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Urban land expansion in China's six megacities from 1978 to 2015

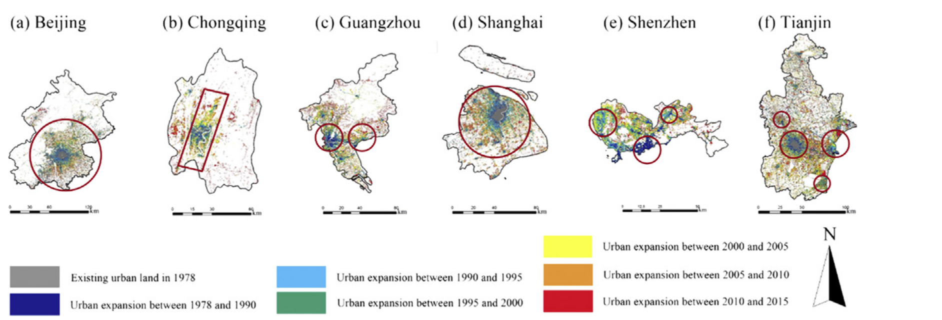
Weicheng Fei, Shuqing Zhao *

College of Urban and Environmental Sciences, and Key Laboratory for Earth Surface Processes of the Ministry of Education, Peking University, Beijing 100871, China

HIGHLIGHTS

- Spatiotemporal dynamics of urban expansion in China's six megacities were quantified.
- Megacities underwent extensive physical expansion over the past four decades.
- The applicability of urban growth theory varied with megacity.
- Wealth creation efficiency observed in all megacities.
- Land use efficiency found in Beijing and Shenzhen.

GRAPHICAL ABSTRACT



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ABSTRACT

Megacities pose both challenges and opportunities for the transition towards sustainability, and understanding the evolution of urbanization in megacities has profound implications for human societies in an increasingly urbanized world. Here, we mapped and quantified spatiotemporal dynamics of urban expansion in China's six megacities (i.e., Beijing, Chongqing, Guangzhou, Shanghai, Shenzhen and Tianjin) from 1978 to 2015, integrating remote sensing and GIS technology combined with landscape metrics and urban growth type analysis. The results show that six Chinese megacities have all undergone extensive physical expansion over the past four decades, and the magnitude of urban expansion is ranked in the order of Shenzhen, Guangzhou, Chongqing, Shanghai, Tianjin and Beijing, with annual growth rates of 11.02%, 8.07%, 5.80%, 5.37%, 4.56% and 3.46%, respectively. The megacities with smaller initial urban areas were associated with higher urban expansion rates. Differences in the direction, extent and location of expansion for each megacity related largely to the topography, policies and urban master planning. Temporal dynamics of urban growth and landscape metrics suggested that the urbanization processes of Beijing, Shanghai, Shenzhen and Tianjin were basically consistent with urban growth theory, while those of Chongqing and Guangzhou did not match the theory well. Temporal coevolution of the urban area with urban population implied efficiency of urban land use in Shenzhen and Beijing, which are the first special economic zone and the capital of China, respectively. The efficiency of wealth creation in the urbanized area base was observed for all Chinese megacities, signifying the effectiveness of urban expansion as a vehicle to promote economic growth. We face the challenge of managing trade-offs between the benefits and costs of urban agglomeration.

1. Introduction

We live in an increasingly urbanized world. In 1970, 36.6% of the world's population was urban; today, 55% of the world's population lives in urban areas, and by 2050, more than two-thirds of the world's population is projected to be urban with as much as 90% of the increase

* Corresponding author.
E-mail address: sqzhao@urban.pku.edu.cn (S. Zhao).

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centered in Asia and Africa (UN, 2018). This mass rush towards cities is forming megacities (i.e., urban settlements with 10 million or more inhabitants). In 1970, there were just 3 megacities in the world. Now, the number of megacities has reached 33, and by 2030, the world is expected to have 43 megacities (UN, 2018). The population of three oldest megacities has been growing rapidly, with Tokyo, New York, and Osaka increasing from 23 million, 16 million, and 15 million in 1970 to 37 million, 19 million, and 19 million in 2015, respectively (UN, 2018).

The rapid increase in the number of megacities and the sheer population size of existing megacities will pose enormous challenges and opportunities for a sustainable future. The maintenance of megacities consumes a huge amount of materials and energy from nearby and distant ecosystems, creating a wide range of environmental and social issues, including the megacities being significant sources of greenhouse gas emissions (Liu et al., 2011; Wunch et al., 2009), strong urban heat islands and heat waves (Choi et al., 2014; Karl and Knight, 1997; Li et al., 2017; Schär et al., 2004), health risks from exposure to air pollution (Han et al., 2018; Parrish and Zhu, 2009), disequilibrium between consumption needs and the availability of energy and material resources (Kennedy et al., 2015; Zhang et al., 2018), and the existence of the worst forms of social inequality (Akhmat and Bochun, 2010). At the same time, megacities are magnets for wealth creation and innovation, and they may require more efficient infrastructure resources on a per capita basis than smaller cities (economies of scale) (Bettencourt, 2013; Bettencourt et al., 2007). Therefore, understanding the evolution of urbanization in megacities is important to achieve sustainable development goals for human societies in an increasingly urbanized world.

China has undergone a strikingly rapid urbanization process since its economic reform starting in the late 1970s. Between 1978 and 2016, the share of Chinese urban population increased from 17.92% to 57%, and the number of cities with population of more than a million grew from 29 to 155 (NBSC, 2016). China now houses six of the world's 33 megacities and is the nation with the most megacities among all countries. Physical urban land expansion is a process indispensable to accommodating the increasing population and to ameliorate the average amount of living space for urban dwellers. The study of how and where urban lands expand will provide another dimension in addition to conventional demographic shifts to understanding the evolution of these megacities. Urban expansion of megacities has been briefly discussed in many previous studies devoted to investigating urban expansion in China. For example, Liu et al. (2005) characterized the spatiotemporal patterns and driving forces of urban land expansion in China from 1990 to 2000 and reported that the amount of expanded urban land in megacities was much higher than the amount of expanded urban land of other cities. Zhang et al. (2016) mapped the urban expansion of 60 typical Chinese cities from the 1970s to 2013 and found that the expansion of Chinese megacities has been higher in both area and rate than the expansion of other cities. In our earlier studies, we found a higher annual growth rate of urban land in two megacities (Beijing and Tianjin) than in the provincial capital in the Jing-Jin-Ji Urban Agglomeration of China over the past three decades (Wu et al., 2015), and we examined the contemporary evolution and scaling of 32 Chinese major cities but did not look into megacities in detail (Zhao et al., 2018). Kuang et al. (2014) compared the urban expansion patterns and rates among the three largest megacities in China and their counterparts in the USA during the past three decades and observed much higher expansion areas in Chinese megacities. Nevertheless, comprehensive studies on the rates, forms, driving forces, as well as similarities and differences of urban expansion within and among all Chinese megacities across a relatively long period with high temporal frequency snapshots are still lacking. Particularly, quantitative study on temporal coevolution of urban attributes of Chinese megacities is rare. Knowledge on how urban population and urban land cover, two aspects of urbanization, coevolve over time will contribute to gaining a sophisticated understanding of the ecology of and for megacities (Bettencourt and West, 2010; Arcaute et al., 2015; Zhao et al., 2018), and then to developing insightful strategies for improving megacity sustainability.

In this study, we mapped and quantified the spatiotemporal patterns of urban expansion in China's six megacities (i.e., Beijing, Chongqing, Guangzhou, Shanghai, Shenzhen and Tianjin) over the past four decades using multitemporal Landsat MSS, TM, ETM+, and OLI satellite images of 1978, 1990, 1995, 2000, 2005, 2010 and 2015. This research attempted to (1) dynamically map the spatial extent of urban land cover; (2) characterize the magnitude, typology, and spatiotemporal dynamics of urban expansion; (3) compare the similarities and differences in locations, rates and patterns of urban expansion among the megacities and identify possible drivers; and (4) analyze the temporal coevolution of the urban population and urban area for six Chinese megacities.

2. Data and methods

2.1. Study area

The six megacities formed in China before 2015 were our research area (i.e., Beijing, Chongqing, Guangzhou, Shanghai, Shenzhen and Tianjin) (NBSC, 2010; UN, 2018) (Fig. 1). Four of the six megacities (i.e., Beijing, Chongqing, Shanghai, and Tianjin) are municipalities under the direct administration of the central government, the highest level of urban administrative unit in China (Chan, 2010). Shanghai has been developing rapidly for over a century due to its unique traffic conditions as well as the Reform and Opening Up policy. Shanghai was the earliest (1995) in China to reach the megacity standard in population and it has always been the most populous city in China (UN, 2018). Beijing, the administrative center of China, has an urban history of >3000 years and a history as a capital of contemporary China for >800 years (Kuang et al., 2014). Beijing is the second largest city after Shanghai to reach the size of a megacity. Tianjin is the economic center of northern China and covers the third pole of Chinese economic growth, the Binhai New Area. The Chongqing municipality was established on March 14, 1997, and it used to be a subprovincial city of Sichuan Province. Chongqing has a total of 38 districts and counties, with the main urban area consisting of nine districts (Dadukou, Nan'an, Yubei, Yuzhong, Banan, Jiangbei, Beipei, Jiulongpo and Shapingba), which is our research area of Chongqing. Guangzhou is the capital and most populous city of Guangdong Province. Shenzhen, located in Guangdong province, was the first Special Economic Zone of China established in 1979. It is also one of the major Chinese import and export ports. Table S1 lists the basic geographic and socioeconomic information for these six megacities.

2.2. Remote sensing of urban land cover change

Seven consecutive series of remote sensing images (i.e., circa 1978, 1990, 1995, 2000, 2005, 2010 and 2015) were selected to derive four decades of land cover information in the study area. Cloud-free Multispectral Scanner (MSS) satellite images (bands 1–4, resolution 60 m) before 1985 and Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM+) satellite images (bands 1–5 and 7, resolution 30 m) after 1985 were obtained from the USGS website (http://www.usgs.gov/, accessed March 16, 2017). The path/row numbers and acquisition dates of the images used in this study are listed in Table S2.

We used ERDAS Imagine version 9.2 and ArcGIS version 10.1 to accomplish the image data processing such as the band combination, image mosaic, reprojection, classification, and classification accuracy assessment. We first resampled the MSS images to a resolution of 30 m to remain consistent with TM and then classified the land cover types into two categories: urban land and nonurban land. Urban land was defined as all nonvegetative areas dominated by man-made surfaces, including residential, commercial, industrial, and transportation space following the same criteria as described in our previous work (e.g., Zhao et al.,

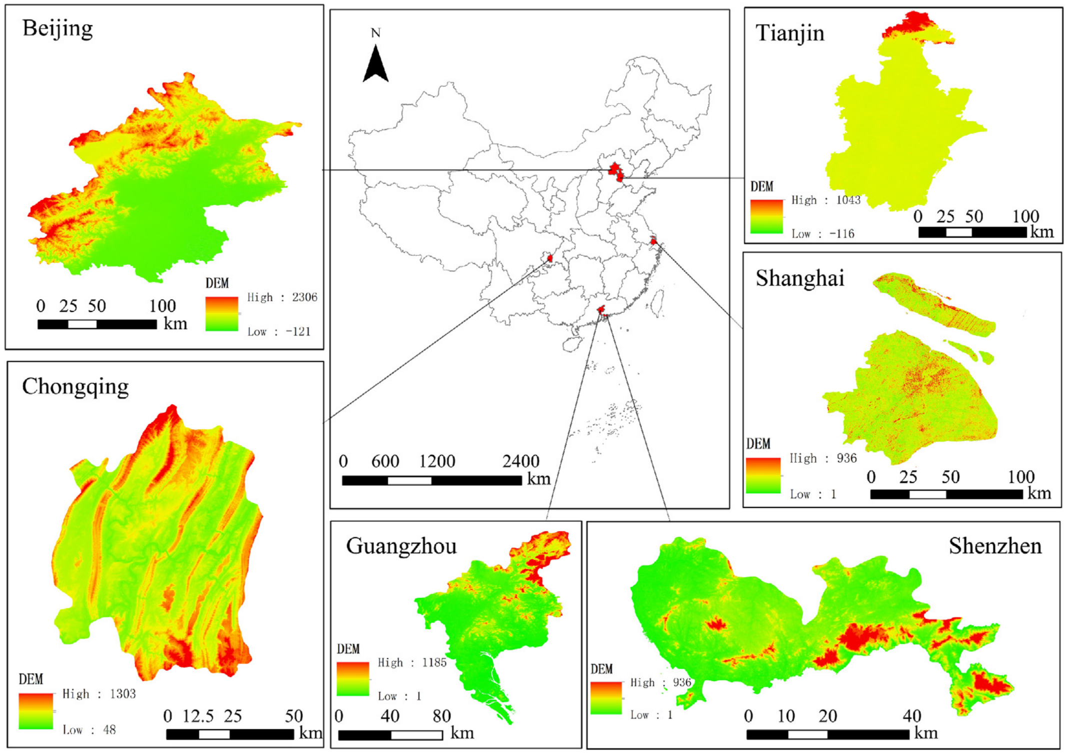

Fig. 1. The location and topography of the study area- Beijing, Chongqing, Guangzhou, Shanghai, Shenzhen and Tianjin. Terrain tends to constrain urban expansion and could place significant impacts on urban expansion.

2015a, 2015b). We used Google Earth Pro® (GE) to assess the accuracy of the classified products (Zhao et al., 2015a; Zhou et al., 2012). Because the high-resolution images were unavailable for the historical years, we used the images that were acquired in 2015 in GE to validate the accuracy of the classification results of 2015, and the classification results before 2015 in the areas only where land cover remained unchanged from 1978 to 2015. The results indicate that the Kappa coefficients of urban land for all megacities were higher than 0.8 for the classification results of 2015 and the results before 2015 (Table S3).

2.3. Landscape metrics

To reflect the landscape changes due to the influence of urbanization, six landscape metrics were chosen in our study: the number of patches (NP), percentage of landscape (PLAND), largest patch index (LPI), landscape shape index (LSI), patch density (PD), and mean patch size (MPS) (Table S4). FRAGSTATS version 3.0 with the eight-neighbor rule was used to calculate the value of the landscape metric (McGarigal and Marks, 1995). We further examined the detailed landscape changes within each megacity. First, four transects (i.e., North-South, East-West, Southeast-Northwest, Southwest-Northeast) cutting across the city center to divide each city into eight sectors were first generated, and the landscape metrics within each sector were calculated to represent the metric value in eight directions. Then, a series of buffer rings along the megacity center with an interval distance of five kilometers was generated, and the landscape metrics within each ring were calculated along the urban-rural gradient. The criteria for selecting landscape metrics were that the metrics should be relevant to the objectives of the study and not be redundant (Riitters et al., 1995; Wu et al., 2011). Compared with other landscape indices, PLAND and PD are more reliable and intuitive to reflect changes in urban land in different directions and at different distances. To avoid redundancy, only these two metrics were demonstrated.

2.4. Annual increase (AI) and annual growth rate (AGR)

We calculated two urban expansion indexes: annual increase (AI) and annual growth rate (AGR), which, respectively, represent the amount and rate of annual urban growth within a certain time period (Zhao et al., 2015a). The AI could be used to compare the speed of the urban expansion during different periods for the same megacity, while the AGR was effective in comparing urban expansion rates for different megacities during the same period. The definitions of AI and AGR are as follows:

$$\mathrm{AI} = \frac{A_{end} - A_{start}}{d} \tag{1}$$

$$\mathrm{AGR} = 100\% \times \left[\left(\frac{A_{end}}{A_{start}} \right)^{\frac{1}{d}} - 1 \right] \tag{2}$$

A_{start} and A_{end} represent the urban land area at the beginning and the end of the period, respectively, while d is the time span of the study.

2.5. Patch size frequency analysis

A patch is defined as a relatively homogeneous area that differs from its surroundings (Forman, 1995), and the spatial organization and fragmentation of urban land for each megacity and each period were studied using patch analysis. The urban patches were divided into 13 size classes (i.e., 0–05 km^2, 0.05–0.25 km^2, 0.25–0.5 km^2, 0.5–1 km^2, 1–2 km^2, 2–5 km^2, 5–10 km^2, 10–20 km^2, 20–50 km^2, 50–100 km^2, 100–200 km^2, 200–500 km^2, >500 km^2) following our previous studies (Wu et al., 2015; Zhao et al., 2015a), and the total area and number of patches of urban land according to these 13 size classes were analyzed.

2.6. Urban growth type

The urban growth types can generally be classified as infilling, edge-expansion, and leapfrogging. Infilling is defined as a new urban patch formed via filling in the gaps within existing urban patches. Edge-expansion is a type of urban growth in which a newly developed urban patch extends outward along the edge of existing urban patches. Leapfrogging growth represents new urban patches developed independently and without overlapping with any existing urban patches (Xu et al., 2007; Zhao et al., 2015a). A metric, E, was used to distinguish between these three types of urban expansion:

$$E = \frac{L_{com}}{P_{new}} \tag{3}$$

L_{com} is the length of the common border between the new urban patch and existing urban patches, and P_{new} is the perimeter of the new urban patch. Leapfrogging occurs when $E = 0$, edge-expansion when $0 < E \leq 0.5$ and infilling when $0.5 < E \leq 1$.

3. Results

3.1. Spatial distribution and magnitude of urban land-use change

From 1978 to 2015, the area of urban land increased from 800.95 km^2 to 2636.54 km^2 for Beijing, 75 km^2 to 605.63 km^2 for Chongqing, 70 km^2 to 1558.53 km^2 for Guangzhou, 312.44 km^2 to 2053.75 km^2 for Shanghai, 16 km^2 to 850.16 km^2 for Shenzhen, and

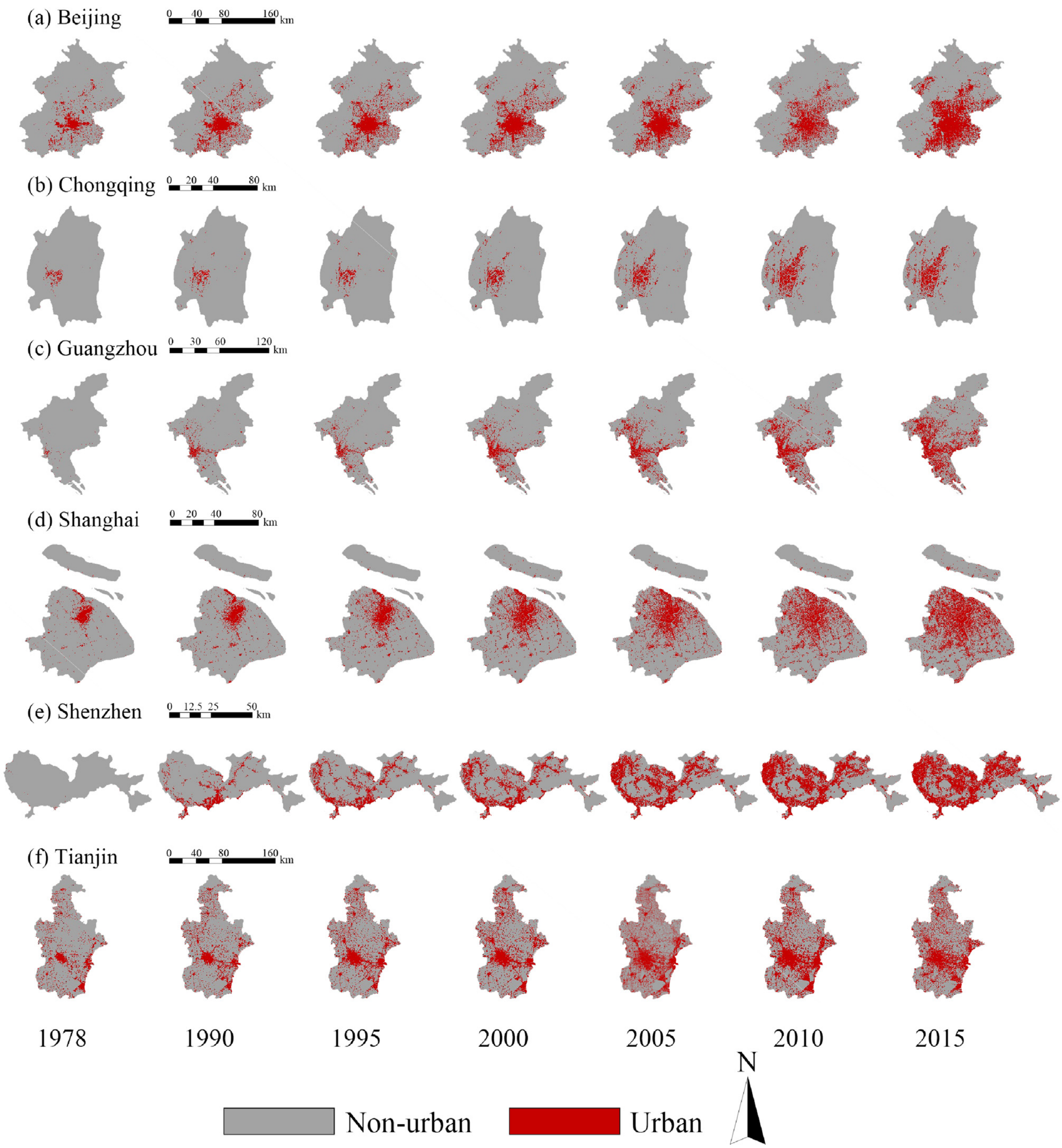

Fig. 2. Change of spatial extent of urban area in Beijing (a), Chongqing (b), Guangzhou (c), Shanghai (d), Shenzhen (e) and Tianjin (f) from 1978 to 2015.

794.67 km^2 to 3943.58 km^2 for Tianjin, respectively. Spatial distributions of the urban extent and urban expansion for six megacities from 1978 to 2015 can be seen in Figs. 2 and 3. Beijing's urban expansion tended to spread outward towards all directions approximately in the form of circles (Fig. 2a and Fig. 3a), similar to its circular traffic system (Tang et al., 2016). Chongqing is a belt shaped megacity that gradually developed along the river. Urbanization in the western part of Chongqing has been active in recent years, as evidenced by the emergence of large urban land areas in 2010–2015 (Fig. 2b and Fig. 3b). For Guangzhou, the original core has been constantly expanding outward, especially in the eastern and southern directions. Meanwhile, a new core in the northern part of the city has gradually formed (Fig. 2c and Fig. 3c). Like Beijing, Shanghai is a typical single core megacity showing a pattern of outward expansion starting from the center. Urban land in Shanghai was concentrated mainly in the north in 1978, while the urbanization process in the north has been more extensive than in the south (Fig. 2d and Fig. 3d). Urban expansion in Shenzhen is like the urban expansion of Guangzhou, which has been characterized by a very rapid urbanization process starting in 1978. A strip expansion along the southern coast occurred from 1978 to 1995, with several urban groups gradually forming within Shenzhen through connecting and aggregating with existing urban patches since 1995 (Fig. 2e and Fig. 3e). The formation and transformation process of Tianjin clearly shows a dual nuclear urban expansion pattern (Fig. 2f and Fig. 3f). The outward urban expansion first occurred in the original core of Tianjin. Then, a nuclear rudiment in the southeast coast formed in approximately 1995, and the interconnection between two city cores eventually formed the shape of a double-nucleated urbanization pattern.

Table 1 lists the annual area increase (AI) and annual growth rate (AGR) of the urban land for six megacities over the past four decades. The AI of urban land for Shanghai reached 118.22 km^2 from 2005 to 2010, which was the highest in four decades. The highest AI of urban

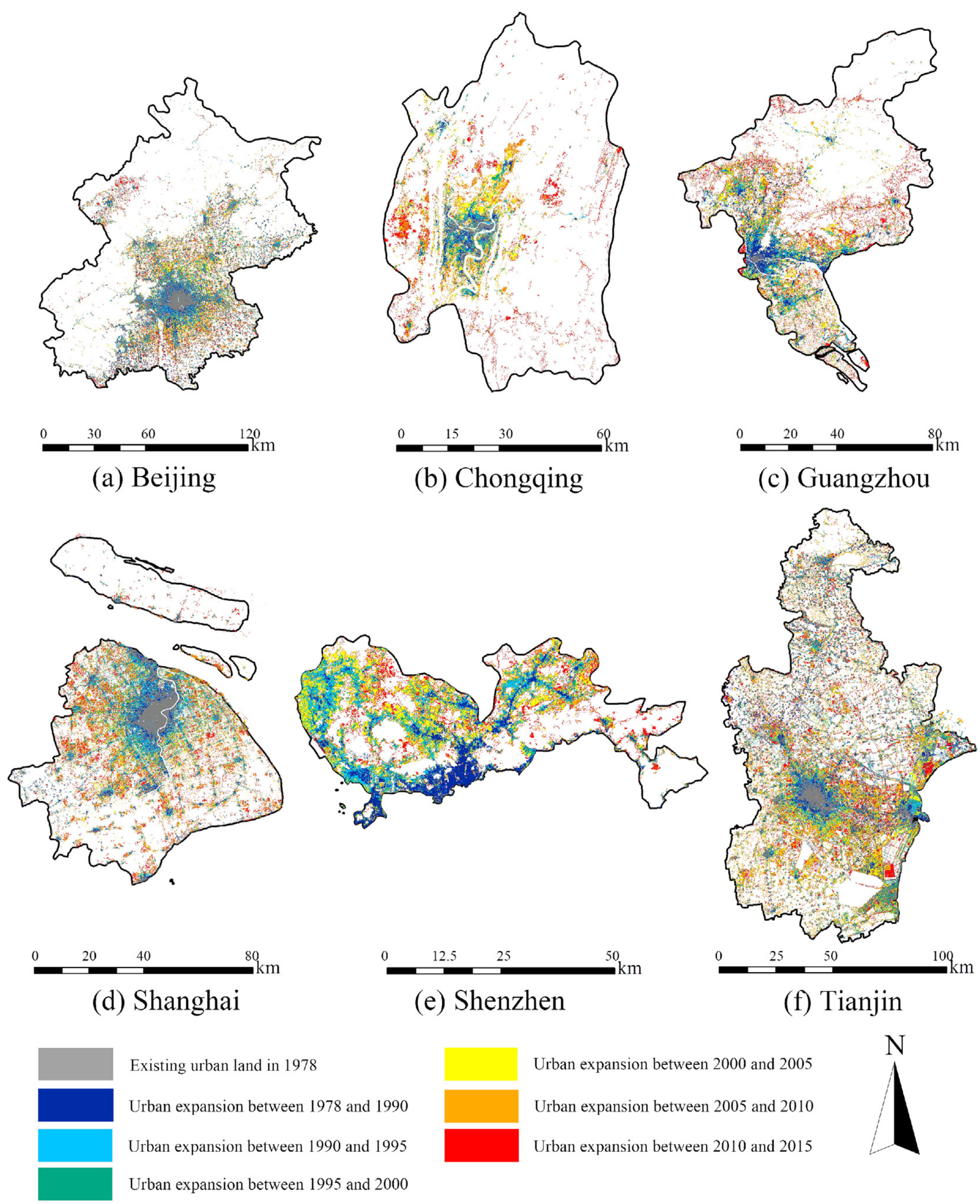

Fig. 3. Spatial distributions of urban expansion for Beijing, Chongqing, Guangzhou, Shanghai, Shenzhen and Tianjin among six neighboring periods from 1978 to 2015.

land for Beijing, Chongqing, Tianjin, and Guangzhou all occurred during the period from 2005 to 2010, while the highest AI of urban land for Shenzhen occurred in 1978–1990. The average AGR for Beijing, Chongqing, Guangzhou, Shanghai, Shenzhen, and Tianjin was 3.46%, 5.80%, 8.07%, 5.37%, 11.02%, and 4.56%. Shenzhen possessed the highest AGR of urban land among all six megacities during three of six neighboring periods from 1978 to 2015, Chongqing experienced the highest AGR during two of the periods, and Guangzhou had the highest AGR in the most recent period.

3.2. Spatiotemporal dynamics of urban expansion

Fig. 4 shows the composition of three urban growth types (i.e., edge-expansion, leapfrogging, and infilling) in the number of patches of the newly developed urban land for six megacities among the six neighboring periods over the past four decades. The results indicate that leapfrogging was the dominant urban growth type for all six megacities during the early stages of urbanization and then, edge-expansion took the lead subsequently. Specifically, the contribution of edge-expansion was relatively stable over time in Beijing, while the contribution of infilling increased sharply and the contribution of leapfrogging declined rapidly starting in 1990. For Chongqing, leapfrogging was the dominant growth type during the period of 1978–1990. Then, the contribution of edge-expansion increased greatly, mostly developing around the existing urban area distributed in the intersection between the two rivers in the region. The contribution of infilling rose rapidly from 2010 to 2015. For Guangzhou, the contribution of leapfrogging reached 88.7% during the period 1978–1990. Since 1995, edge-expansion has played a major role in the contribution of newly developed urban land, accompanied by an increase of infilling growth. For Shanghai, the leapfrogging growth occurred mainly on the periphery of the center during the early periods with a dominant number of small-sized patches, while edge-expansion occurred largely in the outer ring of the existing urban land in the north. The large contribution of infilling appeared during the periods 1995–2000 and 2010–2015. For Shenzhen, leapfrogging was the dominant growth type during the early stage of urbanization. Since 1995, the contribution of leapfrogging has declined rapidly while the contribution of edge-expansion and infilling evidently increased. For Tianjin, leapfrogging growth was more extensive before 1995, and some considerable growth points appeared on the southeast coast during 1990–1995, which was the basis of the Binhai New Area. Since 1995, the Binhai New Area has been further developed and gradually played a radiating role with increasing contribution of edge-expansion and infilling growth.

Edge-expansion growth was the largest areal contributor in the newly developed urban patches in six megacities through all periods except for 1978–1990 and 2010–2015 for Chongqing. Detailed information on the composition of three urban growth types in the total area of the newly developed urban land for six megacities among the six neighboring periods from 1978 to 2015 is provided in Fig. S1. The spatial distributions of these three urban growth types for each megacity across the consecutive periods between 1978 and 2015 are illustrated in Fig. S2.

3.3. Landscape changes in the process of urban expansion

Fig. 5 demonstrates the trends in the urban landscape changes over the past four decades. The PLAND and LPI increased over time for all six megacities, with a sharp rise starting from 2000. The change in the LPI indicated that the area of the largest urban patch (core block) in each megacity has been expanding rapidly. Specifically, Tianjin has displayed a much steeper trend than the other five megacities in terms of the PLAND and LPI, while a more gradual trend was observed for Guangzhou and Chongqing. The fragmentation and complexity of the urban landscape indicated by the LSI, NP, and PD varied among the megacities. These metrics for Beijing all rose before 1990, then gradually declined. The metrics for Chongqing all showed rising trends with fluctuations. For Guangzhou, these three metrics all experienced two peaks: one occurred in 1995 and the other in 2010. The metrics of Shanghai all first rose and then slightly declined. The dynamics of these three metrics for Shenzhen were relatively gentle compared to the other megacities, and they rose before 1995 and have been declining since then. The metrics of Tianjin showed a hump shaped pattern with a peak in 1995. The dynamics of MPS, a measure of average size of urban patches, reflected the changing trends of both PLAND and NP for each megacity.

Fig. 6 demonstrates detailed dynamics of the PLAND and PD in different directions within each megacity. The PLAND of Beijing in each direction has been increasing over time while the PD has been decreasing after 1990, suggesting that the urban landscape of Beijing has become more aggregated over time in all directions. Urbanized area increased more in the western and eastern parts of the city center in Chongqing than in other directions. For Guangzhou, the urban land increased quickly in the southeastern region during 1978 to 1990. Since 1990, a fast increase of urbanization has moved to the northwest, and the PD has started to decrease in all directions. The urbanized area in Shanghai has increased in all directions except for the north at an accelerating pace over time. The urban growth over time in Shenzhen was largely concentrated in the southwestern area although the PD increased in almost every direction. Urban expansion has been faster in the southern and eastern parts of Tianjin than in the north and west. Fig. 7 shows detailed dynamics of the PLAND and PD along the urban-rural gradient within each megacity. The PLANDs of all six megacities generally decreased along the distance gradient from the city center in each period, while their decreasing trends and the locations where the peaks came up varied with the megacity. In contrast, substantial differences existed in PD changes from city center to outskirts for each megacity.

3.4. Patch size frequency distribution

Fig. 8 and Fig. S3 demonstrate the detailed composition of urban lands of different sizes in terms of the number of patches and the total area for each megacity between 1978 and 2015. Overall, the number

Table 1
Annual increase (AI) in urban area (km^2) and annual urban growth rate (AGR) (%) for six megacities among six neighboring periods from 1978 to 2015.

	Megacity	1978–1990	1990–1995	1995–2000	2000–2005	2005–2010	2010–2015	1978–2015
AI (km^2)	Beijing	37.3	36.91	45.87	55.72	109.74	36.97	52.14
	Chongqing	4.36	2.27	16.05	14.43	53.75	18.4	14.41
	Guangzhou	15.13	25.75	34.2	45.6	83.6	65.31	36.49
	Shanghai	15.95	41.83	54.58	80.39	118.22	36.61	48.37
	Shenzhen	17.5	12.43	9.61	17.2	17.00	9.72	14.93
	Tianjin	38.4	47.23	49.65	124.08	200.79	120.02	80.74
AGR (%)	Beijing	4.34	2.92	3.09	3.21	5.2	1.46	3.46
	Chongqing	4.27	1.59	9.47	5.89	14.54	3.35	5.80
	Guangzhou	9.79	7.39	7.14	6.79	8.64	4.81	8.07
	Shanghai	4.21	7.37	6.62	7.02	7.56	1.57	5.37
	Shenzhen	19.38	13.32	6.88	7.24	5.25	2.04	11.02
	Tianjin	4.09	3.7	3.17	6.36	7.4	3.36	4.56

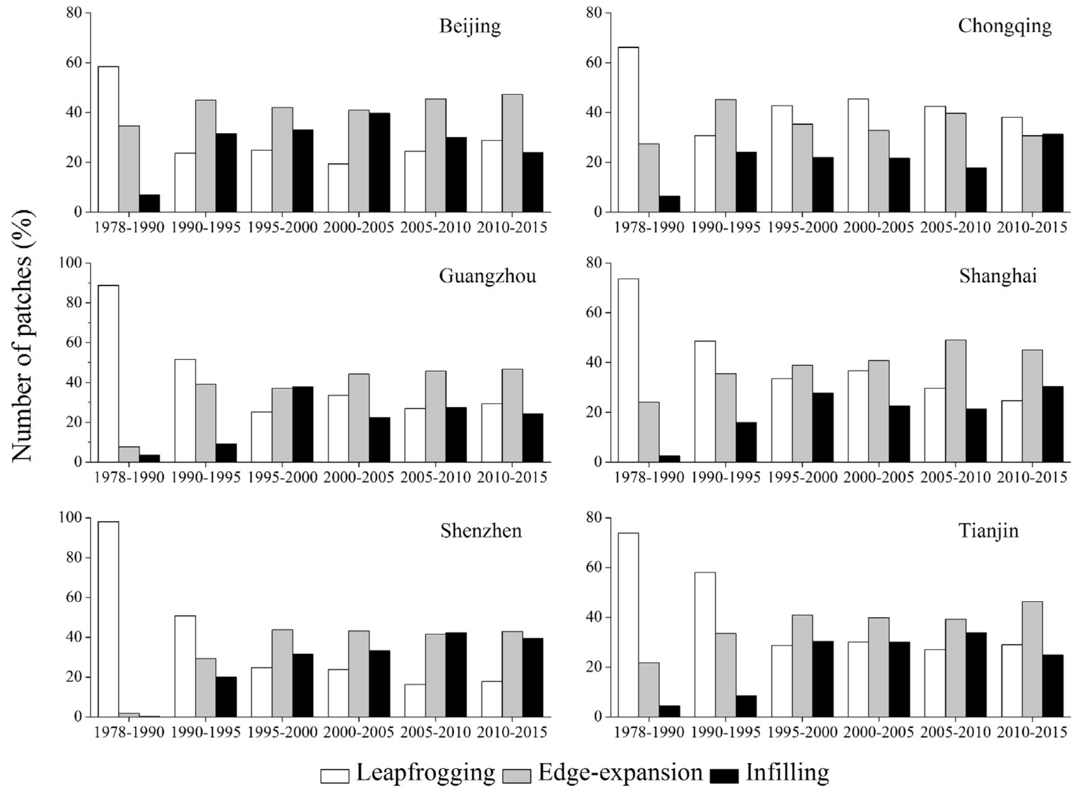

Fig. 4. Composition of three urban growth types in terms of the number of patches of newly developed urban land for six megacities between 1978 and 2015.

and area of patches of different sizes in all megacities have increased over time, suggesting a rapid urbanization process in the megacities over the past four decades. Beijing possessed a single core urban development mode as the number of patches larger than 500 km^2 remained at 1 since that patch formed in 1995, and by 2015, the area of the largest patch had reached 1047 km^2, while the area of the second largest patch was only 71.2 km^2. A similar single core mode was observed in Chongqing and Shanghai. In contrast, Guangzhou, Shenzhen, and Tianjin have gradually formed some sublevel urban cores, and these subcores have continued growing over time resulting in an approximately comparable size for the largest and the second largest urban patch.

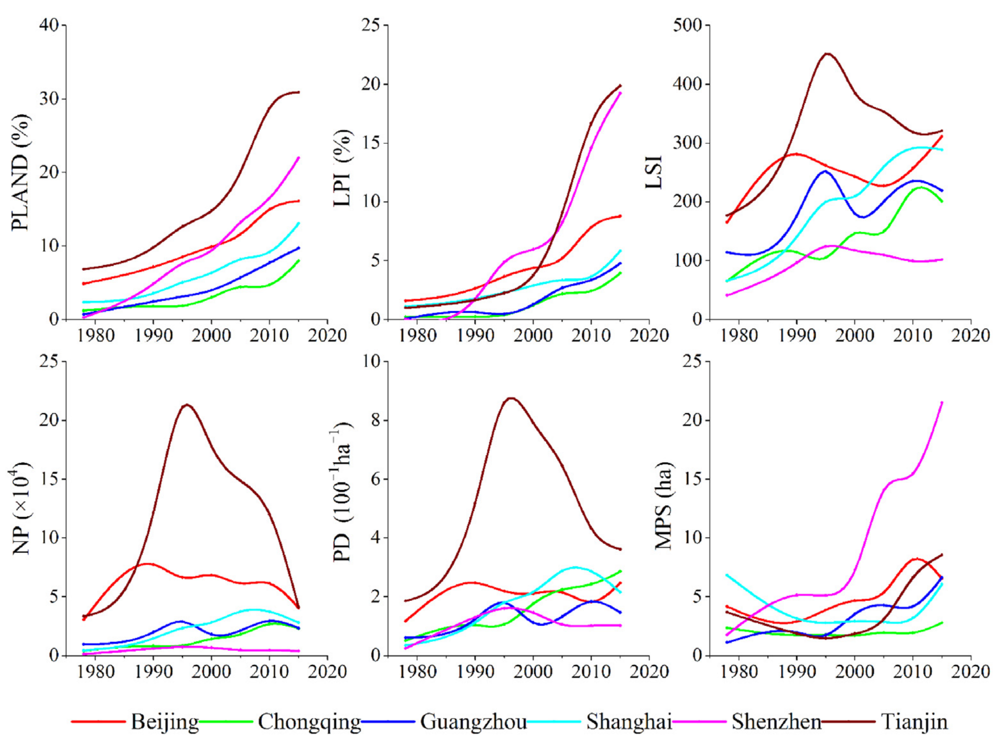

Fig. 5. Dynamics of landscape metrics for the urban land of Beijing, Chongqing, Guangzhou, Shanghai, Shenzhen and Tianjin from 1978 to 2015.

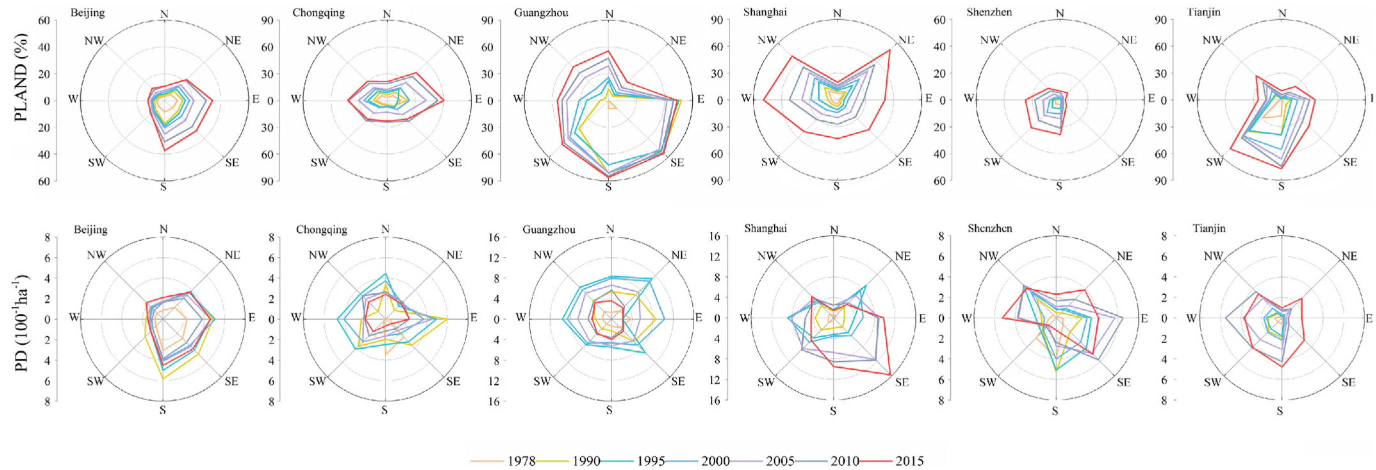

Fig. 6. Dynamics of PLAND (%) and PD (per 100 ha) for the urban land of Beijing, Chongqing, Guangzhou, Shanghai, Shenzhen and Tianjin in eight sectors from 1978 to 2015.

4. Discussion

4.1. Scale of megacity expansion

The six Chinese megacities have all undergone extensive physical expansion over the past four decades. The magnitude of the urban expansion is ranked in the order of Shenzhen, Guangzhou, Chongqing, Shanghai, Tianjin and Beijing, with average annual growth rates of 11.02%, 8.07%, 5.80%, 5.37%, 4.56%, and 3.46%, respectively. The megacities with smaller initial urban areas were associated with higher expansion rates, consistent with the inverse relationship between urban growth rate and city size found based on 32 major cities across China and six cities in the Yangtze River Delta Urban Agglomeration (Zhao et al., 2015a; Fang and Zhao, 2018).

Overall, the expansion process of the megacities has been consistent with China's national development strategies and economic policies. Since the initialization of the Reform and Opening Up policy during the late 1970s, the rapid urbanization of megacities started as the rural population began to be allowed to settle in the cities (Gu et al., 2017). Shenzhen, as the first special economic zone of China, was established in 1979. The first land auction in China, held to attract foreign investment, took place in Shenzhen in 1982. As a result, the annual growth rate of urban expansion during 1978–1990 in Shenzhen was much higher (nearly 20%) than the annual growth rate of urban expansion of other megacities. All megacities have experienced rapid growth in 2000–2010. At the beginning of the 21st century, China joined the World Trade Organization (WTO), and its economic development relied on land-based public financing (Cao et al., 2008), which greatly accelerated urban development across the country, including the megacities. Nevertheless, the expansion rates of these six megacities have all dropped substantially in recent time (2010–2015), probably reflecting the influence of the country's new urbanization strategy of “strictly controlling the scale of large cities, rationally developing small and medium-sized cities, and actively developing small towns” and the “coordinated development of large, medium and small cities and small towns” (Li et al., 2018).

The designation of the city's administrative level and orientation also have had a significant impact on the formation of megacities. For example, Beijing and Tianjin are similar in geography, and they both have a long history of urban construction. However, during the study period, Beijing's urban expansion rate was substantially faster than the urban expansion rate of Tianjin due to Beijing's unique political status that attracts a huge amount of resources and population, accelerating the pace of its urban expansion. Chongqing's urbanization process can be divided into two phases corresponding to changes in its administrative ranks. The establishment of Chongqing as a municipality in 1997 greatly

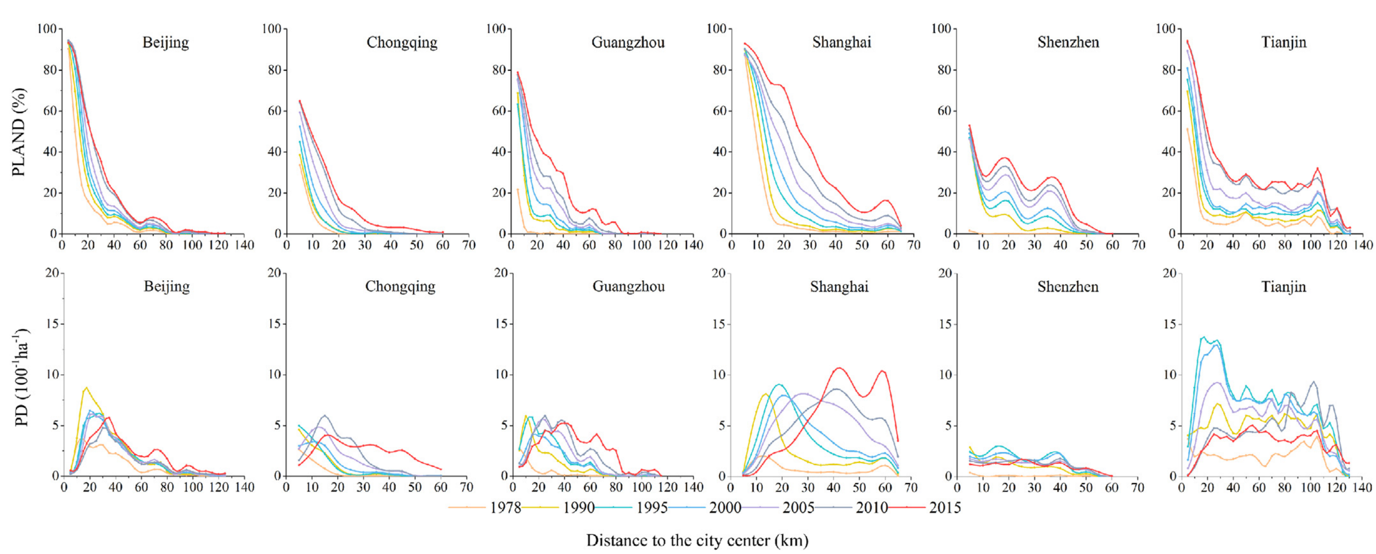

Fig. 7. Dynamics of PLAND (%) and PD (per 100 ha) for the urban land of Beijing, Chongqing, Guangzhou, Shanghai, Shenzhen and Tianjin at different distances (km) from the city center from 1978 to 2015.

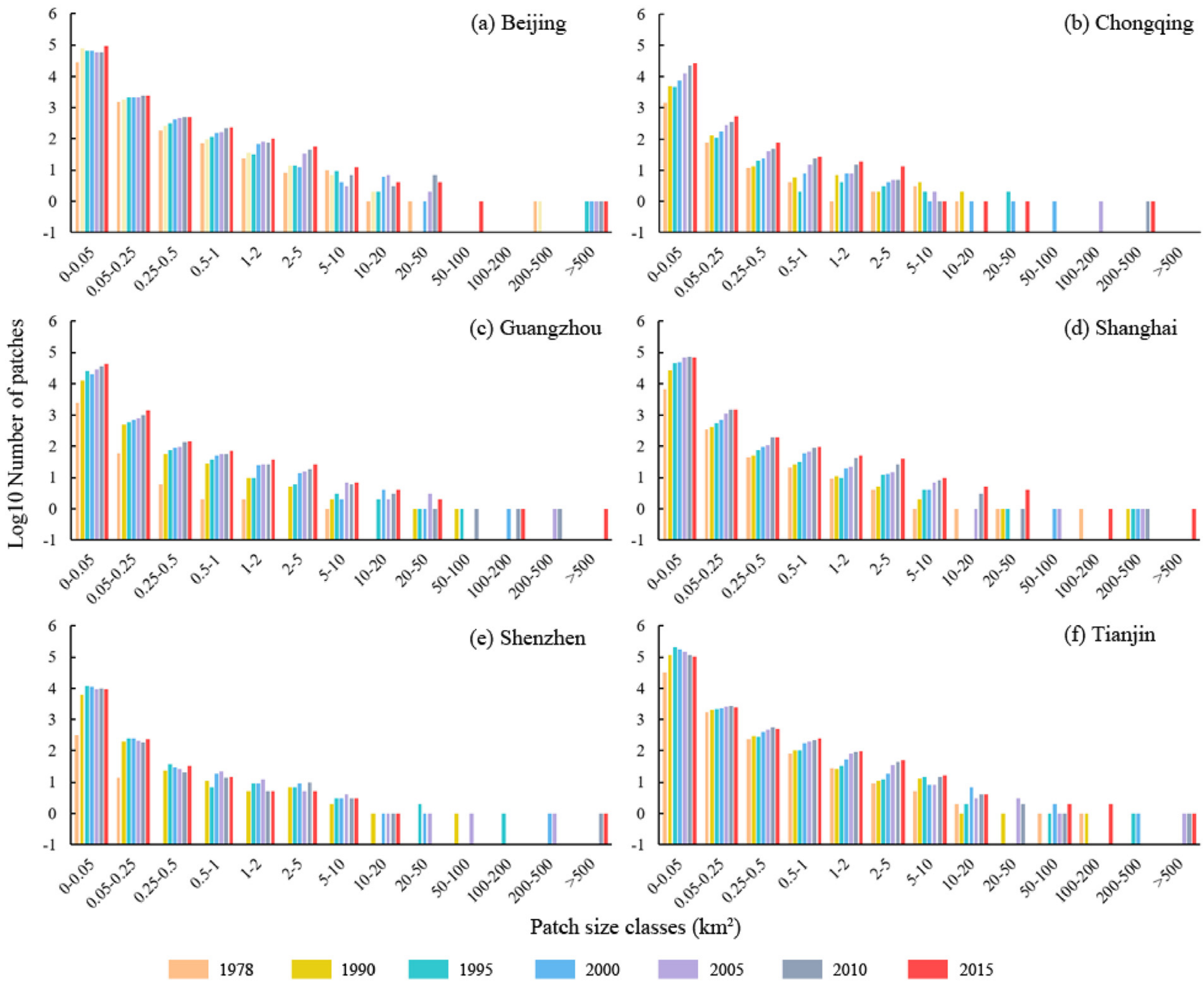

Fig. 8. Frequency distribution of the number of patches of urban land according to 13 patch size classes for six megacities from 1978 to 2015.

facilitated its urbanization process. As a result, the annual growth rate of Chongqing surpassed the annual growth rate of the other megacities during the period of 1995–2000. The annual growth rate of Shanghai, the financial center of China, has been above average and nearly the highest during 2000–2005. Although Guangzhou and Shenzhen are two nuclear cities in Guangdong Province, there have been differences in their urbanization processes. The annual growth rate of the urban land in Shenzhen was substantially faster than in Guangzhou from 1978 to 1995 because of the designation of Shenzhen as the first Special Economic Zone in China. However, the growth rates of these two cities became comparable between 1995 and 2005, and Guangzhou overtook Shenzhen in urban growth speed during recent periods. This pattern indicates that Guangzhou is still in a stage of steady expansion while the expansion of Shenzhen has been restricted by its administrative boundary.

4.2. Spatiotemporal dynamics of megacity expansion and possible drivers

Beijing and Shanghai have displayed a mononuclear polygon pattern, Chongqing a mononuclear belt pattern, Guangzhou and Shenzhen a multinuclear polygon pattern, and Tianjin a double-nucleated polygon pattern. Differences in the direction, extent, and location of the expansion in each megacity have largely been related to the topography, policies, and urban master planning.

The physical land available for development is the basis of urban expansion (Sun et al., 2013; Yue et al., 2013). The expansion of Chongqing, referred to as “the City in the Mountains” in China, has been affected mostly by the local topography that is characterized by many mountains. Urban expansion in Chongqing occurred in the plains along the Yangtze River, and the Jialing River and has been restricted by the terrain. Beijing is the central city of the Jing-Jin-Ji Urban Agglomeration, located in the Huang-Huai-Hai Plain. Its urban expansion has been concentrated mainly in the southeastern plain as the western part of Beijing has a large mountainous area (i.e., the Yanshan mountains). Shanghai, as the core city of the Yangtze River Delta, is found in the Middle Lower Yangtze plains that provide limited physical constraints to its expansion. Tianjin, the other core city of the Jing-Jin-Ji Urban Agglomeration, is found in the northeast region of the North China Plain with the Bohai Sea to the east and the Yanshan Mountains to the north. The Binhai New Area has been built to facilitate the development of the eastern coastal area, and a double-nucleated polygon pattern has gradually been formed for the expansion of Tianjin. Guangzhou and Shenzhen are both situated in the Pearl River Delta Plain with their urban expansion mostly occurring in the flat areas—the western and southern parts of Guangzhou and the western and northern parts of Shenzhen.

Economic development strategies and urban master planning are important anthropogenic drivers of the spatial forms of the urban expansion in megacities, which are consistent with the findings of previous urban expansion studies in the Yangtze River Delta Urban Agglomeration (Tian et al., 2011; Yue et al., 2013), the Jing-Jin-Ji Urban Agglomeration (Wu et al., 2015) and the Pearl River Delta Urban Agglomeration (Sun et al., 2013). During the study period, China implemented many developmental policies such as the Reform and Opening Up, the western development strategy, and the establishment of new state level areas (Chan, 2010), which played crucial roles in the formation and construction of megacities. For example, three new state level areas—Chongqing Liangjiang New Area, Shanghai Pudong New Area, and Tianjin Binhai New Area—were established in 2010, 1992, and 1994, respectively, which agreed well with a high fraction of the leapfrogging patches and a high urban growth rate during the corresponding periods. Guangzhou and Shenzhen are two major cities that have benefited from the Reform and Opening Up that was initiated during the late 1970s as indicated by the fraction of leapfrogging growth in the number of newly developed urban patches that is higher than in other megacities during the period of 1978–1990, particularly for Shenzhen, which is China's first special economic zone. For the western megacity, Chongqing, the establishment of the Liangjiang New Area in 2010 further enhanced the construction of the core area along the river plain, resulting in the increasing contribution of the infilling growth, both in the number and area of newly developed urban patches, during the period of 2010–2015 (Qu et al., 2014). Shanghai's urbanization was greatly affected by the construction of the Pudong New Area. With the establishment and development of the Pudong International Airport and Pudong New Area, the urbanization process in the eastern part of Shanghai has accelerated, resulting in a larger expansion to the northern and eastern areas than to the south. As mentioned above, the establishment of the Binhai New Area in 1994 contributed to the formation of the new city core in the eastern coastal area and the double nuclear polygon urbanization pattern of Tianjin. In addition, the Urban Master Plan of Tianjin in 2009 designated the Binhai New Area as a principal urban development area, setting this New Area as a new administrative district in the administrative divisions of Tianjin in 2009 (Yan, 2006). Correspondingly, much of the urban expansion that spread out from the fringes of existing urban patches has occurred in the Binhai New area in recent times. For Guangzhou, the establishment of the Nansha New District in the south and the development of the Huangpu District in the east have enabled Guangzhou to form a multicore spatial pattern. The urban expansion of Guangzhou in recent years was accomplished primarily by connecting the existing urban patches, indicated by the increase in the urban landscape area over time in almost all directions, but there has also been a sharp decrease in patch density in recent times. This pattern corresponds to the Guangzhou Urban Master Plan (2001—2010), which proposed a development strategy of "expansion in the south, optimization in the north, further development in the east, and connection to the west" (Gong et al., 2014). For Shenzhen, its Urban Master Plan (1996–2010) officially determined the special economic zone to be the center, while the Western, Central, and Eastern developmental axes were formed along the northern traffic line. During the period of 2000–2005, there was a large-scale edge-expansion area in the eastern area, which was related to the establishment of Baoan Airport in 2001.

4.3. Test of the urban growth theory

Megacities are currently the highest urban form that can fully reflect the general urbanization processes (Sorensen, 2011). Therefore, megacities are the ideal places to test the theory of urban growth. Urban growth theory proposes that the spatial evolution of cities consists of a process of two-phases—diffusion and coalescence that can be characterized by the temporal dynamics of the landscape metrics and urban growth type (Dietzel et al., 2005a, 2005b). In the diffusion stage, leapfrogging is generally the major urban growth type while the landscape metrics such as the number of patches (NP) and patch density (PD) increase. Meanwhile, in the coalescence stage, the role of edge-expansion and infilling growth is more pronounced with the mean patch size (MPS) increasing and PD decreasing.

We found that Beijing, Shanghai, Shenzhen, and Tianjin were basically consistent with urban growth theory while the specific time spent in these two alternative phases varied depending on the megacity. The urbanization process of Beijing changed from diffusion to coalescence in approximately 1990 when peaks in the NP and PD both appeared, with urban growth shifting from the major contribution by leapfrogging to edge-expansion and infilling. The year 2005 separated the urbanization process of Shanghai into two distinct phases as the NP and PD of the urban land in Shanghai experienced a substantial increase before 2005, followed by a decrease while the MPS kept descending before 2005 and then rose. The fraction of leapfrogging growth substantially decreased starting in 2005 along with an increase in edge-expansion and infilling. Differing from other megacities, the urbanization process in Shenzhen started from scratch in 1978. However, in a very short time (roughly 1978–1995), Shenzhen completed the diffusion phase of its urbanization process and gradually entered the coalescence stage since 1995, characterized by its NP and PD both increasing before 1995 and then decreasing, and the fraction of leapfrogging growth was higher before 1995, particularly during the period of 1978–1990. The urbanization process of Tianjin can clearly be divided into two stages with the turning point occurring in 1995 as the NP and PD of Tianjin both rose sharply before 1995 and then decreased, and the MPS changed into a U-shape with the bottom appearing in approximately 1995. Furthermore, the fraction of infilling urban growth obviously increased while the fraction of leapfrogging decreased after 1995. In contrast, the urbanization of Chongqing and Guangzhou did not match well with the urban growth theory. The temporal dynamics of urban growth and landscape metrics suggest that Chongqing is still in the diffusion stage and Guangzhou has already undergone a cyclical process of diffusion-coalescence phases during the study period.

4.4. Temporal coevolution of urban area with urban population and GDP

Urbanization is a complex process involving drastic changes in physical, demographic, and socioeconomic dimensions. To gain a more complete understanding of the urbanization process of Chinese megacities, we further examined the temporal coevolution of the physical urban expansion with population and GDP for these six megacities (Fig. 9). Using the power scaling law, which has been successfully adopted to scale many urban attributes across space and time (Bettencourt et al., 2007; Zhao et al., 2018), we found the scaling coefficient of the urban population vs. urban area were not consistent for the six megacities. The scaling coefficient was higher than 1.0 for Shenzhen (1.37) and Beijing (1.1), suggesting that the growth in urban population increasingly outpaced area expansion, whereas it was <1 for the rest of the megacities, varying from 0.66 for Guangzhou and 0.78 for Chongqing, indicating that the urban population growth progressively lagged behind the area expansion. A population densification process was associated with a decrease in the urbanized area per capita found in Shenzhen and Beijing, implying the economies of scale and efficiency in urban land use. Although diseconomies of scale in terms of the urbanized area existed for Chongqing, Guangzhou, Shanghai, and Tianjin, the scaling coefficient was larger than the global average of 0.5, as the global expansion of urban areas has been on average twice as fast as the growth in urban population in recent decades (Angel et al., 2011), signifying that megacities are relatively better positioned than smaller cities in the efficiency of their urban infrastructure.

The scaling coefficients of the urban GDP vs. urban area have been consistently larger than 1 for all six megacities, ranging from 2.17 for Guangzhou to 4.57 for Beijing (Fig. 9), showing that the urban GDP growth greatly exceeds the megacity expansion over time. It is not surprising to see the effectiveness of the wealth creation efficiency in the urbanized area bases in all Chinese megacities because urban expansion has been widely pursued as a practical vehicle to promote economic growth in China (Xu, 2008; Lin and Yi, 2011). However, the fast and extensive pace of the urban expansion of megacities has had significant implications on the environment, and how megacities expand in a sustainable way is a huge challenge.

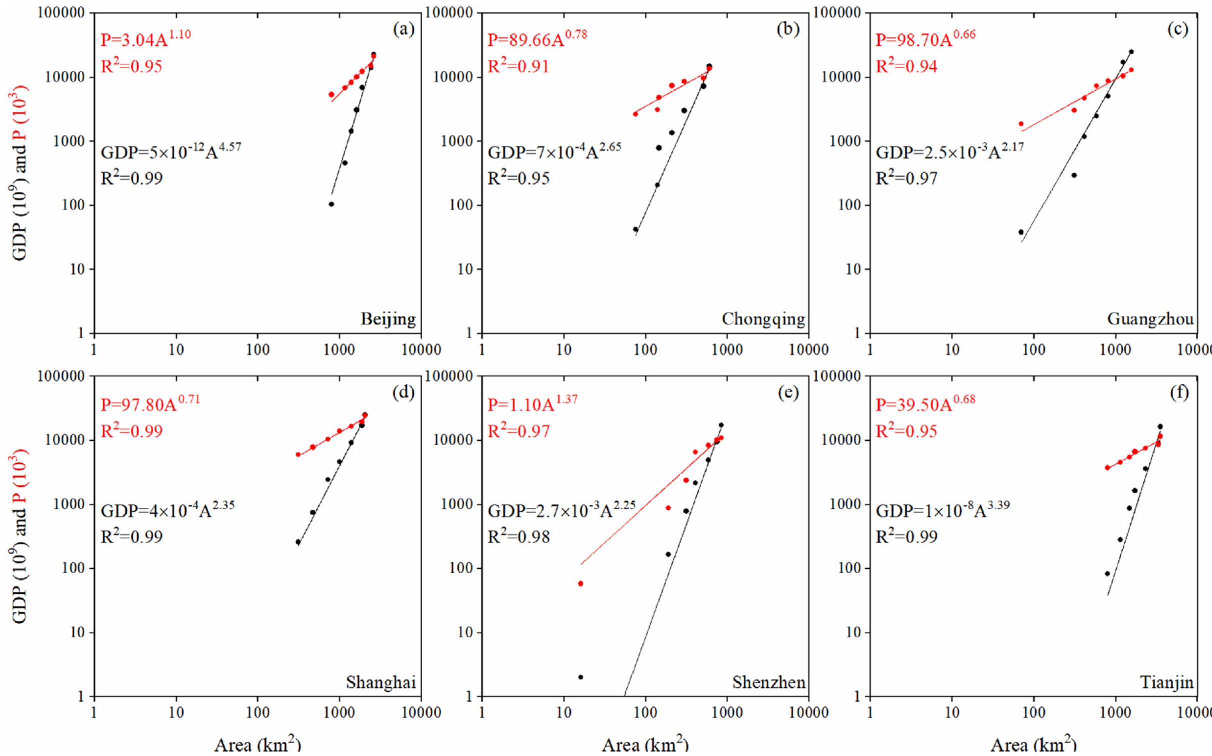

Fig. 9. The allometric relationship between urban GDP vs. urban area, and urban population vs. urban area.

5. Conclusions

China's rapid urbanization in parallel with its rapid economic growth over the past four decades has received worldwide attention. There is still a lack of comparative studies on the rates, forms, driving forces, as well as similarities and differences of urban expansion within and among Chinese megacities. This study provided a comprehensive understanding of the spatiotemporal dynamics of urban expansion in all six Chinese megacities and temporal coevolution of their urban attributes.

Extensive physical expansion has occurred in six Chinese megacities over the past four decades. The magnitude of the urban expansion is ranked in the order of Shenzhen, Guangzhou, Chongqing, Shanghai, Tianjin and Beijing. Similarities and differences in urban expansion among megacities generally corresponded well to the country's national development strategies and the designation of the administrative level and orientation of the city. The direction, extent, and location of urban expansion within each megacity was related largely to the topography, policies, and urban master planning.

The urbanization processes of Beijing, Shanghai, Shenzhen and Tianjin, characterized by two alternative phases (diffusion and coalescence), were basically consistent with urban growth theory whereas the urbanization processes of Chongqing and Guangzhou did not match the theory well. Temporal coevolution of urban area with urban population and GDP might imply that megacities are relatively better positioned than smaller cities in the efficiency of their urban infrastructure and wealth creation although diseconomies of scale in terms of the urbanized area did exist in four of six megacities. Megacities present both opportunities and challenges towards a sustainable future for human societies.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.02.008.

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