, ZHAO Xiaoli, LIU Bin, WANG Xiao, YI Ling, ZUO Lijun, XU Jinyong, HU Shunguang, SUN Feifei, WANG Yafei

(*Aerospace Information Research Institute*, *Chinese Academy of Sciences*, *Beijing* 100094, *China*)

Abstract: Based on Remote Sensing (RS) and Geographical Information System (GIS) technology, urban expansion of 75 cities in China from the 1970s to 2020 was reconstructed by visual-interpretation method, which described the growing process of urban lands and its influences on local land use structures synchronously. By employing annual expansion area per city and urban expansion density, spatial-temporal characteristics and macro patterns of urban expansion were analyzed from the aspects of regional-distributions, administrative-levels and population-sizes comprehensively. Results indicate that: 1) urban expansion in China was universal, distinct, persistent, periodic and fluctuating. In the past five decades, urban lands of 75 monitored cities in China expanded dramatically from 3606.26 km^2 to 30 521.13 km^2. 2) Though urban expansion presented significant differences from the aspects of regional distribution, administrative levels, and population sizes, it exhibited a deceleration trend in the 13th Five-Year Plan among all kinds of cities. 3) Cultivated lands were the first land resource for urban expansion, and 55.17% of newly-expanded urban lands appeared by encroaching this land use type. China's urban expansion has caused sustained pressure on cultivated land protection, especially in super megacities, and the contradiction between urban expansion and cultivated land protection will always exist. 4) The compactness of urban lands in China increased before 1987 and reduced in the next three decades, which was consistent with the implementation of major policies and the deployment of national strategies, and is expected to become compact with a stopping declining or even rebounding after the 13th Five-Year Plan.

Keywords: urban expansion; pattern; regional distribution; administrative level; population sizes; Remote Sensing (RS); China

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1 Introduction

Urban lands are the concentrated embodiment of human civilization, with high-density population and social-economic activities (Sarvestani et al., 2011; Liu et al., 2016; Liu et al., 2018; Yang et al., 2021). It is predicted that the proportion of global urban population will reach to 68% (United Nations, 2018) by 2050, which will further be stimulated worldwide urban expansion. As the largest developing country, urbanization in China proceeded with an amazing speed. In 1978, the urbanization rate of China was only 17.92%, and exceeded 60% in the end of 2019, and is expected to increase to 70% by 2030 (UNDP in China and Institute for Urban and Environmental Studies, CAS, 2013). Therefore, urban expansion in China is also obvious and has attracted worldwide attention (Sun and Zhao, 2018) because of its unexpected speed, massive scales, univer-

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Corresponding author: ZHANG Zengxiang. E-mail: zx_zhang@263.net; WANG Xiao. E-mail: wangxiao98@radi.ac.cn

sal phenomena, and the policy guidance. Rapid urban expansion is the reflection of social progress, and induced a series of socio-economic and environmental issues. Furthermore, due to faster rate of urban expansion than population growth (Seto et al., 2011; Haase et al., 2013), the decline of urban land densities has become a global trend and affected patterns of urban lands (Kroll and Haase, 2010; Xu et al., 2019a).

Urban expansion is the most direct manifestation of urbanization, and focuses on the key contents of land use changes. At present, it has become the one of the hot fields for researching urban development at home and abroad. Abundant studies about urban expansion have provide scientific references for optimizing the urban development guideline. They cover all scales from single city (He et al., 2006; Yu, 2017) to regional (Kuang, 2011; Ye, 2013), national (Liu, 2005a) and even global scales (Kuang et al., 2020), and their contents include extracting information of urban expansion (Liu et al., 2005b; Yu et al., 2007), analyzing spatial-temporal characteristics (Estoque and Murayama, 2015; Kantakumar, 2016), revealing driving forces (Zhu et al., 2001; Zhang and Su, 2016), evaluating effects of urban expansion on ecological environment (Rodríguez et al., 2015; Li et al., 2017), depicting patterns of urban lands (Jiao, 2015), *etc*. On the whole, urban expansion is full of complexities and heterogeneities (Xu et al., 2019b). When revealing urban expansion differences, previous studies always focused on regional disparities or comparing spatial-temporal differences of cities in a certain region or belonging to one kind of cities. Actually, urban expansion is high-related to many factors, such as natural conditions, population, economic levels, and political guidance, *etc*. However, relatively little attention has been paid to reveal urban expansion differences from multiple aspects systematically.

As one of spatial exhibitions of urban expansion, the pattern of urban lands is closely related to economic development, the efficiency of land use, and the ecological environment (Glaeser, 2004; Morris, 2013), *etc*. Nowadays, various methods and models are built up to depict it (Xu, 1997; Wilson, 2003; Xu, 2007; Jiao, 2015; Shi, 2019), and they have developed from the method improving stage to the extensively application stage, particularly in exploring the spatial-temporal characteristics of urban expansion patterns in typical cities or regions (Xu, 2019a). However, patterns of urban lands in China on the national scale have not yet been recognized comprehensively.

Intermsofthesescarcities,wemappedtheurbanexpansionand its influences on local land use by using visual-interpretation method, and retrieved urban expansion database of 75 cities in China during the 1970s–2020 with high-frequencies. Then, we quantify the basic characteristic of urban expansion and depict its differences from aspects of spatial distributions, administrative levels and population sizes on the basis of national policies and series of Five-Year Plans (Xu and Heikkila, 2020). Last but not the least, by employing the improved urban land density index, we reveal pattern dynamics of urban lands from three aspects mentioned above. By carrying out this study, execution effects of regional and national policies on urban development can be accessed in some extent, which is beneficial to making more sustainable urban planning and strategies. Additionally, comprehensively recognizing urban expansion process and dynamics of urban lands' pattern could also provide scientific data for the compilation of a reasonable land source guideline.

2 Materials and Methods

2.1 Study area

To meet the needs of national economic construction and environmental protection, Land Resources Team of Aerospace Information Research Institute, Chinese Academy of Sciences carried out urban expansion of China based on Remote Sensing (RS) and GIS technology for 40 yr. At present, 75 typical cities have been monitored, including 4 municipalities, 28 provincial capitals, 2 special administrative regions, and 41 prefecture-level cities and below (named 'other cities' thereafter, including 5 municipalities with Independent Planning Status, i.e., Dalian, Qingdao, Ningbo, Xiamen and Shenzhen) (Fig. 1). These 75 cities were chosen as sample cities in this study by fully considering their administrative levels, urban functions, urbanization levels, spatial distributions, social-economic levels, population sizes, and available multi-source remotely sensed imagery. By 2020, except Hong Kong, Macao and Taipei, total urban population in other 73 monitored cities were 2.187×10^8, accounting for 50.08% of that in China. In terms of geographical zoning, administrative classification standard and population size dividing criterion,

Fig. 1 Spatial distribution of 75 cities in China

these 75 cities distributed in eight regions (Gu et al., 2017), and were classified into four administrative levels (municipalities, special administrative regions, provincial capitals, other cities) and five population-size levels (super mega, mega, large, medium, and small cities) on the basis of urban population in 2019 (Fig. 1).

2.2 Data sources

More than 1700 scenes of multi-source remote sensing imageries with the spatial resolution ranging from 19.5 m to 80.0 m, were adopted to extract urban expansion information. These data consist of 151, 849, 557, 67 and 129 scenes of Landsat Multispectral Scanner (MSS), Thematic Mapper (TM) or Enhanced Thematic Mapper Plus (ETM+), Operational Land Imager (OLI), China-Brazil Earth Resources Satellite (CBERS) Charge-coupled Device (CCD), and Environmental Satellite (HJ–1) CCD imagery, respectively. Due to the limitation of remotely sensed imagery acquisition, the monitoring time of the 75 sample cities was not uniform in the 1970s. Urban expansion in the initial stage was very slowly. Therefore, different starting times for the monitoring in the 1970s have a few influences on the follow-up analysis. By using visual-interpretation method (Zhang et al., 2014), totally 1732 phases of urban lands actualities and 1657 phases of influences of urban expansion on local land use were completed (Table 1).

This monitoring has the advantage of high-frequency and long-term, and its contents include urban actualities in every monitored time nodes and influences of urban expansion on local land use in all monitored periods. Taking Beijing for example, Figs. 2a and 2b exhibit urban expansion process and its influences on cultivated lands of Beijing in the past five decades.

2.3 Methods

2.3.1 Annual expansion area per city

Annual expansion area per city (*AEAC*) was employed to describe the process of urban expansion in detail. This index has advantages in eliminating the influences

Table 1 Monitoring periods and frequencies of 75 monitored cities in China

Cities	Period	Frequency	Cities	Period	Frequency	Cities	Period	Frequency
Beijing	1973–2020	29	Harbin	1976–2020	20	Nanning	1973–2020	21
Shanghai	1975–2020	20	Qiqihar	1976–2020	22	Beihai	1973–2020	20
Tianjin	1978–2020	22	Nanjing	1979–2020	20	Fangchenggang	1973–2020	22
Chongqing	1978–2020	21	Wuxi	1973–2020	25	Haikou	1973–2020	19
Shijiazhuang	1979–2020	20	Xuzhou	1973–2020	27	Chengdu	1975–2020	21
Tangshan	1976–2020	22	Hangzhou	1976–2020	22	Nanchong	1977–2020	22
Qinhuangdao	1973–2020	33	Ningbo	1974–2020	22	Guiyang	1973–2020	25
Handan	1973–2020	28	Hefei	1973–2020	22	Kunming	1974–2020	19
Xingtai	1975–2020	26	Bengbu	1975–2020	23	Lijiang	1974–2020	18
Baoding	1973–2020	28	Fuzhou	1973–2020	20	Lhasa	1976–2020	20
Zhangjiakou	1975–2020	22	Xiamen	1973–2020	21	Shigatse	1973–2020	20
Chengde	1975–2020	22	Quanzhou	1973–2020	22	Xi'an	1973–2020	22
Cangzhou	1976–2020	29	Nanchang	1976–2020	20	Yan'an	1974–2020	27
Langfang	1976–2020	26	Jinan	1979–2020	20	Lanzhou	1978–2020	21
Hengshui	1975–2020	34	Qingdao	1973–2020	21	Wuwei	1973–2020	22
Taiyuan	1977–2020	20	Zaozhuang	1974–2020	23	Xining	1977–2020	22
Datong	1977–2020	22	Zhengzhou	1976–2020	23	Yinchuan	1978–2020	20
Hohhot	1976–2020	19	Wuhan	1978–2020	22	Zhongwei	1973–2020	27
Baotou	1977–2020	24	Yichang	1973–2020	23	Urumqi	1975–2020	16
Chifeng	1975–2020	21	Changsha	1973–2020	20	Karamay	1975–2020	19
Shenyang	1977–2020	24	Xiangtan	1973–2020	22	Kashgar	1972–2020	19
Dalian	1975–2020	21	Hengyang	1973–2020	21	Khorgos	1975–2020	18
Fuxin	1975–2020	23	Guangzhou	1977–2020	21	Taipei	1972–2020	17
Changchun	1976–2020	19	Shenzhen	1973–2020	23	Hong Kong	1973–2020	18
Jilin	1979–2020	20	Zhuhai	1973–2020	22	Macao	1973–2020	20

of city number, different time nodes of monitoring and the scale of urban lands on urban expansion process (Zhang et al., 2014), and is described as below:

$$AEAC = \frac{\sum_{i=1}^{N} \frac{UA_{i(t+n)} - UA_{i(t)}}{n}}{N}$$

where $AEAC$ indicates the annual expansion area per city. $UA_{i(t+n)}$ and $UA_{i(t)}$ are the urban areas of city i at time t+n and t. n represents the time interval; and N is the city number.

2.3.2 Urban land density

To describe urban dynamic patterns of China systematically and scientifically, urban land density (ULD) index (Jiao, 2015) was adopted and improved in this study. Three basic principles must be followed when constructing concentric rings covering urban lands. First, all concentric rings started from the city center. Second, for polycentric cities, multiple centers were considered when build up concentric rings. Third, considering the scale of urban lands from aspects of regional distributions, administrative levels, and population sizes, rings with 500 m equidistance should cover all urban lands of one city in different monitoring phases. ULD is defined as follows:

$$ULD = \frac{A_{\text{urban}}}{A_{\text{buildable}}} \times 100\%$$

where A_{urban} and $A_{\text{buildable}}$ are areas of urban lands and the total land areas excluding water bodies and sea areas in concentric rings. Furthermore, tidal flats and bottomlands belonging to water bodies are easily converted into urban lands (Zhang et al., 2014). Therefore, these two kinds of water bodies are considered when calculating buildable lands.

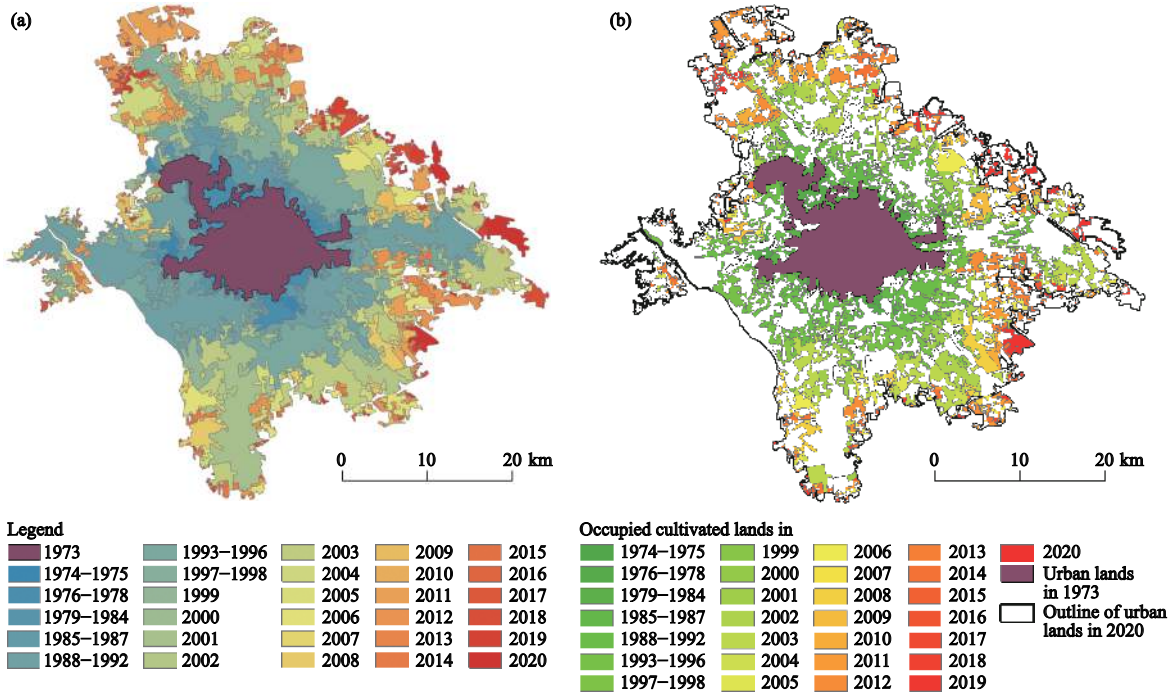

Fig. 2 Urban expansion process (a) and its influences on local cultivated lands (b) of Beijing during 1973–2020

According to empirical studies, the *ULD* always reduced from the city center to the urban fringe with an inverse 'S-shape'. In this study, this attenuation formula was adopted to calculate the corresponding parameter to describe the pattern of urban lands in China from the macro aspect.

$$f(r) = \frac{1-c}{1+e^{\alpha\left(\frac{2r}{d}-1\right)}} + c$$

where f indicates the *ULD*; r is the distance to the city center; c, d, and α are parameters which can be calculated by fitting f and r with the formula above. Among these three parameters, c and d are the background value of the *ULD* in the hinterland of a city, and the approximate boundary between the urban fringe and the urban hinterland, respectively. Parameter α can depict patterns of urban lands. The higher the parameter α is, the more compact pattern of urban lands in one city is.

3 Results

3.1 Spatial-temporal characteristics of urban expansion in China

In the past five decades, urban lands in China expanded dramatically and presented obvious temporal differences. Meanwhile, urban expansion differences were embodied directly from the aspects of regional distributions, administrative levels, and population sizes. By recognizing these differences fully and scientifically, we can not only assess the execution of national policies about urban development effectively to a certain extent but also draw up reasonable urban development plans after 2020.

3.1.1 Basic characteristics of urban expansion

Urban expansion in China is universal and distinct (Fig. 3). In the 1970s, urban lands in 75 monitored cities only amounted to 3606.26 km^2 with an average of less than 50 km^2 per city. The scales of urban lands were relatively small in the early stage of monitoring; specifically, the scales of urban lands in all monitored cities were less than 200 km^2. In the next 50 yr, Chinese cities developed vigorously, and the scales of urban lands increased significantly. By 2020, urban lands in 75 cities reached 30 521.13 km^2 with an average of 406.95 km^2 per city, increasing by 7.46 times of that in the 1970s; and urban lands in more than half of the monitored cities were larger than 200 km^2, exceeding the maximum scale of cities in the 1970s. Urban expansion in these 75 cities was distinctively different. As a typical city of the 'Reform and Opening-up Policy' and the fastest growing city in China, urban expansion in Shenzhen witnessed the process of China becoming rich and strong. Remote-sensing monitoring showed that

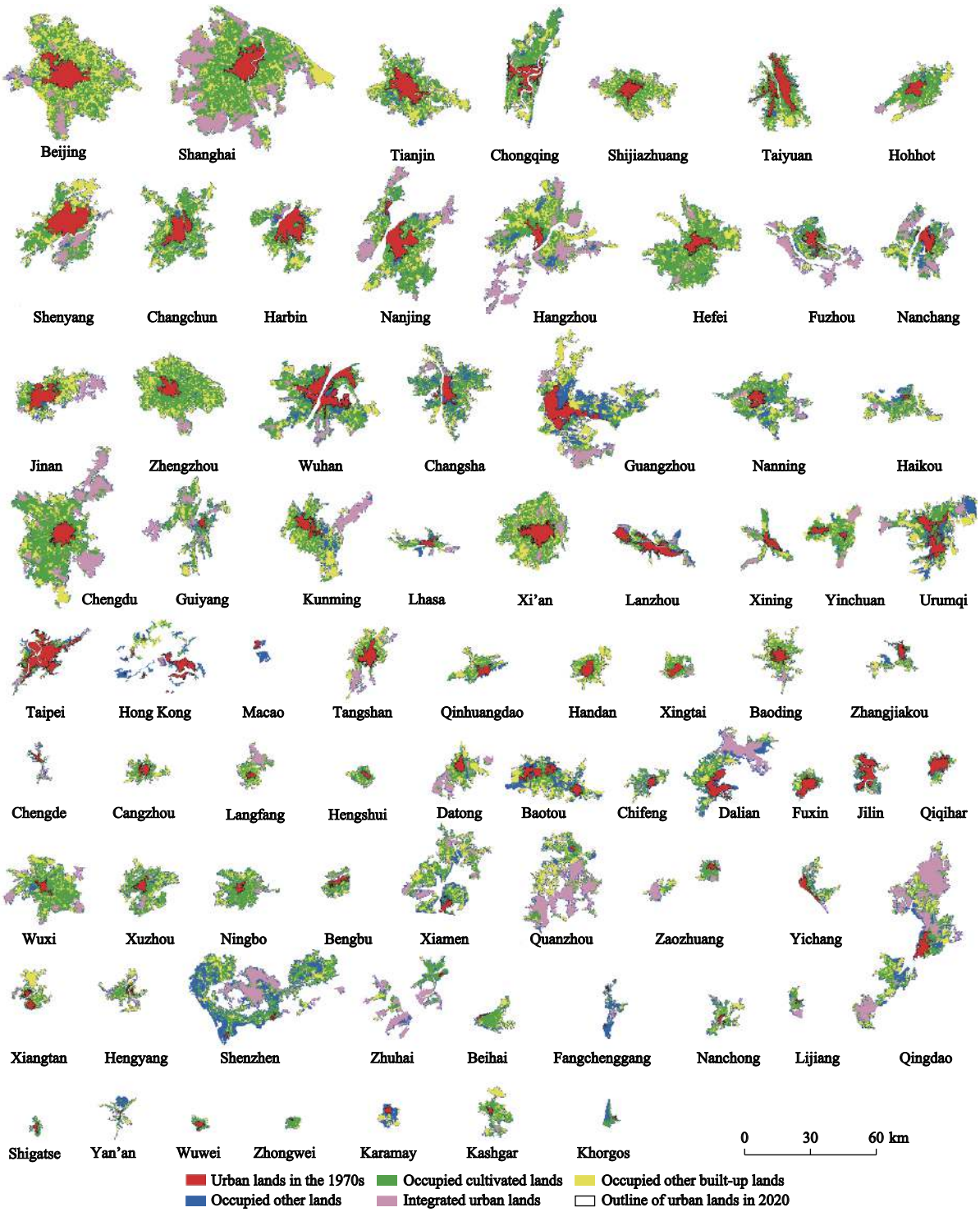

Fig. 3 Urban expansion of 75 monitored cities in China and its influences on local land use during the 1970s–2020

Shenzhen was the city with the most significant change among the 75 monitored cities. In the 1970s, it was only a small fishing-town with only 6.87 km^2 of urban lands, but its urban lands expanded to 1139.83 km^2 in 2020, which was 165.91 times of the initial monitoring period. Taipei expanded the most slightly because of historical reasons, with urban lands increasing by only 0.62 times of that in the initial period.

Since the 1970s, urban expansion in China was persistent, periodic, and fluctuating (Fig. 4). It presented an increase trend and underwent one slow and stable expansion stage before 1987, one accelerating expansion

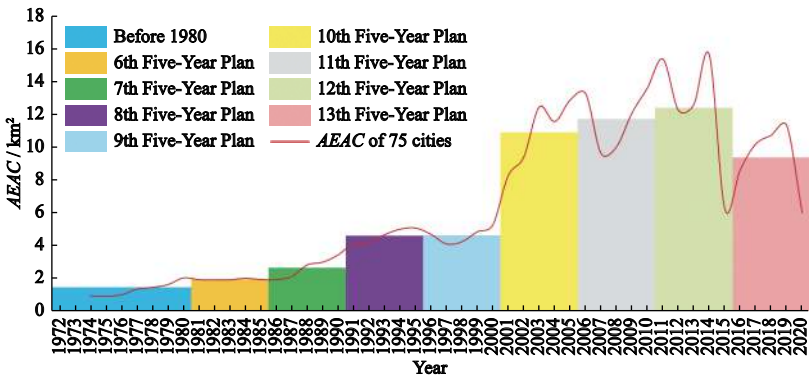

Fig. 4 Urban expansion speed of China during the 1970s–2020. *AEAC* is annual expansion area per city

stage during 1987–2000, and one high-speed fluctuating expansion stage after 2000, which was consistent with the implementation of major policies and the development of national strategies. In detail, urban expansion in China exhibited various characteristics during different Five-Year Plans for national economic and social development (named 'Five-Year Plan' thereafter). Before 1980, China was in the early stage of the 'Reform and Opening-up Policy', and its urban expansion was slow with an *AEAC* of only 1.44 km^2. In the next 40 years, China underwent eight Five-Year Plans (i.e., the 6th, 7th, 8th, 9th, 10th, 11th, 12th, and 13th Five-Year Plans in 1981–1985, 1986–1990, 1991–1995, 1996–2000, 2001–2005, 2006–2010, 2011–2015, and 2016–2020, respectively. Before the 13th Five-Year Plan, urban lands started to expand rapidly, but China's economic system recently transformed from the planned system to the market system, and the focus of urban expansion mostly took place in the eastern coastal areas. Therefore, the speed of its urban expansion was much slower than that after 2000. After 2000, China joined the World Trade Organization (WTO), integrated into the globalized market system rapidly, and successively implemented strategic plans for the development of the western region, the revitalization of the northeastern region, and the rise of the central region. China's urban expansion continued at a high speed and presented a fluctuating acceleration. Moreover, 74.42% of increased urban lands in the past five decades emerged after 2000. With the in-depth implementation of 'New-type Urbanization' and 'Urban-rural Integration Plan', urban expansion and its spatial layout optimization became an inevitable trend. Therefore, the speed of urban expansion in China slowed down after entering the 13th Five-Year Plan and is expected to reduce successively.

3.1.2 Differences of urban expansion

Since the implementation of the 'Reform and Opening-up Policy', Chinese cities developed rapidly. Due to the obvious differences of natural conditions and imbalanced social-economic development levels, urban expansion presented various characteristics among different regions. The urban expansion process is a direct reflection of the implementation of national strategies. By describing the urban expansion of different regions, we can also evaluate the effects of the executions of various regional development strategies to a certain extent. Overall, urban expansion in East China was the fastest with an average *AEAC* of 9.76 km^2, followed by South China (8.34 km^2), Central China (7.53 km^2), Southwest China (6.32 km^2), Northeast China (5.73 km^2), North China (5.34 km^2), Northwest China (3.51 km^2), and the Hongkong-Macao-Taipei region (named 'HMT' region thereafter) (1.98 km^2) (Fig. 5). The speeds of urban expansion in the first four regions were higher than the national average, and more slowly than the national level in the four other regions.

As the most dynamic region of Chinese economy and the first region opening-up to the outside world, East China has remarkable innate advantages in urban expansion, and its urban expansion was the most rapid and entered the high-speed stage the earliest. Since the 1970s, the urban lands of East China have expanded by 13.23 times, experiencing the low-speed and stable expansion stages before 1987, the rapid-expansion stage in 1987–2000, and the high-speed fluctuation stage after 2000. Since 2000, the regional development strategies of China have gradually shifted from giving priority to the development of the eastern coastal areas to the coordinated development of the whole country. In 2000–2005, the advantage of urban expansion in East

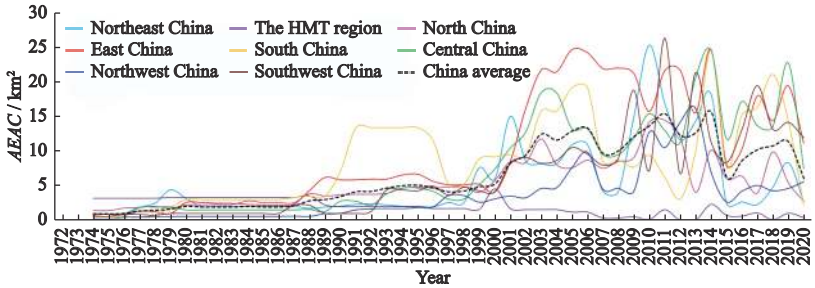

Fig. 5 Spatial differences of urban expansion in China, the 1970s–2020. HMT is Hong Kong-Macao-Taipei region

China was still evident. However, the urban expansion speed in this region fluctuated and declined in the following 15 yr and was even caught up with by other regions.

With the second fastest speed of urban expansion among eight regions, urban lands in South China expanded by 15.49 times in the past 50 yr. By establishing the Shenzhen Special Economic Zone, the open degree of South China was strengthened. Furthermore, the strategy of 'Developing the Eastern Coastal Areas First' greatly stimulated the rapid development of this region and resulted in its high-speed expansion that appeared as early as the late 1980s, and its subsequent expansion process was basically synchronized with that of East China. However, due to its small per capita land areas and limited space for expanding, and the efficient implementation of the new urbanization and the urban-rural integration, the gap of urban expansion in South China with the seven other regions narrowed down gradually.

Central China was deeply affected by the 'Rise of Central China' strategy. On December 26, 2016, 'To promote the rise of Central China in the 13th Five-Year Plan' was issued by the National Development and Reform Commission. The urban expansion process of this region was further stimulated by strengthening the status of provincial capitals, such as Changsha, and supporting the development of Wuhan and Zhengzhou as national central cities. Since the 1970s, urban lands in Central China have expanded by 6.52 times. Furthermore, the implementation of the strategy of 'Rise of Central China' also effectively reduced the imbalance of urban development between the east and central regions. Even after 2010, the speed of urban expansion in Central China began to significantly overtake that in North China, East China, and South China.

The implementation of the 'Western Development' strategy was the main driving force for the growth of urban lands in Southwest China. From the 1970s to 2020, urban lands in this region expanded by 11.25 times with its average speed higher than the national level. Before 2008, the speed of urban expansion in this region was lower than the national average, whereas fluctuated frequently and became higher than the national average in the following 10 yr. Therefore, the execution of the 'Western Development' strategy was effective and can reduce the imbalance of urban development between the east and the west to a certain degree.

Though Northeast China had a good economic basis in the 1970s, its urban expansion was not the most obvious on the whole. From the 1970s to 2020, urban lands in this region increased by 2033.92 km^2, 4.22 times of that in the early stage of monitoring; and experienced one continuous acceleration stage in the 1970s, a low-speed and steady expansion stage from the 1980s to the early and middle 1990s, a rapid acceleration stage in the late 1990s, an acceleration stage in the first decade of the 21st century, and a deceleration stage in the first decade of the 21st century. On September 29, 2003, the 'Northeast Revitalization Strategy' was officially initiated. However, urban development responding to the implementation of this strategy was not intuitive and significant. The expansion speed of urban lands in this region was lower than the national level for most of the time.

Benefiting from the implementation of 'developing the eastern coastal areas first' strategy, urban lands in North China increased by 5.72 times in the past five decades, and its urban expansion process was basically consistent with the national trend. Note that the 'Beijing-Tianjin-Hebei Coordinated Development' strategy was executed effectively. After 2010, urban expansion fluctuated significantly, and the focus of urban development transformed from the simple urban spatial expansion to the urban coordinated development.

With scarce precipitation, arid climate, sparse population, and an economic structure dominated by resource-

based industry and traditional agriculture, urban expansion in Northwest China has insufficient inherent geographical advantages. Therefore, in the early stage of monitoring, the scales of urban lands in this region were generally small, reaching only 259.13 km^2. Compared with other regions, the speed of urban expansion in this region was the second slowest, and the time of entering the rapid expansion stage was relatively late. Its speed of urban expansion was generally lower than the national average. Before 2005, the gap of its urban expansion speed with the national average increased continuously. Since then, the gap narrowed down and even surpassed the national average in 2013. This result was directly related to the in-depth implementation of the 'Western Development' strategy and the extensive construction of the New Silk Road. However, in the next seven years, the speed of urban expansion in this region presented a decreasing trend, which was correlated to the implementation of the 'New-type Urbanization' and 'Optimizing the Spatial Pattern of Land' strategies.

The urbanization levels of the HMT region were higher than those of the seven other regions in the 1970s because of historical reasons. However, resulting from geographical conditions, urban lands in this region lacked abundant space for expansion, and their scales were generally small. In the 1970s, only urban lands measuring 234.48 km^2 existed, and the increase of this value was not evident. By 2020, urban lands expanded to 526.48 km^2, which was 2.25 times of that in the initial monitoring period. Overall, the speed of urban expansion in the HMT region presented a decreasing trend, which was obviously different from other regions.

Apart from regional differences, urban expansion was also unbalanced from the aspects of administrative levels and population sizes. Unlike regional differences, urban expansion processes are highly co-related to urban administrative levels and population sizes. Though urbanization processes of Hong Kong and Macao proceeded faster than those of other 73 cities before the 1970s, space for their urban expansion was limited on the whole. Therefore, urban lands in these two cities expanded slowly in the past five decades, with an average *AEAC* of only 2.00 km^2. In the past five decades, further attention was paid to the internal construction and intensive land use in Hong Kong and Macao. Among the other 73 cities, obvious urban expansion with high speed and early acceleration stage always emerged in cities with high administrative levels (municipalities > provincial capitals > other cities) and huge population sizes. From the aspect of administrative level, urban lands in municipalities expanded the fastest with an average *AEAC* of 19.92 km^2 and entered the acceleration-expanding stage as early as the 1980s, followed by provincial capitals and other cities (Fig. 6a). In provincial capitals, their urban lands grew slower than those in municipalities, and their acceleration stage of urban expansion appeared almost five years later those in municipalities. Urban lands in other cities expanded the most slowly with an average *AEAC* of only 3.37 km^2 and entered the acceleration stage after 2000. Among the five population-sized cities, super megacities played a leading role in Chinese urban expansion, with evidently earlier acceleration stage than the four other types of cities, followed by megacities, large cities, medium cities, and small cities (Fig. 6b). According to urban expansion speed and expansion area per city, the ranks of five population-sized cities are super megacities, megacities, large cities, medium cities, and small cities in descending order. Before the Chinese economic transformation in the 1990s, urban lands in large, medium, and small cities expanded synchronously, with a relatively slow and stable expansion speed. In the next two decades, they all entered the acceleration-expanding stage successively and presented different expansion characteristics. Medium and large cities entered the acceleration-expansion stage 10 yr earlier than small cities. Urban expansion in super megacities and megacities was basically consistent. Note that the urban expansion speeds in these two types of cities decreased in a fluctuating manner after 2005, and the decrease degree in the former was larger than in the latter, which was the direct reflection of national policies' effective execution.

3.2 Urban expansion patterns of China

By analyzing the urban expansion patterns of China, we can assess the rationality of urban expansion and reveal the dynamics of urban expansion patterns.

3.2.1 Basic characteristics of urban land density in concentric rings

In general, the pattern of urban lands in China is relatively extensive, with the average *ULD* in concentric rings of 26.21% in 2020. The distribution of Chinese *ULD* was imbalanced with a variance of 0.008. Among these 75 cities, *ULD*s in 48% of cities were higher than

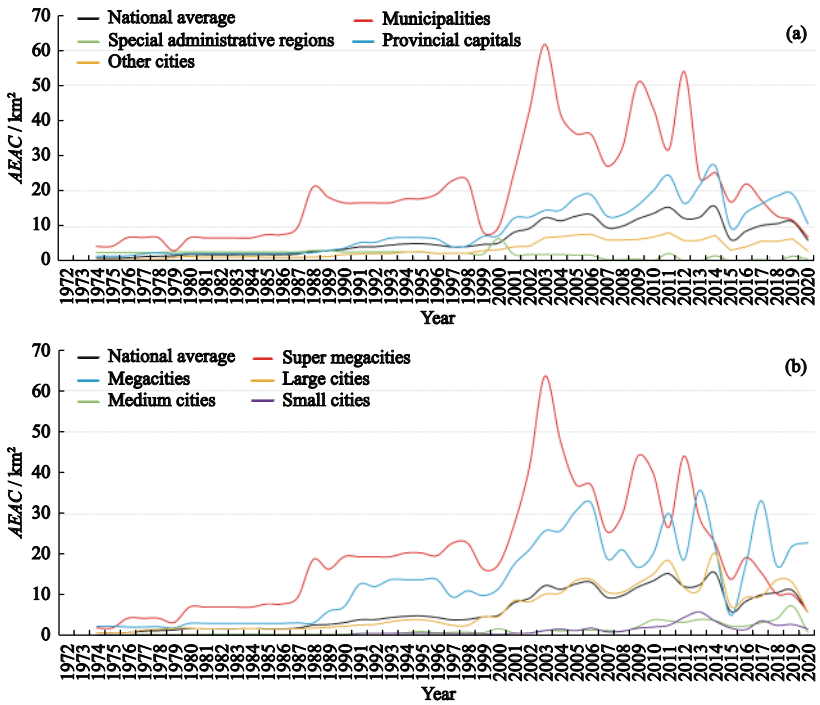

Fig. 6 Administrative level (a) and population-sized (b) differences of urban expansion in China during the 1970s–2020

the national average, of which Beihai had the highest value of 50.77%; and *ULD*s in more than half of monitored cities were lower than the nation level, of which Yan'an had the lowest *ULD* of only 6.58% (Fig. 7).

Urban expansion of China is synchronous with the implementation of national strategies and policies. To present the temporal variations of *ULD*s, we selected the 1970s, 1987, 1996, 2000, 2010, and 2020 as the important time points by fully considering the development stages of China and the balance of the time span division simultaneously (Fig. 8a). In the past 50 yr, the *ULD* of China decreased with the distance from the city center, which decreased slowly at the beginning, dropped down quickly, and then decreased slowly again (Fig. 8b). Before 2000, the urban expansion of China mainly occurred within 10 km from the city center. In the next 20 years, increased urban lands mainly emerged within 20 km. With the process of urban expansion, the attenuation trend of *ULD*s became more and more moderately from the 1970s to 2020, which indicated that newly-expanded urban lands also appeared in an infilling-expansion way, apart from the edge-expansion and leap-frog ways. Furthermore, some distinct bumps emerged in 1996, 2000, and 2010, describing the dynamics of urban expansion patterns with obvious polycentric urban patterns after the 1990s (Fig. 8b).

3.2.2 *Dynamics of ULD in concentric rings*

Since the 1970s, the *ULD* has presented an increase trend in general and changed dramatically in different periods (Fig. 8a). Before 1987, urban lands always expanded on the basis of the original outline of urban lands or along the main traffic lines. Moreover, the concentric rings covering urban lands increased from 27 to 31. Therefore, the *ULD* in this period increased from 21.81% in the 1970s to 23.55% in 1987. After 1987, especially after the early 1990s, China's real estate industry developed rapidly, which promoted the urban expansion process and resulted to the rapid growth of urban lands with an increase of 2769.62 km^2. However, the concentric rings also increased quickly from 31 to 60, resulting in the *ULD* decreasing to 22.59% in 1996 unexpectedly. In the next 20 years, the social-economic level was enhanced rapidly, and urban expansion entered the high-speed stage with an amazing increase of 16 675.36 km^2, leading to the increase of *ULD* directly. The dynamics of *ULD*s in this period fully confirmed the decisive role of national socioeconomic level on urban development. After 1996, the *ULD* underwent two rapid increase stages in 1996–2000 and in 2010–2020 and one relative stable stage in 2000–2010. During the period 1996–2000, the Chinese economy was severely affected by the Asian financial crisis. To

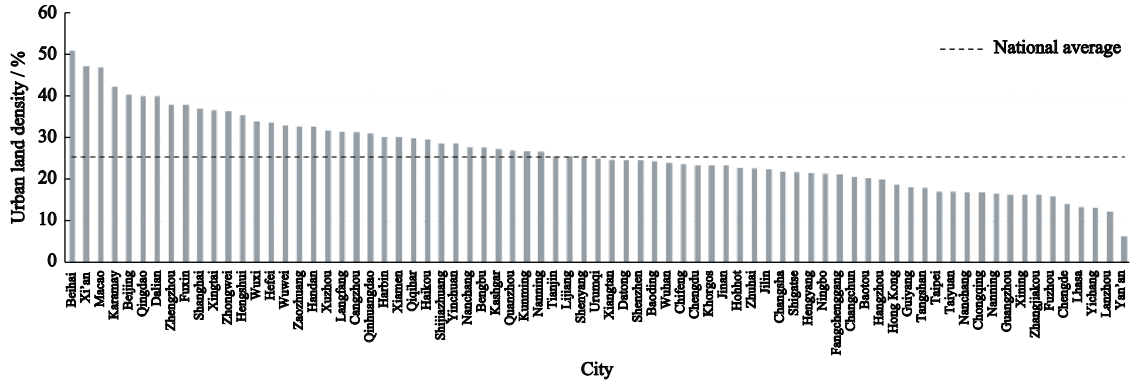

Fig. 7 Urban land density in concentric rings of 75 monitored cities in China in 2020

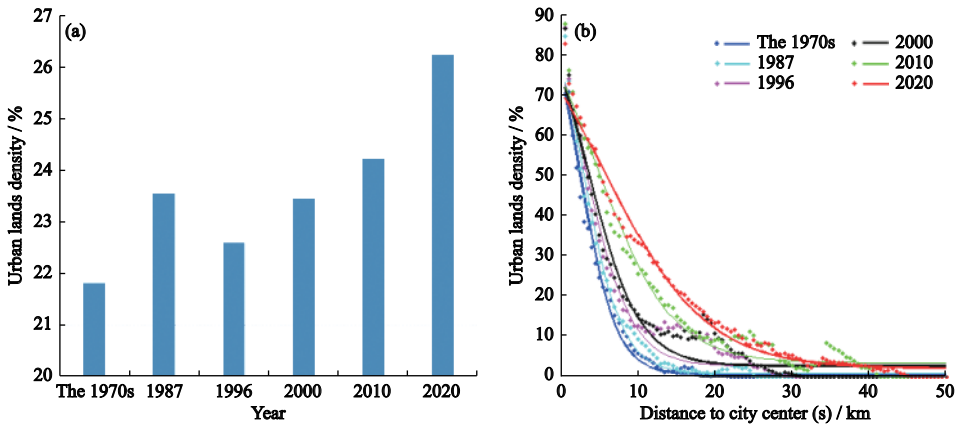

Fig. 8 Urban land density (a) and its attenuation trend (b) of 75 cities in China, the 1970s–2020

ensure the stable development of China, multiple reform policies were executed by the State Council of China. Urban expansion still proceeded with the average speed in 1987–1996. Moreover, the concentric rings changed slightly. Finally, the *ULD* increased rapidly with an annual increase of 0.22%. From 2000 to 2010, China joined the WTO, which further stimulated the urban expansion. Meanwhile, national strategies, such as 'Western Development', 'Northeast Revitalization', and 'Rise of Central China' were executed successively, and urban expansion in different regions was stimulated. During the past 10 yr, a total of 8494.73 km^2 newly-increased urban lands emerged, accounting for 37.91% of the increased urban lands in the past 50 yr. However, the concentric rings evidently increased, resulting from the uncontrolled urban expansion and the abuse of local land resources. Therefore, the increase rate of the *ULD* slowed down with an annual increase of only 0.08%. In the recent 10 yr, urban lands grew by 8180.63 km^2, similar to that in 2000–2010. However, the concentric rings only slightly increased from 82 to 90. Thus, the *ULD* increased significantly from 24.22% in 2010 to 26.21% in 2020, which reflected the effects of the 'New Urbanization' implemented during this period.

3.2.3 Dynamics of urban expansion patterns

The attenuation of *ULD* in China has an inverse 'S shape' from the city center to the urban periphery (Fig. 8b). Parameter α characterizes the shape of the curve of the *ULD*, and a higher α means a more compact urban pattern. Cross-sectionally, the values of urban patterns in China present an inverted 'V shape' (Table 2). Before 1987, China was still in a planned economy, the real estate industry has not yet sprung out, and slight urban expansion emerged with a weak driving of profits. During this period, urban lands mostly spread outwards on the basis of the original urban outlines, and the urban pattern was relatively compact with α increasing from 1.080 in the 1970s to 1.192 in 1987. After the 1980s, with the deep implementation of the process of 'Reform and Opening-up', China's economy and society entered a new stage of development, and the real estate industry became a new hotspot of investment in China, which strongly stimulated urban expansion. During 1987–1996, urban lands mostly adopted the edge-expansion and the

Table 2 Pattern evolutions of urban lands in China and its differences among eight regions, four administrative levels and five population sizes

Difference	Region	Parameter	1973	1987	1996	2000	2010	2020
	China average	α	1.080	1.192	1.106	1.048	1.001	0.859
		Adjusted R^2	0.982	0.987	0.951	0.951	0.972	0.985
Spatial differences	Northeast China	α	2.276	2.371	2.134	1.756	1.173	1.443
		Adjusted R^2	0.995	0.991	0.987	0.993	0.983	0.989
	The HTM region	α	0.748	0.677	0.983	0.940	1.053	1.075
		Adjusted R^2	0.973	0.985	0.980	0.984	0.986	0.988
	North China	α	2.002	1.796	1.580	1.594	1.451	1.723
		Adjusted R^2	0.965	0.968	0.927	0.932	0.970	0.967
	East China	α	1.068	1.527	1.602	1.555	1.319	1.197
		Adjusted R^2	0.974	0.987	0.955	0.969	0.962	0.980
	South China	α	0.415	0.713	0.066	0.120	0.338	0.198
		Adjusted R^2	0.879	0.893	0.840	0.840	0.843	0.905
	Central China	α	0.517	0.759	1.055	1.115	1.058	0.798
		Adjusted R^2	0.963	0.970	0.975	0.989	0.985	0.987
	Northwest China	α	0.976	1.089	1.263	0.841	0.951	1.053
		Adjusted R^2	0.925	0.927	0.923	0.878	0.945	0.956
	Southwest China	α	0.956	1.532	1.300	1.297	1.250	0.764
		Adjusted R^2	0.969	0.986	0.982	0.978	0.987	0.945
Administrative differences	Municipalities	α	1.229	1.826	1.507	1.466	1.566	1.845
		Adjusted R^2	0.995	0.990	0.985	0.988	0.974	0.982
	Special administrative regions	α	0.682	0.352	0.831	0.578	0.681	0.699
		Adjusted R^2	0.954	0.933	0.947	0.956	0.965	0.973
	Provincial capitals	α	1.339	1.668	1.641	1.535	1.453	1.135
		Adjusted R^2	0.991	0.995	0.986	0.988	0.996	0.992
	Other cities	α	1.479	1.575	1.737	1.736	1.204	0.734
		Adjusted R^2	0.986	0.981	0.876	0.742	0.913	0.912
Population differences	Super megacities	α	1.056	1.403	0.998	1.062	1.457	1.328
		Adjusted R^2	0.987	0.992	0.985	0.978	0.973	0.987
	Megacities	α	1.051	0.579	0.541	0.595	0.829	0.603
		Adjusted R^2	0.990	0.978	0.959	0.978	0.983	0.973
	Large cities	α	1.460	1.802	1.978	1.808	1.487	1.261
		Adjusted R^2	0.988	0.993	0.998	0.996	0.995	0.995
	Medium cities	α	1.915	1.684	2.041	2.126	1.497	1.365
		Adjusted R^2	0.986	0.997	0.995	0.989	0.991	0.985
	Small cties	α	2.101	2.199	1.615	1.589	1.351	1.416
		Adjusted R^2	0.985	0.963	0.969	0.982	0.968	0.979

Notes: Parameter α and Adjusted R^2 are employed to describe the pattern of urban lands and the fitted effect. The higher of these two parameters, the more compact pattern of urban lands and the better of the fitted effect. HMT is Hong Kong-Macao-Taipei region

leapfrog-expansion in the concentric rings. During this period, the urban pattern of China became increasingly dispersed with α decreasing to 1.106 in 1996. In the next four years, although the acceleration of urban expansion was restrained due to the unprecedented crisis and challenges of the global socioeconomic development, newly-increased urban lands still emerged in the edge-expansion manner, leading to the successive reduction of α. After 2000, α decreased continuously and reached 0.859 in 2020, even smaller than the initial value in the 1970s, but the reducing rate of α was controlled. In the 14th Five-Plan of China, developing cities orderly, planning urban spatial structure rationally, and improving the efficiency of urban lands have become the important goals of Chinese land planning. Therefore, patterns of urban lands in China are expected to become compact with α stopping from declining or even rebounding.

4 Discussion

4.1 Influences of urban expansion on local land use

Urban expansion is a process involving the rapid land-use change and has profound influences on local land resources, such as cultivated lands, woodlands, grasslands, and water bodies. With large scales, relatively concentrated distributions, and evident urban expansion, most Chinese cities are located in East and Central China where regions with a relatively long history of agriculture are also found. Therefore, cultivated lands have become the main land source of urban expansion since the 1970s. In the past five decades, 12 362.60 km^2 of cultivated lands in 75 monitored cities were occupied by urban lands, accounting for more than half of the newly-expanded urban lands and having direct influences on the sustainable development of local economy and food security strategies. In the urban expansion process, cultivated lands' losses presented an accelerating trend, and the lost speed evidently slowed down in recent years. The contribution of cultivated lands to urban expansion ranged from 50% to 70%, and this value had a decrease trend in general, which reflected the effects of the executions of cultivated land protection. Moreover, the encroachment of cultivated lands by urban expansion was the most evident in super megacities. Further attention should be paid to the impact of urban expansion on food production.

Over the past 50 yr, population and socioeconomic development were the main driving forces of urban expansion in China. However, in the long historical process of the birth and development of cities, topography and other natural factors were the prerequisite factors for the emergence and development of urban lands and an important natural evaluation index for optimizing land use structure. The analysis showed that urban lands in China mainly distributed in areas with low altitude and relatively flat terrain. By analyzing the relationship between the distribution and topography of urban lands, the potential and problems of urban expansion can be evaluated to an extent (Fig. 9). In the 1970s, the quantity of urban lands of the 75 cities soared rapidly with the increase of altitudes and slopes and reached the peak in regions with an altitude of 9 m and a slope of 3°. Then, urban lands reduced dramatically as altitudes and slopes increased. More than half of urban lands were distributed in areas with altitudes ranging from 0 to 56 and slopes less than 5° in the 1970s. In the past five decades, the newly-expanded urban lands mostly concentrated in areas with lower elevations and flatter slopes. By 2020, more than half of urban lands emerged in areas with altitudes ranging from 0–40 m and slopes less than 4°. That is, urban expansion prefers to emerge in flat areas, which tend to be high-density areas of cultivated lands. Therefore, China's urban expansion has caused sustained pressure on cultivated land protection, and the

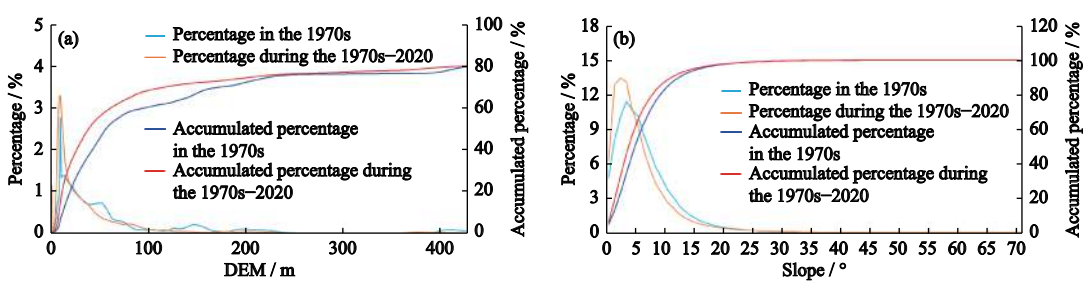

Fig. 9 The relationship between urban lands' distribution and DEM (a) and the relationship between urban lands' distribution and slops (b)

contradiction between urban expansion and cultivated land protection will always exist. Only by fully considering the efficient use of land and reasonably developing cultivated land reserve resources can cities achieve sustainable development.

Rural settlements and other construction lands are the second land sources of urban expansion in China and have even become the first land sources in Baotou, Guangzhou, Handan, Jinan, Quanzhou, and Xiangtan. Since the 1970s, 7277.24 km^2 of other construction lands have been integrated into urban lands in 75 monitored cities, including 3504.88 km^2 of rural residential lands and 3772.36 km^2 of industrial construction lands (industrial parks, transportation lands, and economic development zones). The contribution rate of these lands to urban expansion was 32.48%, which was 58.87% of the encroached cultivated lands and 2.63 times of other occupied lands. The integrated speeds of other construction lands presented obvious stages and fluctuations, which were consistent with the dynamic trends of urban expansion. Rapid urban expansion provided additional employment opportunities for farmers living in suburban areas and improved their living standards. However, such an expansion also generated some negative effects for rural settlements, one of which was the appreciable phenomenon of 'urban villages' (UVs). During the rapid urban expansion process, several rural settlements were expropriated. Due to the high cost of demolition and resettlement, most of these rural settlements were completely preserved and gradually surrounded by expanding urban areas, forming UVs. Nowadays, UVs are widely distributed in China's major cities, such as Guangzhou, Shenzhen, and Wuhan. Although they can provide cheap housing for many migrant workers, they affect the urban landscape seriously with low land use efficiency and generate environmental, health, and safety hazards. To promote the efficient use of lands in UVs and conduct urban sustainable development effectively, the transformation of UVs is inevitable.

Other lands occupied by urban lands refer to land use types excluding encroached cultivated lands and other construction lands. These other lands comprise four first-level and 18 second-level land use classifications, such as woodland, grassland, water body, sea area, and unused land. Other lands occupied by urban lands also commonly exist in every monitored city and present temporal differences. In general, the speeds of other lands encroached by urban lands fluctuated obviously and presented an increase trend. In 2003, the speeds reached the peak and exhibited a decrease trend in recent years, especially in 2019–2020. Compared with cultivated lands and other construction lands, other lands have smaller contributions to urban expansion and are profoundly affected by natural conditions. For example, the proportion of grasslands occupied by urban expansion in Northwest China is much higher than that in other regions. In South China, where woodlands and water bodies are densely distributed, the probability of woodlands and water bodies occupied by urban expansion is high. Furthermore, the occupation of sea areas is one of the characteristics of urban expansion in coastal cities and is mainly realized by marine reclamation engineering. After rapid growth and extensive construction, the marine reclamation engineering of China has entered the rational development stage today. However, on the background of global warming, sea-level rise and land subsidence pose important threats to the sustainability of land use in reclamation areas. Therefore, assessing the risk of sea-level rise before, during, and after the reclamation project is necessary. Meanwhile, we should improve the efficiency of land use in these areas and enhance the rationality and sustainability of the land space development in coastal cities.

4.2 Differences of urban expansion patterns

Urban expansion patterns in China exhibit different characteristics from the aspects of regional distributions, administrative levels, and population sizes. By recognizing urban expansion patterns systematically from these factors, we can make urban sustainable development planning further scientifically.

The compactness of urban lands presents significant regional differences (Table 2). In the 1970s, most urban lands in China were in a spontaneous state, and location conditions played an important role on the patterns of urban lands. The parameter α values in Northeast China (2.276) and North China (2.002) were higher than the national average, which resulted to the compact urban land patterns in these two regions. In the six other regions, patterns of urban lands were relatively dispersed, with parameter α values of 1.068, 0.976, 0.956, 0.748, 0.517, and 0.415 in East China, Northwest China, Southwest China, the HMT region, Central China, and South China, respectively. For the past half century,

with the continuous implementation of urban development planning and strategies at national and regional scales, the compactness of urban lands in different regions has undergone great changes. Overall, urban lands in the HMT region, East China, Central China, and Northwest China became increasingly compact with parameter α increasing. By contrast, urban lands in other four regions became increasingly dispersed, with parameter α decreasing, especially in Northeast China. By 2020, North China has the highest α, and its urban lands were the most compact, followed by Northeast China, East China, Northwest China, Central China, and Southwest China. South China still had the lowest urban land compactness with a parameter α value of only 0.198.

A small correlation was observed between urban land compactness and city administrative levels. The patterns of urban lands in municipalities and special administrative regions became increasingly compact, with parameter α increasing slightly from 1.229 and 0.682 in 1973 to 1.845 and 0.699 in 2020. On the contrary, patterns of urban lands in the two other kinds of cities became increasingly dispersed, with parameter α reducing moderately from 1.339 to 1.135 in provincial capitals and decreasing rapidly in other cities from 1.479 to 0.734. The patterns of urban lands in special administrative regions were the most dispersed; parameter α was far lower than the national average, but its compactness had been presenting an increasing trend since the 1970s. Given the lack of rational planning, urban lands in municipalities expanded relatively uncontrolled before 1996; therefore, their patterns became dispersed with parameter α increasing at first and then decreasing. After 1996, urban expansion in municipalities was consistent with the implementation of national policies and strategies about urban development. Therefore, the patterns of urban lands in municipalities became increasingly compact during 1996–2020, with parameter α being higher than that in other cities. The temporal characteristics of parameter α in provincial capitals revealed the effects of the execution of national policies. Although parameter α presented a decreasing trend, its decrease was relatively slight. Apart from focusing on urban construction, the improvement of land use efficiency and the optimization of the spatial distribution of land resources were also considered in provincial capitals. In the 1970s, the patterns of urban lands in other cities were the most compact with the highest α. Before 2000, this status remained unchanged. However, after 2000, less attention was paid to the optimization of the urban spatial patterns of other cities. The patterns became increasingly dispersed, with parameter α reducing dramatically. By 2020, parameter α was even lower than the national average.

The patterns of urban lands in super megacities became increasingly compact with parameter α increasing from 1.056 in 1973 to 1.328 in 2020. On the contrary, the compactness of urban lands in the four other population-sized cities reduced in the past five decades, of which parameter α in small-sized cities decreased the most dramatically with a reduction of 0.685, followed by medium-sized cities, megacities, and large cities with a decrease of 0.550, 0.448, and 0.199, respectively. In general, parameter α is negatively correlated with population sizes. That is, the larger the urban population size, the smaller the value of α. This phenomenon was particularly significant in the early monitoring period. In 1973, the patterns of urban lands in small-sized cities were the most compact with a parameter α value of 2.101, followed by medium-sized cities and large cities. The compactness of megacities and super megacities was the lowest with a parameter α value of 1.051 and 1.056, respectively. After 1987, this characteristic was broken gradually. With the improvement of urbanization, a series of urban development planning about megacities and above were issued to coordinate the development of cities with different population sizes. Therefore, the patterns of urban lands in megacities and super megacities became increasingly compact, but their compactness was still lower than that in cities with small population sizes. Meanwhile, the urban lands of small, medium, and large cities were extensive, leading to a decreasing trend of compactness of urban lands in these cities, especially in small cities with parameter α decreasing more obviously than other cities. In the recent 10 years, the patterns of urban lands in small cities became the most compact again, with parameter α rebounding from 1.351 in 2010 to 1.416 in 2020. By contrast, the patterns of urban lands in other kinds of cities became increasingly dispersed, but the decrease intensity of parameter α was smaller than that in the early stage of monitoring, which indicated that a series of urban sustainable development strategies restrained the uncontrolled expansion of urban lands in these cities, but

their effects were expected to be further enhanced.

5 Conclusions

Since the 'Reform and Opening-up' policy, China has undergone rapid urbanization process. Urban expansion is a good illustration of this phenomenon. On the basis of remote sensing and GIS technology, we quantified, analyzed, and mapped the high-frequency and long-term urban expansion process in China in the past five decades. We found that China has experienced a large-scale growth of urban lands since the 1970s. Urban expansion was popular phenomenon among 75 monitored cities, with urban lands increasing from 3606.26 km^2 in the 1970s to 30 521.13 km^2 in 2020. Urban expansion in China is persistent, periodic, and fluctuating, and exhibited an increase trend, which was consistent with the implementation of national strategies. Urban expansion affected cultivated lands the most seriously, and will generated sustained pressures on cultivated land protection; followed by other built-up lands, including rural settlements and other construction lands; urban expansion also affected other land use types, such as woodland, grassland, water body, *etc*., and the strength of these influences were co-related to the natural conditions. Obvious differences of urban expansion can be exhibited from the aspects of urban regional distributions, administrative-levels and population-sizes. The speed of urban expansion in East China was the fastest, followed by South China, Central China, Southwest China, Northeast China, North China, Northwest China, and the HMT region, which responded to the implementation of the regional development strategies of China. Urban expansion processes are highly co-related to urban administrative levels and population sizes. Obvious urban expansion with high speed and early acceleration stage always emerged in cities with high administrative levels and huge population sizes. On the whole, the pattern of Chinese urban lands was not compact. From the aspects of regional distributions, administrative-levels and population-sizes, attenuations of *ULD* among different type of cities all exhibited an inverse 'S shape' from the city center to the urban periphery. The compactness of urban lands in China increased before 1987 and then decreased continuously after the next 33 yr, but the reducing rate was controlled in recent years. Patterns of urban lands in China are expected to become compact with the optimizing of spatial patterns of land sources.

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