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Research Paper

A comparative study of urban expansion in Beijing, Tianjin and Shijiazhuang over the past three decades

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HIGHLIGHTS

- We mapped and compared urban land expansion in the Jing-Jin-Ji Urban Agglomeration.
- Beijing, Tianjin and Shijiazhuang demonstrated different urban growth patterns.
- The composition of urban growth type varied with city and time.
- Landscape responses to urban expansion changed at different scales.
- A considerable regional disparity in urban expansion magnitude and speed was observed.

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ABSTRACT

Detailed comparative studies on spatiotemporal patterns of both urbanized area and urban expansion over a relatively long timeframe are rare. Here, we compared spatiotemporal patterns of urbanization in three major cities (i.e., Beijing, Tianjin and Shijiazhuang) in the Jing-Jin-Ji Urban Agglomeration using multi-temporal Landsat MSS, TM, and ETM+ images data of circa 1980, 1990, 1995, 2000, 2005 and 2010 integrated with Geographic Information System (GIS) techniques and landscape analysis approaches. A multi-scale analysis on the landscape responses to urban expansion from regional landscape to city and within city levels was performed. Results showed that urban area in Beijing, Tianjin and Shijiazhuang has expanded from 801 km^2, 795 km^2 and 682 km^2 to 2452 km^2, 3343 km^2 and 1699 km^2, increasing annually at 3.7%, 4.7% and 3.2%, respectively. Spatially, Beijing, Tianjin and Shijiazhuang have presented a mononuclear concentric polygon pattern, a double-nucleated polygon-line pattern, a sectorial point pattern, respectively, resulting primarily from their respective topographic constraints as well as urban planning and policy. Landscape responses to urban expansion varied with time and scale investigated, suggesting a general understanding on landscape metrics at regional or city level may fail to reveal detailed within city landscape dynamics under the impacts of urban expansion. The Jing-Jin-Ji Urban Agglomeration faces a great challenge to manage trades-offs between narrowing down intra-regional disparity and maintaining regional economic and ecological benefits.

1. Introduction

Unprecedented urbanization, characterized by demographic shift from rural to urbanized areas and urban land expansion, has taken place globally in the last several decades. The world urban population increased from 1.35 billion in 1970 to 3.63 billion in 2011, a 169% increase (UN, 2012). Urban land expansion has occurred more dramatically. Global urban area, which has quadrupled during 1970–2000 (Seto, Fragkias, Guneralp, & Reilly, 2011), is reported to grow on average twice as fast as urban population in recent years (Angel, Parent, Civco, & Blei, 2011) and expected to triple the global urban area in circa 2000 by 2030 (Seto, Güneralp, & Hutyra, 2012). As the most drastic form of land-use/land-cover change (Turner, Lambin, & Reenberg, 2007; Vitousek, Mooney, Lubchenco, & Melillo, 1997), urban expansion has affected ecosystem functioning and services at local to global scale (Bolund & Hunhammar, 1999; Grimm et al., 2008; McDonnell & Pickett, 1990; Zhao et al., 2006). Moreover, urban expansion is associated with socioeconomic problems such as congestion, urban unemployment and lack of public services (Bloom, Canning, & Fink, 2008). To

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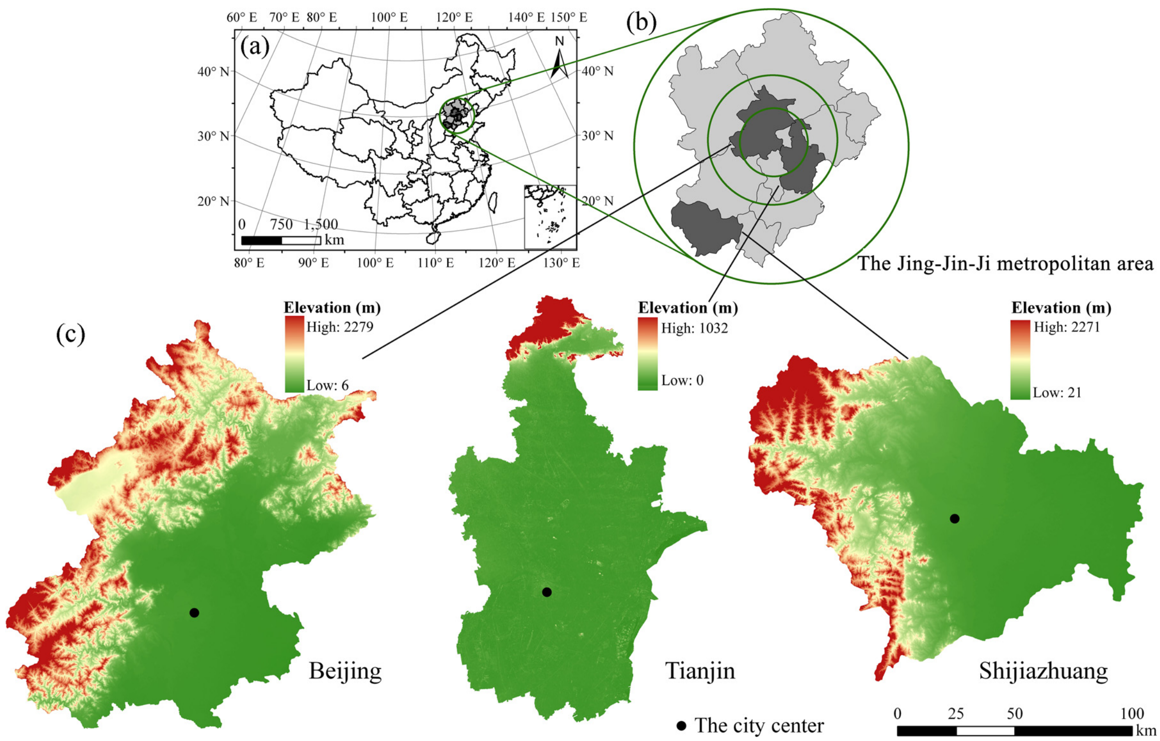

Fig. 1. The location and administrative division of the study area—Beijing, Tianjin and Shijiazhuang: (a) The study area in China, (b) The study area in the Jing-Jin-Ji metropolitan area, (c) Topography and the city center (the place of the the municipal government) of Beijing, Tianjin and Shijiazhuang.

date, while demographic urbanization has been well-documented, physical urbanization (i.e., urban land expansion) is relatively less understood, and comparative studies on urban expansion among different cities are limited (Huang, Lu, & Sellers, 2007; Schneider & Woodcock, 2008; Wu, Jenerette, Buyantuyev, & Redman, 2011). In fact, characterizing urban land expansion is the prerequisite to not only understand the urbanization process itself, its driving forces, and ecological consequences but also support optimal urban planning and management strategies (Wu & Hobbs, 2002).

Remote Sensing (RS) offers frequent and consistent data across large geographic areas and Geographical Information Systems (GIS) provide spatial data analysis functions (Blaschke, Hay, Weng, & Resch, 2011), which have made spatially explicit detection on urban expansion more convenient and accurate (Chen, Zeng, & Xie, 2000). The development of landscape ecology in the past few decades has arguably provided a new perspective for urban expansion study (Berling-Wolff & Wu, 2004; Shi, Sun, Zhu, Li, & Mei, 2012). Landscape ecology approaches such as landscape metrics (Herold, Scepan, & Clarke, 2002; Weng, 2007), patch dynamics (Pickett & Rogers, 1997), and gradient analysis (Ji, Ma, Twibell, & Underhill, 2006; Luck & Wu, 2002) can help characterize the spatiotemporal patterns and dynamics of urban expansion. With increased availability of satellite RS data and rapid development of GIS and landscape ecology approaches, many studies have been conducted to quantify urban expansion in various cities around the world (Seto et al., 2011; Solon, 2009).

As the world's most populous country, China has been experiencing a remarkable urbanization process since the initialization of the reform and opening up policy in the late 1970s (Normile, 2008). From 1978 to 2011, urban area in China has expanded six times and the number of cities has grown from 193 to 657 (NBSC, 2012; The World Bank, 2012). The three largest urban agglomerations (i.e., the Yangtze River Delta, the Pearl River Delta and the Jing-Jin-Ji) have pioneered the nation in urbanization processes. Although many studies can be found focusing on urban expansion in the Yangtze River Delta (Tian, Jiang, Yang, & Zhang, 2011; Xu, Liu, & Zhang, 2007; Yue, Liu, & Fan, 2013) and the Pearl River Delta (Lv, Dai, & Sun, 2012; Seto & Kaufmann, 2003; Sun, Wu, Lv, Yao, & Wei, 2013), few were on the Jing-Jin-Ji Urban Agglomeration (He, Tian, Shi, & Hu, 2011; Tan, Li, Xie, & Lu, 2005; Xiao et al., 2006). Particularly, cross-city comparative studies employing spatially explicit and consistent data sets, especially with high temporal frequency of snapshots of urban conditions over long time periods, and landscape ecology approaches are sorely lacking in the region. The Jing-Jin-Ji Urban Agglomeration is located at the edge of China's ecologically fragile environment and faces the most serious problems of water resource shortage (Jiang, Zhuang, Xu, & Lei, 2008) as well as dust and smog weather (Wu, Zhao, Zheng, & Lu, 2012). In particular, the "7.21" torrential rain disaster in 2012 and the continuous severe pollution weather in December of 2013 profoundly exposed the problems of urban development and planning, highlighting the necessity of a clear understanding on urban expansion in this Urban Agglomeration (Zhou, 2012).

In this study, we quantified and compared spatiotemporal patterns of urbanized area and urban expansion in three main cities (i.e., Beijing, Tianjin and Shijiazhuang) in the Jing-Jin-Ji Urban Agglomeration over the past three decades covering six periods (i.e., circa 1980, 1990, 1995, 2000, 2005 and 2010) using multi-temporal Landsat RS data integrated with GIS techniques and landscape ecology approaches. The objectives of this study were to (1) dynamically map locations and extents of urban land, (2) quantify spatiotemporal patterns of urban expansion, and (3) compare similarities and differences of general trends of urbanization, spatially explicit urban growth patterns, and temporal change of landscape metrics at regional landscape, city and within city scales.

2. Data and methods

2.1. Study area

The Jing-Jin-Ji Urban Agglomeration, located in the eastern part of the North China Plain, belongs to the Bohai Rim and consists of

Table 1
Basic geographic and socioeconomic information for three main cities in the Jing-Jin-Ji Urban Agglomeration.

	Beijing	Tianjin	Shijiazhuang
Latitude (N)	39°28′–41°05′	38°34′–40°15′	37°27′–38°47′
Longitude (E)	115°24′–117°30′	116°43′–118°04′	113°30′–115°20′
Elevation (m)	6–2279	0–1032	21–2271
Area (km^2)	16,400	11,632	14,065
Population (Million)[a]	19.6	12.9	10.2
GDP (Billion RMB)[a]	1411.4	922.4	340.1

[a] From NBSC (2011). 1 RMB approximately equals 0.16 US Dollar.

Table 2
RS data used in this study.

Periods	Beijing		Tianjin		Shijiazhuang	
	Path/row	Date	Path/row	Date	Path/row	Date
1980	133/32	1978.9.20	132/32	1979.9.4	133/33	1981.7.21
	132/32	1980.8.21	132/33	1979.9.4	133/34	1981.8.8
					134/33	1981.7.22
1990	123/32	1989.10.1	122/32	1988.10.7	124/33	1989.2.2
	123/33	1989.10.1	122/33	1988.7.3	124/34	1989.2.2
1995	123/32	1995.9.16	122/32	1995.11.12	124/33	1994.7.2
	123/33	1995.12.5	122/33	1995.11.12	124/34	1995.7.5
2000	123/32	2000.8.20	122/32	2000.5.25	124/33	2000.5.7
	123/33	2000.8.20	122/33	2000.5.25	124/34	2000.5.7
2005	123/32	2005.7.25	122/32	2005.8.27	124/33	2005.6.22
	123/33	2005.7.25	122/33	2005.10.14	124/34	2005.6.22
			123/32	2005.9.3		
2010	123/32	2010.8.8	122/32	2010.10.28	124/33	2010.7.6
	123/33	2010.8.8	122/33	2010.9.10	124/34	2010.7.6
	124/32	2010.8.15	123/32	2010.11.4		

10 cities (Fig. 1a and b). Our study areas are three main cities of the Jing-Jin-Ji Urban Agglomeration – Beijing, Tianjin and Shijiazhuang (Fig. 1c). Beijing and Tianjin are two municipalities under direct administration of the Central Government, both surrounded by Hebei province. Beijing, with a city history of more than 3000 years and a capital history of more than 800 years, is the capital of contemporary China as well as the political and cultural center of the whole country. City shape and patterns have therefore abundant historical flavors. Tianjin, bordering Beijing to the northwest and Bohai Sea to the southeast, is the largest open port city and economic center in the northern China. In 2009, three coastal districts (i.e., Hangu, Tanggu and Dagang) of Tianjin formed into Binhai New Area, which is considered as the third pole of Chinese economic development (Li, 2008). Shijiazhuang, as the political, economic and cultural center of Hebei province, is the provincial capital nearest to China's capital (within 300 km to the southwest of Beijing). Table 1 lists the basic geographic and socioeconomic information for these three main cities in the Jing-Jin-Ji Urban Agglomeration.

2.2. Remote sensing data and data processing

We used Landsat images obtained from the USGS website (http://www.usgs.gov/, accessed December 22, 2012) as the main source of data to acquire the long term land cover information of the study area, which covered six time periods (circa 1980, 1990, 1995, 2000, 2005, and 2010). Cloud-free Multispectral Scanner (MSS) satellite images (bands 1–4) before 1985 have a resolution of 60 m by 60 m and cloud-free Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM+) satellite images (bands 1–5 and 7) after 1985 have a resolution of 30 m by 30 m. The path/row numbers and acquisition dates of images used in this study are listed in Table 2.

Data processing (e.g., band combination, image mosaic, re-projection and image enhancement) was accomplished using professional image processing software ERDAS Imagine version 9.1 and ArcGIS version 9.3. Four broad land cover types (i.e., urban land, natural cover, cropland, and water body) were classified based on these images using the maximum likelihood method (Strahler, 1980). We further merged the other three types as non-urban area after classification because the urban land was the focus of our study (Fig. 2). The MSS classifications were resampled to a resolution of 30 m × 30 m to keep consistent with that of TM. Accuracies of the classified products as measured by the Kappa coefficients were assessed according to the method proposed by Zhou, Zhao, and Zhu (2012). Specifically, spot images (acquired in 2010) in Google Earth Pro® were used to validate the classification results of 2010 and those before 2010 only in the areas land cover remained unchanged from 1978 to 2010. Results showed that the overall Kappa coefficients were more than 0.80 for all cities (Table 3), which met the accuracy requirement of land cover change evaluation (Foody, 2002).

2.3. Analyses on urban land change for six time periods

2.3.1. Landscape metrics

We chose six class-level landscape metrics to characterize landscape changes under the impact of urbanization: Percentage of Landscape (PLAND), Largest Patch Index (LPI), Landscape Shape Index (LSI), Number of Patches (NP), Patch Density (PD), and Mean Patch Size (MPS) (Table 4). These metrics are relevant to the objectives of our study and not redundant (Riitters et al., 1995; Wu et al., 2011). The values of the metrics were calculated using FRAGSTATS version 3.3 with the eight-neighbor rule (McGarigal & Marks, 1995).

To examine detailed spatial patterns of landscape changes, we further analyzed within-city landscape metrics in different

Table 3
Summary of accuracy assessment for image classification using Kappa coefficients.

	Beijing	Tianjin	Shijiazhuang
Prior to 2010	0.87	0.87	0.93
2010	0.80	0.83	0.85

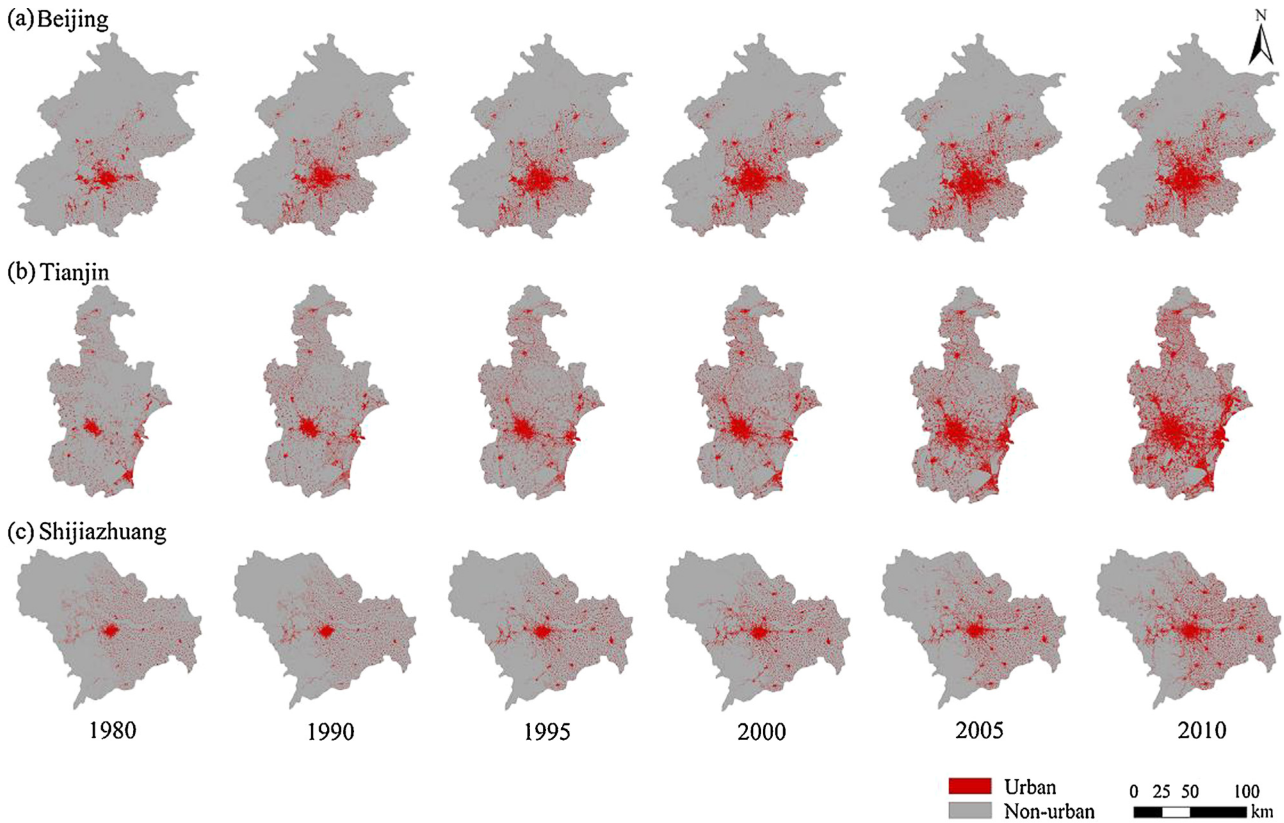

Fig. 2. Change of spatial extent of urban areas in Beijing (a), Tianjin (b) and Shijiazhuang (c) from 1980 to 2010.

directions and along urban-rural gradient of each city. We first assumed the place of the municipal government as the city center of each city (Fig. 1c). North-South and East-West transects cutting across the city center were used to divide each city into four sectors: the northeast (NE), the southeast (SE), the southwest (SW) and the northwest (NW), and landscape metrics in each sector were then calculated to reflect landscape characteristics in different directions. Finally, a series of buffer rings with distances of 5 km were generated from the city center, and the landscape metrics between each two buffer rings from the centers to the edges of three cities were calculated to quantify the landscape patterns along urban-rural gradient.

2.3.2. Patch size frequency analysis

To investigate the detailed size composition of urban patches, the frequency distributions of total area and number of patches for urban land according to 13 patch 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) were generated.

2.4. Analyses on urban expansion for five neighboring periods

2.4.1. Annual increase (AI) and annual growth rate (AGR) of urban land

We calculated two indexes – AI and AGR of urban land – to quantify the magnitude of urban expansion. The former directly measures annual changes of urban areas and is effective for comparison of urban expansion for the same city over different periods, while the latter eliminates the size effect of cities and is more appropriate for comparison of urban expansion for different cities in the same period. The two indexes were defined as follows:

$$\mathrm{AI} = \frac{A_{end} - A_{start}}{d} \quad (1)$$

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

where AI (km^2 per year) and AGR (%) are the annual growth extent and the annual growth rate of urban land respectively, A_{start} and A_{end} are the extent of the urban area at the start and end period respectively, and d is the time span of the study in years.

Table 4
Landscape metrics used in this study adopted from McGarigal and Marks (1995) and Luck and Wu (2002).

	Acronym	Name of landscape metric (units)	Description
Area metrics	PLAND	Percentage of landscape (%)	The percentage of the total landscape made up of the corresponding class
	LPI	Largest patch index (%)	The proportion of total area occupied by the largest patch of a patch type
Shape metrics	LSI	Landscape shape index	The landscape boundary and total edge within the landscape divided by the total area, adjusted by a constant for a square standard
Density metrics	NP	Number of patches	Total number of patches for each individual class
	PD	Patch density (Number/100 ha)	The number of patches of per 100 ha
	MPS	Mean patch size (ha)	Average patch size

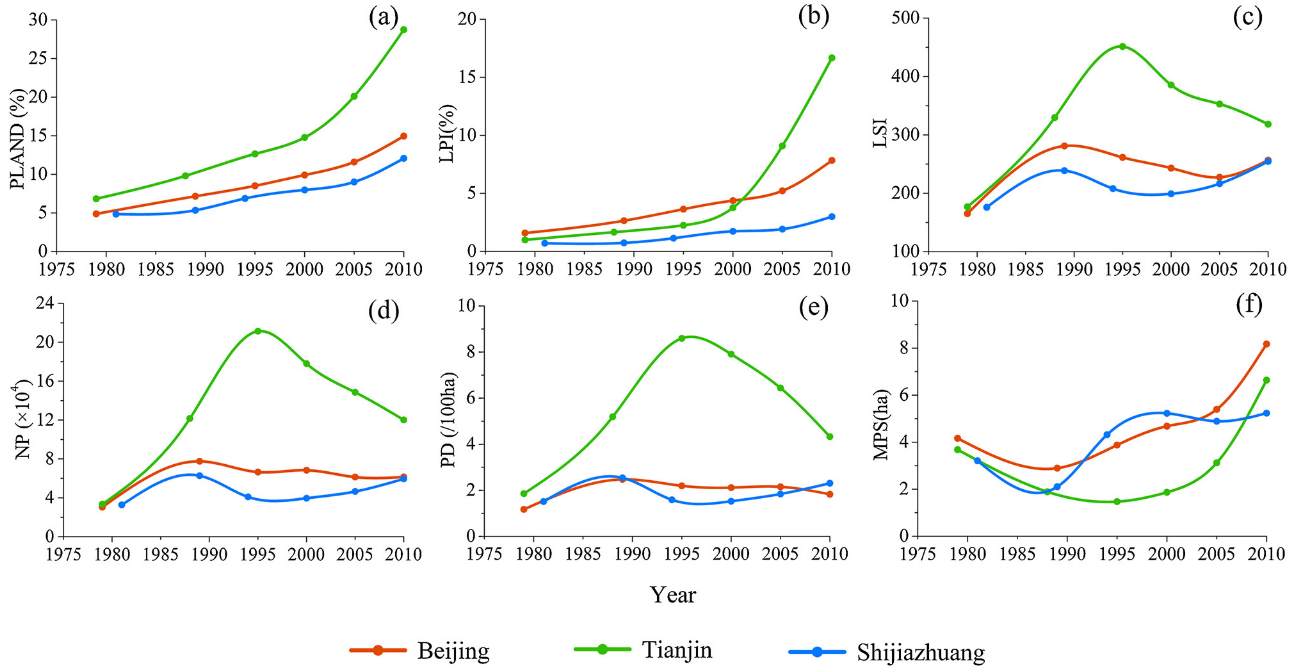

Fig. 3. Landscape metrics for the urban land of Beijing, Tianjin and Shijiazhuang from 1980 to 2010: (a) PLAND (%), (b) LPI (%), (c) LSI, (d) NP ($\times 10^4$), (e) PD (per 100 ha) and (f) MPS (ha).

2.4.2. Urban growth types

Urban growth was divided by Forman (1995) into three types: infilling, edge-expansion and outlying. Urban Growth Type Index (GTI) was calculated to define these three urban growth types using the following equation according to Xu et al. (2007):

$$GTI = \frac{L_{com}}{P_{new}} \quad (3)$$

where P_{new} represents the perimeter of a newly developed urban patch, L_{com} is the length of common edge of this newly developed urban patch and existing urban patch or patches, and GTI is urban growth type index, ranging from 0 to 1. Urban growth type is defined as infilling, edge-expansion and outlying when GTI > 0.5, 0 < GTI ≤ 0.5, GTI = 0, respectively.

3. Results

3.1. Urban land change for six time periods

Over the past three decades, Beijing, Tianjin and Shijiazhuang all have undergone rapid urbanization (Fig. 2), which can be seen from the continuous expansion of their urban land. Specifically, Beijing has witnessed its urban land expanding almost in every direction from the original urban core, presenting a mononuclear polygon urbanization pattern (Fig. 2a). Besides the expansion of its original urban core in Tianjin, a secondary nuclear rudiment took initial shape in the southeast coast in 1995 and then gradually combined with the original urban core into a line, forming a double-nucleated polygon-line urbanization pattern (Fig. 2b). The urban land of Shijiazhuang concentrated in the east of the city with many small growth points scattering centrifugally out of the urban core, representing a point urbanization pattern (Fig. 2c).

Fig. 3 demonstrates the features and trends of urban landscape change for three cities over the past three decades. As urbanization proceeded, PLAND and LPI showed a monotonic increasing trajectory for all three cities with a much steeper trend for Tianjin than that of Beijing and Shijiazhuang (Fig. 3a, b). The urban area percentage increased from 4.9% to 15.0% for Beijing, 6.8% to 28.7% for Tianjin, and 4.8% to 12.1% for Shijiazhuang (Fig. 3a). The LPI of Tianjin had rose sharply since 2000 and stood out since 2005 because of the combination of two nuclei (Fig. 3b). Fragmentation and complexity of landscape in Beijing and Tianjin increased first and then decreased, as indicated by the bell-shaped patterns of LSI, NP and PD, and the peak occurred in 1990 for Beijing and in 1995 for Tianjin, respectively. However, the LSI, NP and PD of Shijiazhuang increased before 1990, followed by a decline from 1990 to 2000, and then increased again afterwards (Fig. 3c–e). Temporal patterns of MPS for three cities were generally opposite to those of NP (Fig. 3f), suggesting a more intense impact of NP on MPS than that of PLAND in our study area given MPS was determined by both PLAND and NP.

To further understand the detailed spatial patterns of the landscape within-city, we charted landscape metrics in different directions (Fig. 4) and at different distances from city centers of each city (Fig. 5). To avoid redundancy, only two metrics were presented: PLAND to represent urban area proportion and PD to represent landscape fragmentation. PLAND increased over time for all directions of the three cities, with the largest urban percentage in the SE sector of both Beijing and Tianjin, and in the east sector of Shijiazhuang (Fig. 4a). PD increased first and then decreased for all directions of the three cities, but there were some distinct features for different cities (Fig. 4b). Specifically, for Beijing, PD increased before 1990 and decreased afterwards for all directions. For Tianjin, the largest PD changed from SE to NW with 1995 as the dividing line, suggesting the aggregating urban expansion trend of Binhai New Area. For Shijiazhuang, the largest PD changed from SE in 1990 to NE in 2010, which resulted from the northward urbanization policy of the city in the early 21st century (Fan, 2008). Along with the distance to the city center, PLAND presented a truncation pattern for Beijing, and a trailing pattern for both Tianjin and Shijiazhuang (Fig. 5a), while PD presented a unimodal pattern for Beijing and Shijiazhuang, and a bimodal pattern for Tianjin (Fig. 5b). Specifically, for Beijing, PLAND decreased rapidly to zero from the city center to the periphery, urban area of the city center kept as high as over 93% over the past three decades, reflecting the mononuclear urbanization pattern. The unique peak of PD spread outwards over time but

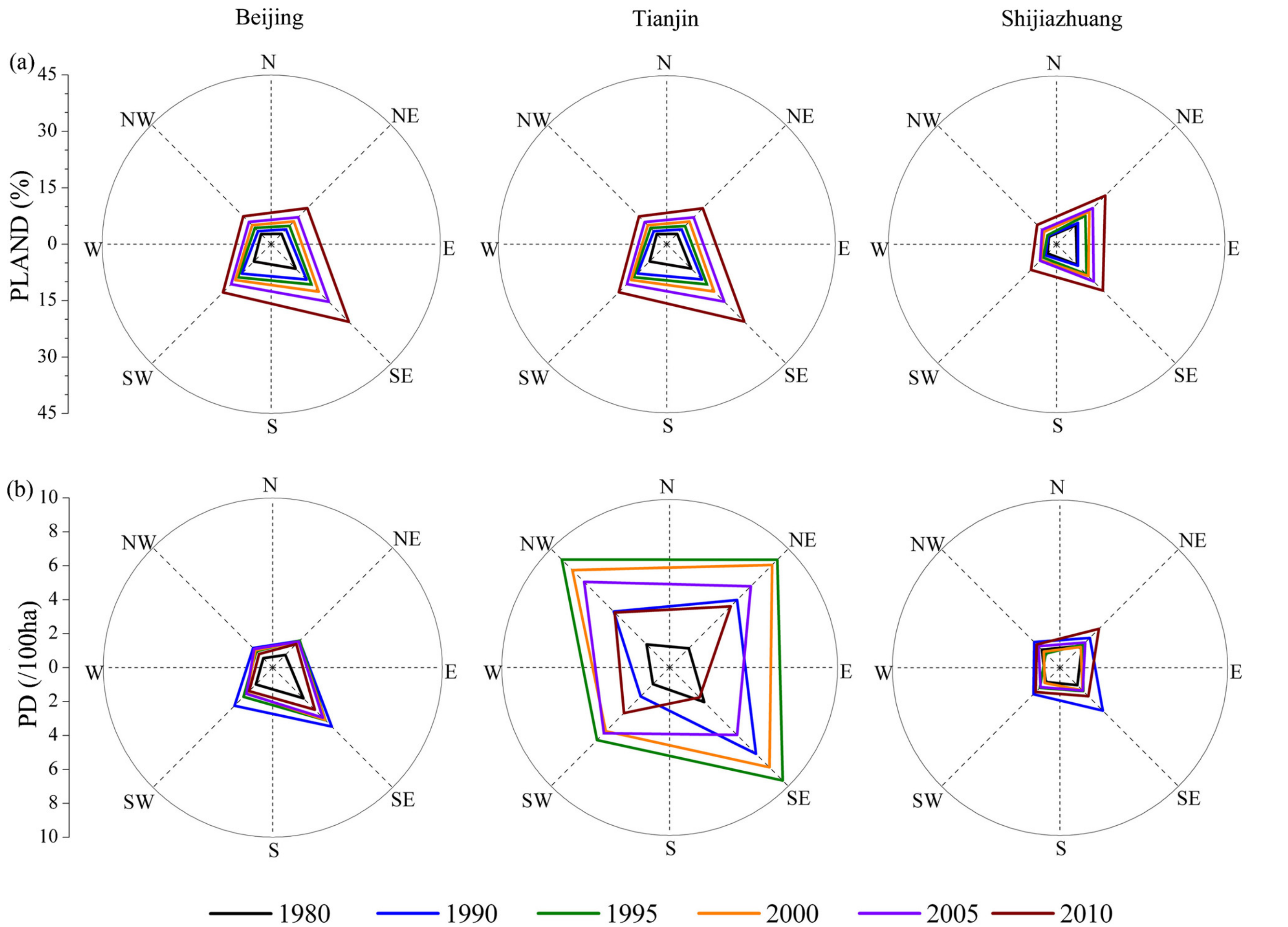

Fig. 4. Landscape metrics for the urban land of Beijing, Tianjin and Shijiazhuang in four sectors (NE, SE, SW and NW) from 1980 to 2010: (a) PLAND (%) and (b) PD (per 100 ha).

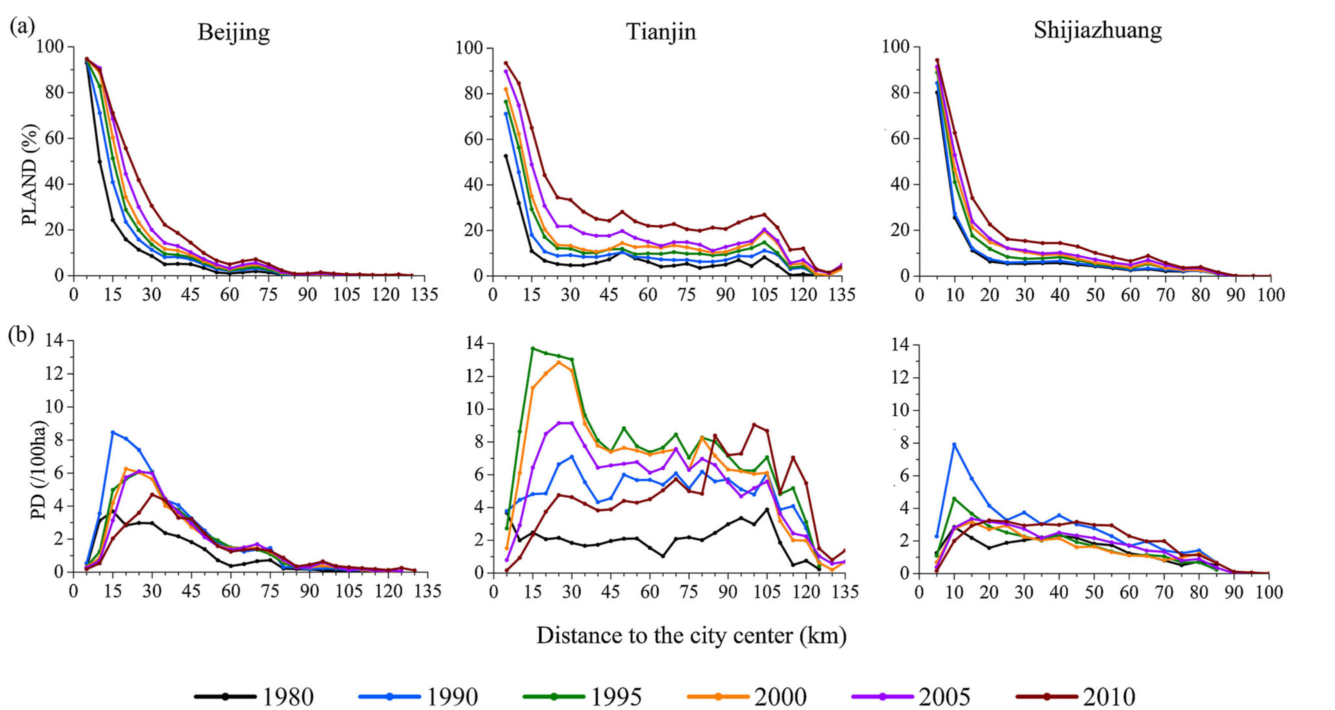

Fig. 5. Landscape metrics for the urban land of Beijing, Tianjin and Shijiazhuang at different distances (km) from the city center from 1980 to 2010: (a) PLAND (%) and (b) PD (per 100 ha).

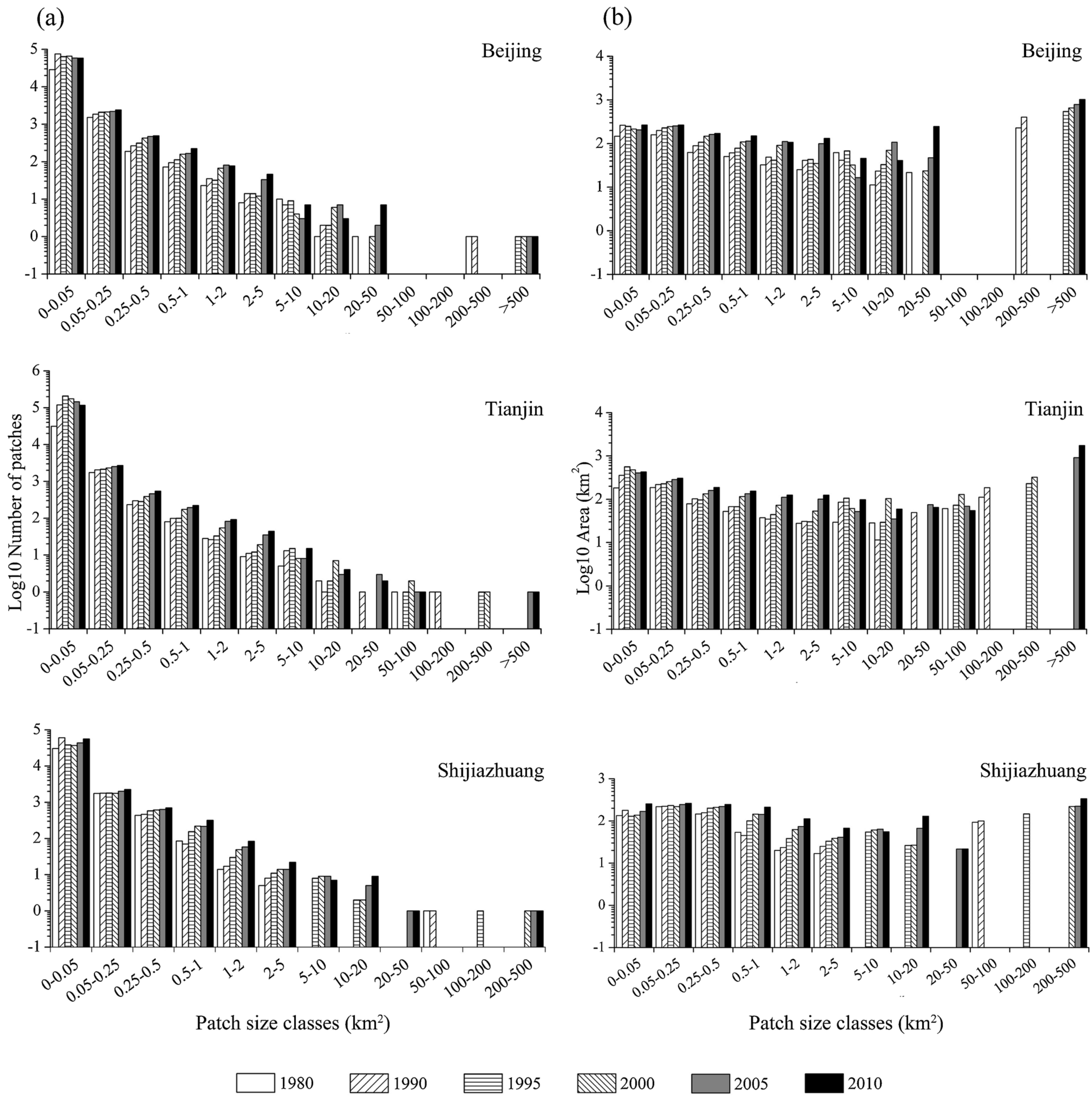

Fig. 6. Frequency distribution of the number of patches (a) and total area (b) of urban land according to 13 patch size classes for three cities from 1980 to 2010.

kept between 10 and 30 km from the city center. PD increased for almost all the distances from 1980 to 1990 but decreased significantly for the area near the center after 1990, implying the decrease of landscape fragmentation of existing built-up area. For Tianjin, PLAND decreased with distance to the city center within 25 km, kept relatively stable from 25 to 105 km and increased again at about 105 km, showing a double-nucleated pattern. The area with the largest increase of urban land changed from the city center (1980–1990) to Binhai New Area (1990–2005) and then to the intermediate zone between them (2005–2010). The outwards moving of the peak of PD from 10–40 km where the old city-center located to 80–120 km where Binhai New Area distributed, indicating a more highly fragmented landscape of Binhai New Area over time. For Shijiazhuang, PLAND decreased along with distance rapidly within 20 km but slowly at 20–90 km, where many small growth points were located, corroborating the point urbanization pattern. The peak of PD occurred at about 10–20 km to the city center constantly over time.

More micro-level analysis on patch composition and configuration was provided in the frequency distributions of total area and number of patches of urban land according to 13 patch size classes for three cities over various time periods (Fig. 6). Overall, the number of patches decreased as the patch size increased for all three cities across the entire study period (Fig. 6a), while the total areas of small and large patches were larger than that of medium patches, showing a U-shaped pattern along with patch size classes (Fig. 6b). However, there were differences in the evolution of number and total area for a given patch size class among three cities. Small patches can characterize patterns of new urban growing points. An evident increase in both the number and total area of patches with size smaller than 0.05 km^2 over time was observed only in Shijiazhuang, corroborating its point urbanization pattern. The largest

Table 5
Annual increase (AI) in urban area (km^2) and normalized annual urban growth rate (AGR) (%) for three cities among five neighboring periods from 1980 to 2010.

		1980–1990	1990–1995	1995–2000	2000–2005	2005–2010	Average
AI (km^2)	Beijing	37.3	36.9	45.9	55.7	109.7	53.2
	Tianjin	38.4	47.2	49.7	124.1	200.8	82.2
	Shijiazhuang	8.7	42.7	26.0	29.1	86.4	35.0
AGR (%)	Beijing	3.9	2.9	3.1	3.2	5.2	3.7
	Tianjin	4.1	3.7	3.2	6.4	7.4	4.7
	Shijiazhuang	1.2	5.1	2.5	2.5	6.0	3.2

urban patch can to a certain extent reflect dynamics of the urban core. For example, the largest urban patch in Beijing expanded from 200–500 km^2 during 1980–1990 to a scale of over 500 km^2 since 1995 and over 1000 km^2 in 2010 when the four historical center districts and three suburban districts were combined together. Its second largest patch, however, has been smaller than 50 km^2 over the past three decades, suggesting a mononuclear urbanization pattern. For Tianjin, its original urban core, as the largest urban patch, has expanded from 100–200 km^2 during 1980–1990 to 200–500 km^2 during 1995–2000, and the second and the third largest patches (Binhai New Area) have continually expanded and combined with the largest urban patch in 2005, making the largest urban patch amounted to more than 500 km^2 since 2005, signifying its double-nucleated polygon-line urbanization pattern. For Shijiazhuang, the largest urban patch expanded from 50–100 km^2 during 1980–1990 to over 200 km^2 since 2000, implying that large patches were polymerizing small patches to enlarge themselves.

3.2. Urban expansion for five neighboring periods

The magnitude of urban expansion revealed by AI (km^2) and normalized AGR (%) for three cities among five neighboring periods from 1980 to 2010 are listed in Table 5. The largest AI occurred during 2005–2010 for all three cities, and the smallest AI was during 1990–1995 for Beijing and 1980–1990 for Tianjin and Shijiazhuang. After removing the effect of city size, Beijing, Tianjin and Shijiazhuang had an average AGR of 3.7%, 4.7% and 3.2%, ranging from 2.9% to 5.2%, 3.2% to 6.4%, and 1.2% to 6.0%, respectively.

Fig. 7 illustrates the spatiotemporal distributions of urban expansion for three cities over the past three decades. Beijing expanded nearly all around its initial urban core, forming a mononuclear concentric rings model. It is noteworthy that some satellite towns occurred during 1980–1990 as a result of the urbanization of rural area in Beijing (Fig. 7a). For Tianjin, a considerable growth point appeared in the southeast coast during 1990–1995 which was the rudiment of Binhai New Area. Binhai New Area took shape during 1995–2000 and thereafter acted as a secondary nuclear and promoted urbanization between the original urban core and the coastal area, forming a double-nucleated model (Fig. 7b). For Shijiazhuang, urban expansion generally developed toward the east as a sectorial pattern. The development of new growth points away from the urban core was observed during both 1980–1990 and 1990–2000. Its urban expansion occurred more aggregately around the urban core since 2000, with a shift in direction from the southeast during 2000–2005 to the northeast during 2005–2010 (Fig. 7c).

Three urban growth types (i.e., infilling, outlying and edge-expansion) were identified for the newly developed urban area to reflect the detailed spatial distributions of urban expansion (Fig. 8). In Beijing, outlying growth was distributed sparsely at outskirts, edge-expansion growth occurred next to the periphery of existing urban land, and infilling growth filled the gaps between them. Both edge-expansion and infilling growth expanded outwards over time, corroborating its layer structure. For Tianjin, outlying growth was more extensive, reaching as far as the entire city, edge-expansion growth appeared mainly around the original urban core during 1980–1990 and in the southeast coast afterwards, and infilling

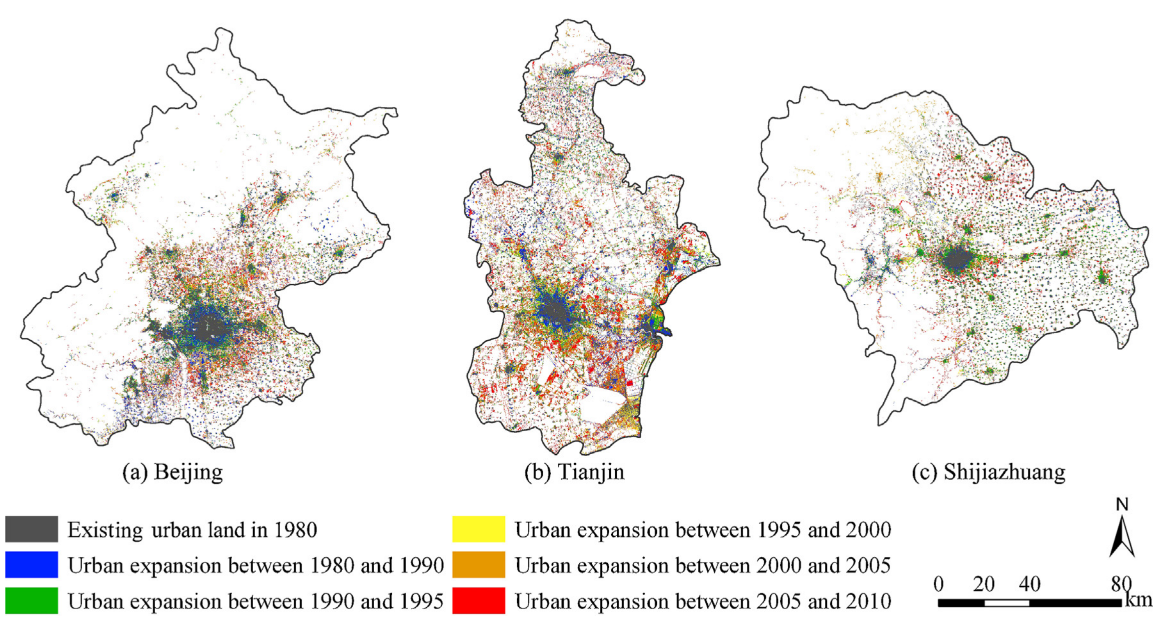

Fig. 7. Spatial distributions of urban expansion for Beijing, Tianjin and Shijiazhuang among five neighboring periods from 1980 to 2010.

growth, adhering to the existing urban land and edge-expansion growth, played an important role in linking the original urban core and Binhai New Area, especially during 2005–2010. For Shijiazhuang, outlying growth occurred mostly in the east of the city during 1980–1990 to form new growth points. Edge-expansion and infilling growth enlarged these points during 1990–2000, thus developing into a point urbanization pattern. However, from 2000 to 2010, edge-expansion and infilling growth was mainly distributed around the urban core with a tendency moving northward.

The compositions of three urban growth types during two neighboring periods over the past three decades for all three cities are presented in Fig. 9. Both number proportion (Fig. 9a) and area proportion (Fig. 9b) of patches changed with some similarity for the three cities: outlying growth experienced a process of decrease and infilling growth increased during the study period. Edge-expansion, however, remained relatively stable. The three cities also exhibited discrepancy in the compositions of urban growth types. In terms of the number of patches, infilling growth was always the primary type for Shijiazhuang, however, infilling surpassed outlying in number of patches in 1990 and 1995 for Beijing and Tianjin, respectively. This suggested that urban expansion of Beijing and Tianjin reached more area away from existing urban land in the early stage of urbanization. In respect of the area proportion, edge-expansion contributed the largest for all three cities during the entire study period except the period 1990–1995 for Tianjin. It should be noted that infilling growth in Shijiazhuang accounted for the largest proportion of the number of patches (over 45.4%) while limited proportion in the area (less than 0.35%), which corroborated the point urbanization of Shijiazhuang.

4. Discussions

4.1. Comparisons in the magnitude of urban expansion among three cities

Beijing, Tianjin and Shijiazhuang have all experienced dramatic urban expansion over the past three decades. From 1980 to 2010, their urban lands showed a 2.1 times, 3.2 times and 1.5 times increase in area. The magnitude of urban expansion ranking as Tianjin, Beijing, and Shijiazhuang from high to low might be related to their differences in physical context. First, physical factors such as elevation and slope are basic constraints to urban expansion. Lower elevation and smaller slope were generally associated with higher urban expansion. The general observation shown in the three cities as the elevation of newly developed urban land ranged between 7–1370 m (averaged 75.0 m with a slope of 1.4°), 0–588 m (averaged 9.1 m with a slope of 1.0°) and 23–1472 m (averaged 104.4 m with a slope of 1.6°) for Beijing, Tianjin and Shijiazhuang, respectively, agreed with the ordering of urban expansion magnitude. Second, coastal location created good development opportunity for Tianjin, including preferential policy for Binhai New Area, convenient marine transport and massive foreign directional investment (FDI) (Gu & Liu, 2012). Conversely, the physical location near Beijing imposed negative "shadow effect" on Shijiazhuang, just as a larger tree canopy deprives smaller trees and undergrowth of access to sunlight (Evans, 1985). Beijing's unique political privilege as the capital of China induced multi-source industries and resources to overwhelmingly locate themselves in it rather than in neighboring cities and thus facilitated its urban expansion.

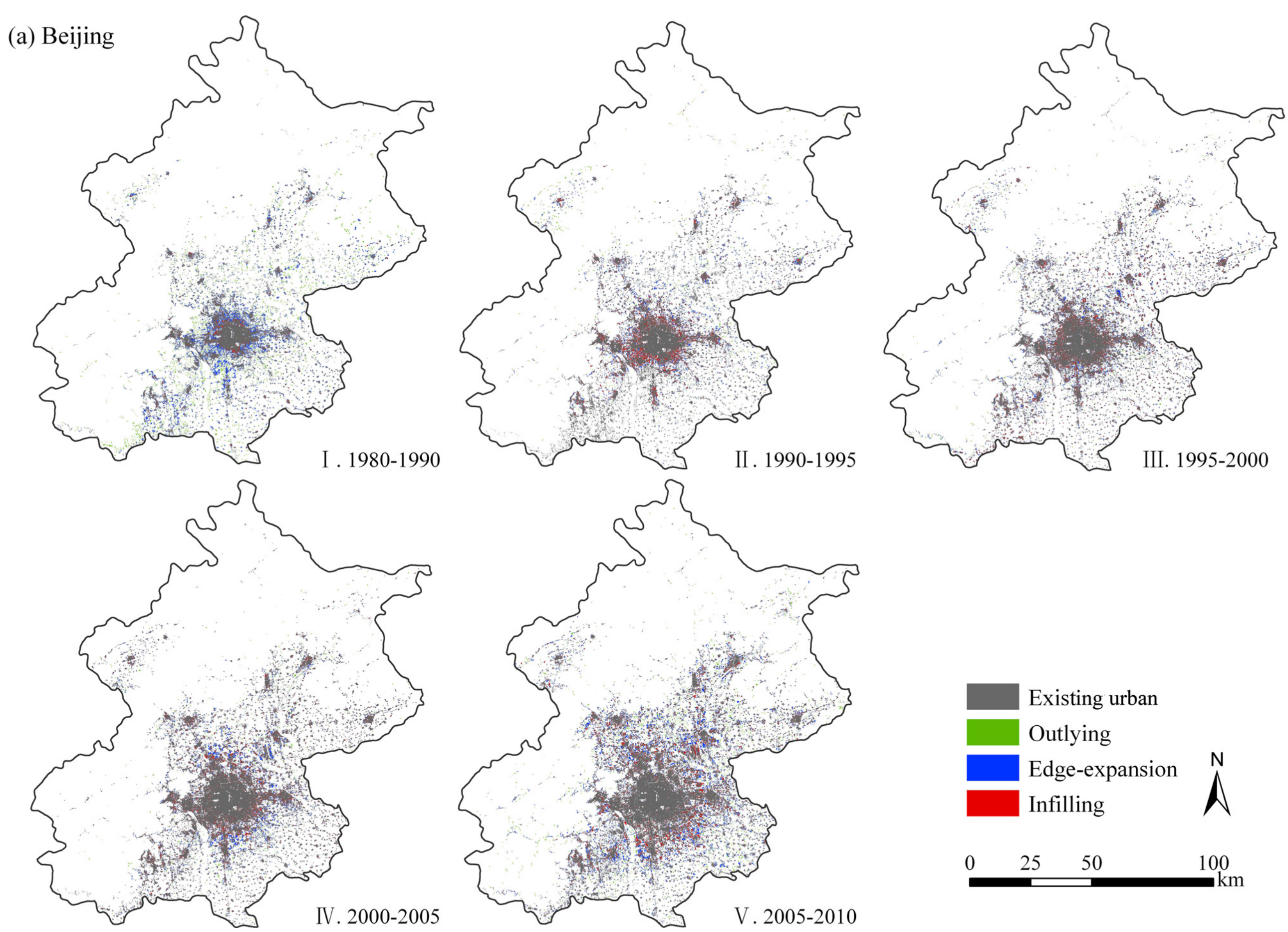

Fig. 8. Spatial distributions of three urban expansion types for Beijing (a), Tianjin (b) and Shijiazhuang (c) among five neighboring periods from 1980 to 2010.

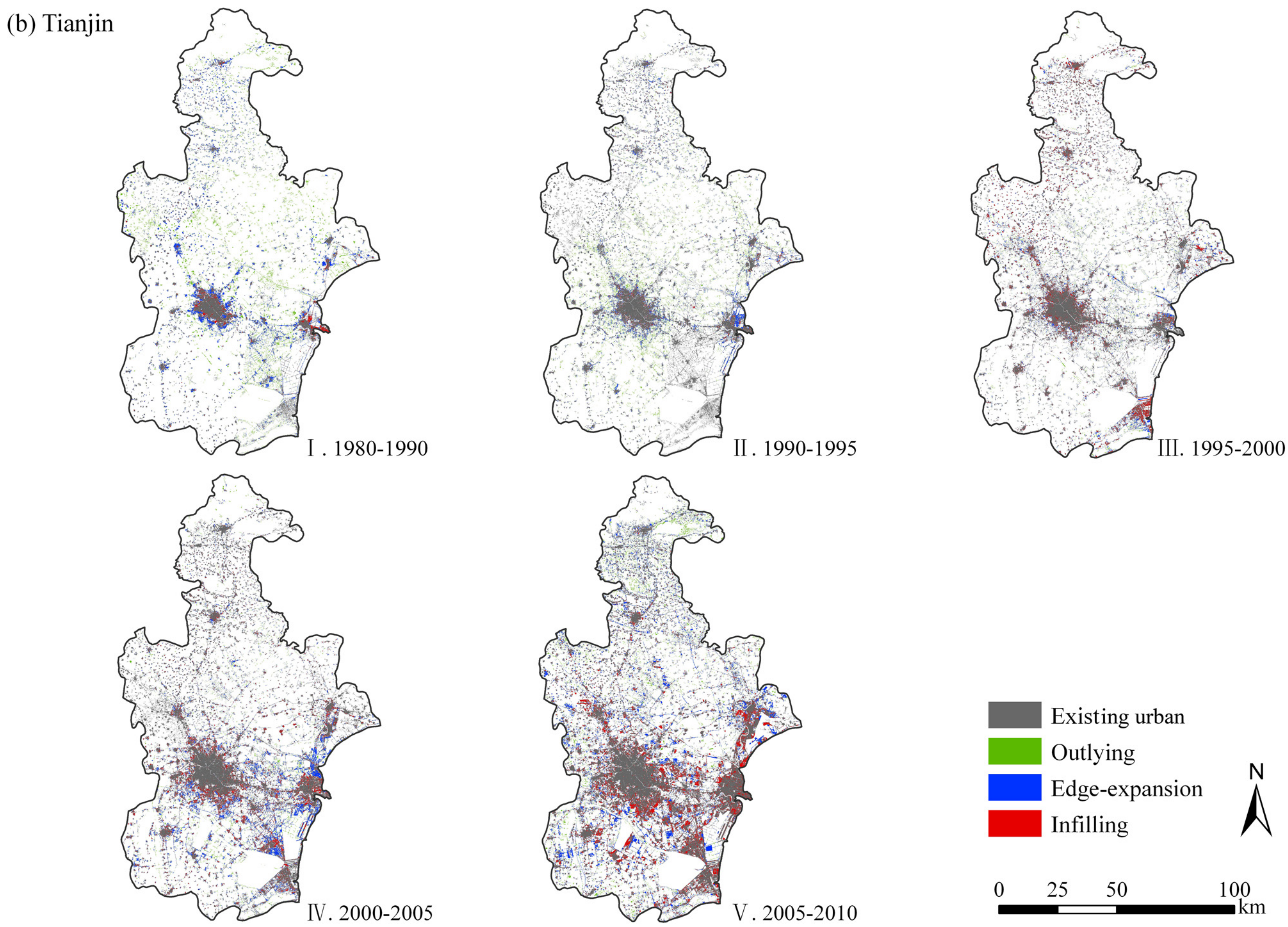

Fig. 8. (*Continued*)

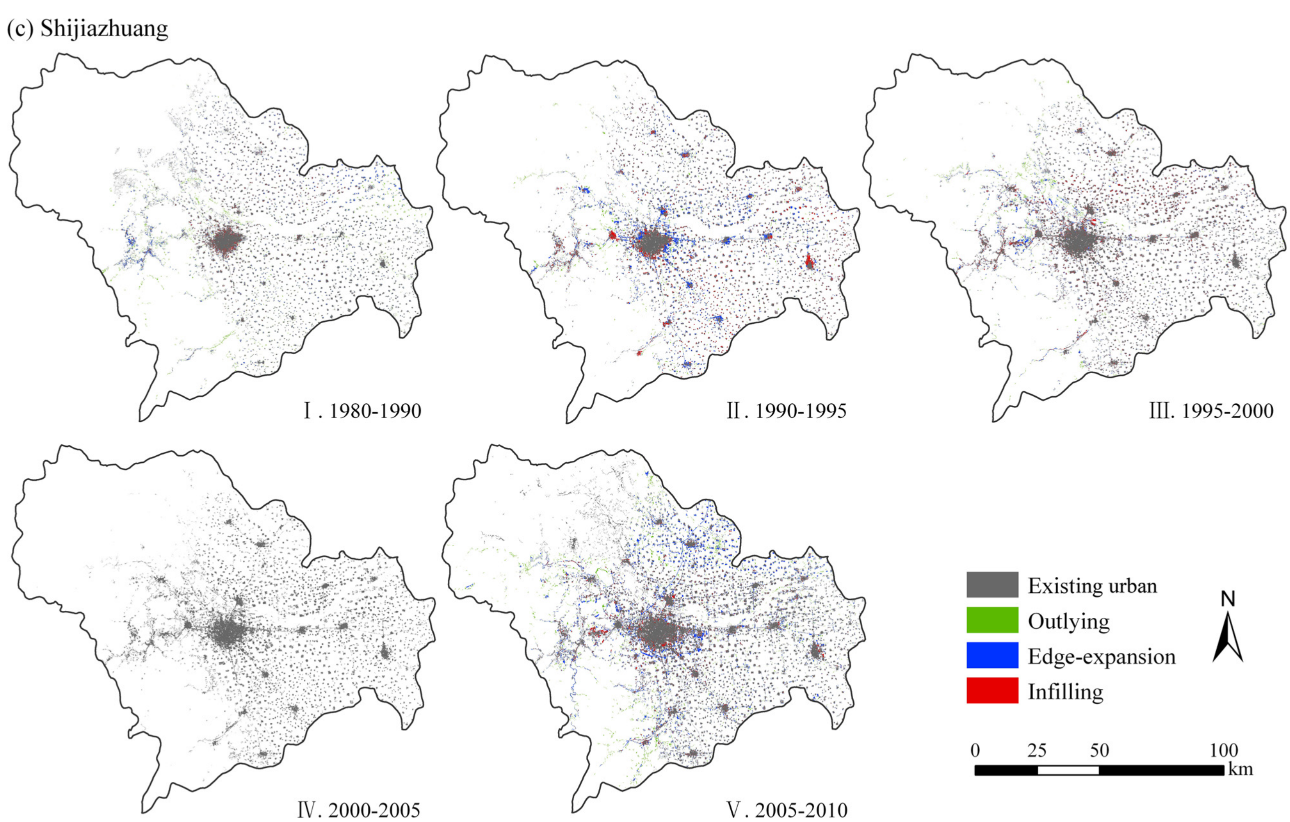

Fig. 8. (*Continued*)

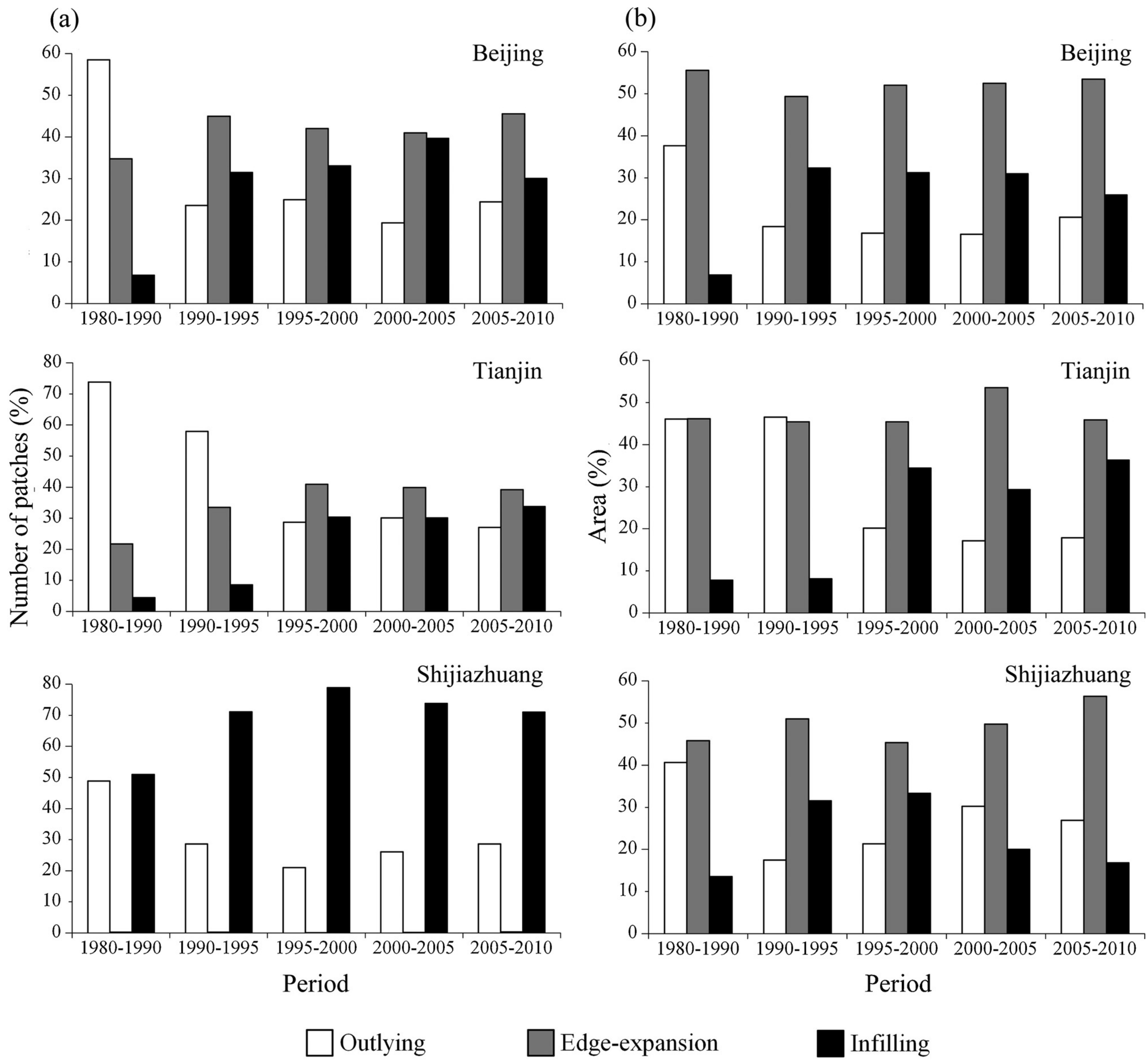

Fig. 9. The composition (%) of three urban expansion types for the number of patches (a) and area (b) of newly developed urban patches in Beijing, Tianjin and Shijiazhuang among five neighboring periods from 1980 to 2010.

Moreover, with harder political restrictions, cities located in Beijing's "shadow" had lower opening-up level than those away from the capital (Sun, Zhang, Hu, Zhou, & Yu, 2013). The Asian Development Bank (ADB) even named part of the Jing-Jin-Ji Urban Agglomeration as "the poverty belt around Beijing-Tianjin" (ADB & Hebei Provincial Finance Bureau, 2004).

However, it should be noted that AGR of Shijiazhuang exceeded Beijing during 2005–2010, which might be related to the policy of industrial transfer out of Beijing. To safeguard the capital's ecological security, Beijing has transferred some high resource consumption and high pollution enterprises to Hebei Province in recent years (Duvivier & Xiong, 2013). Over 400 enterprises had been moved from Beijing to Heibei Province during 2001–2010. Industries transferred to Shijiazhuang spurred the construction of industrial parks and thus accelerated its point urbanization. At the same time, environmental problems in Shijiazhuang became more evident. The proportion of days with qualified air quality (i.e., equal to or above Grade II) in Shijiazhuang dropped from 88.3% in 2012 to 11.5% in 2013 while the proportion of days with heavily polluted air quality (i.e., Grade V) increased from zero in 2012 to 39.8% in 2013 (Ministry of Environmental Protection of China, 2013). Many studies have demonstrated that urban expansion has negative impact on the environment (Gurjar, Butler, Lawrence, & Lelieveld, 2008; Shao, Tang, Zhang, & Li, 2006), and the deterioration of air quality in Shijiazhuang corrobates these studies. It should be realized that environmental degradation of Shijiazhuang might have negative impacts on the sustainable development of not only Shijiazhuang itself but also the entire Jing-Jin-Ji Urban Agglomeration, and more studies on the environmental inter-connections among cities in the region should be conducted.

Therefore, it is a great challenge to manage trade-offs between narrowing down intra-regional disparity and maintaining regional economic and ecological benefits for the Jing-Jin-Ji Urban Agglomeration. Beijing and Tianjin stand out as distinct cities in the Jing-Jin-Ji Urban Agglomeration, other cities such as Shijiazhuang, however, played the roles of hinterland to provide resources and suffered from pollution. This model, which has hindered integrative development of the entire Jing-Jin-Ji region, is distinct from the other two Urban Agglomerations in China. The Yangtze River Delta Urban Agglomeration presents multiple interconnected centers (Suzhou, Hangzhou, Nanjing, Ningbo and Wuxi) besides the centrally placed Shanghai, which in turn encourages growth in neighboring cities/towns (Zhu & Zheng, 2012). For the Pearl River Delta Urban Agglomeration, although Guangzhou and Shenzhen are also the "double-nuclei", other cities all have a clear specialization of leading industry and traffic network among cities is well developed (Lv et al., 2012). In contrast, although Beijing, Tianjin and Shijiazhuang were all stimulated by the Regional Development of the Jing-Jin-Ji Urban Agglomeration and had a breakthrough during 2005–2010 in urban expansion (evidenced by striking rise of urban land in both area and rate), substantive regional integration is far from realization for this region. A holistic functional orientation and infrastructure construction would be an essential prerequisite for the regional development in a sustainable way, which need to be taken into account in the future urban planning of the Jing-Jin-Ji Urban Agglomeration.

4.2. Spatial comparisons for urban expansion among three cities

Urban growth pattern varied with city as Beijing, Tianjin and Shijiazhuang demonstrated a mononuclear polygon, a double-nucleated polygon-line, and a sectorial point urban expansion pattern, respectively. There were some detailed distinct characteristics in directions and hotspots of urban expansion within each city, which can be ascribed to the influence of topography as well as urban planning and policy. Beijing and Shijiazhuang suffered from the restriction of the Taihang Mountains in the west and the Yanshan Mountains in the north. Therefore, urban expansion of Beijing was mainly concentrated in the southeast of the city and urban expansion of Shijiazhuang presented an eastward sectorial urban expansion pattern. In the later stage of our study period, urban expansion patterns for all three cities were more closely related to urban planning and policy. This phenomenon is similar to the previous urban expansion studies in the Yangtze River Delta Urban Agglomeration (Tian et al., 2011; Yue et al., 2013) and the Pearl River Delta Urban Agglomeration (Sun et al., 2013). Urban Master Plan of Beijing (2004–2020) proposed the strategy of "developing to the south and the east" and appointed Tongzhou District as "the New Town of Beijing" (Tongzhou District Government of Beijing, 2008), as a consequence, the urban expansion in southeast part of Beijing became more intensive during the period 2005–2010. Urban Master Plan of Tianjin (2005–2020) stressed the importance of Binhai New Area as a principle urban development area besides the downtown (Xie, Xu, Duan, & Xu, 2012) and the administrative division adjustment of Tianjin in 2009 defined Binhai New Area as a new administrative district instead of Tanggu, Hangu and Dagang Districts (Binhai New Area government of Tianjin, 2010). These have further driven the urbanization of Binhai New Area and even the inland areas, leading urban expansion of Tianjin to a particular process along a corridor inland from coastal areas. Urban Master Plan of Shijiazhuang (2006–2020), which proposed the development strategy of "spanning to the north" in consideration of strengthening cooperation with Beijing and Tianjin, has resulted in its shift in urban expansion direction during 2005–2010 (Fan, 2008). In summary, for all three cities, the general extent of urban expansion was restricted by topography condition while the local patterns and dynamics of urban expansion were driven by urban planning and policy.

The dominant urban growth type has experienced a shifting from outlying to infilling for all three cities over time, which was consistent with the findings from the existing studies on cities in the Yangtze River Delta (Xu et al., 2007) and the Pearl River Delta (Sun et al., 2013). However, the turning points and driving forces differed among three cities. Beijing is the earliest to experience the shift. In the 1980s, Beijing witnessed an obvious increase of satellite towns distributed about 60–80 km from the city center since the Interim Provisions for Accelerating the Development of Satellite Towns in Beijing was promoted in 1984. However, since 1990, urban expansion of Beijing has shifted from outlying dominated to infilling dominated, depending largely on ring roads (Yang, Shen, Shen, & He, 2012). Outside "the old Beijing" (usually referring to the area inside the second ring), five main ring roads have been built (i.e., the third ring built in 1994, the forth ring built in 2001, the fifth ring built in 2003 and the sixth ring built in 2009); each of them has led to a new round of urban expansion, especially edge-expansion growth. Also, the flourish of Zhongguancun and Chaoyang Central Business District (CBD) after 1995 as well as the development of Olympics Parks after 2001 has fueled urban expansion of suburban area instead of scattered rural areas, forming a more compact urban form. The turning point from outlying to infilling for Tianjin was in 1995 when Master Plan of Binhai New Area was completed, resulting in a more compact urban expansion of this area. During 2005–2010, infilling growth occurred in the inlands between the original core and Binhai New Area, and consequently the urban morphology of whole Tianjin became more compact. Urban expansion of Shijiazhuang turned from scattered expansion in the periphery to a more aggregated growth in the center around 2000. This was related to Urban Master Plan of Shijiazhuang (1997–2010), which highlighted farmland protection by controlling urban population and urban land expansion strictly.

Infilling urban growth type is generally associated with a compact urban development and outlying with a dispersed one. Whether a compact urban pattern has more merits than a dispersed (scattered) one has long been a hot topic (Lin & Fuller, 2013; Zhao, Song, Tang, Shi, & Shao, 2011). Compact patterns are believed to create smaller ecological footprint, which will lead to agricultural land protection, energy consumption efficiency and transportation cost reduction; dispersed patterns, however, can leave more space for native species and green belts between urban patches as well as decrease the overall load of human stressors on ecosystems (Gordon & Richardson, 1997; Schneider & Woodcock, 2008). Although it is beyond our strength with results above to address this issue, we believe each city should reach a balance between urban intensification and extensification according to its own development model to maximally benefit both urbanites and the environment.

4.3. Landscape responses of urban expansion

The effects of urban expansion on the landscape vary with scale (Wu, 2004). Our study provided a multi-scale analysis on the landscape responses to urban expansion in the Jing-Jin-Ji Urban Agglomeration from regional landscape to city and within-city levels. At regional scale, landscape fragmentation and irregularity increased in the early stage of urbanization, which is consistent with the general observation that urbanization tends to cause an increase in landscape fragmentation and irregularity (Collinge, 1996). However, since 1990, 1995 and 2000 for Beijing, Tianjin and Shijiazhuang, respectively, a decrease in their landscape fragmentation and irregularity suggested that urban planning can adjust urban expansion types to avoid unrestricted acceleration of landscape fragmentation and irregularity and landscape responses to urban expansion are not always monotonic but vary with space and time.

At city level along the urban-to-rural gradient, Beijing showed an obvious gradient in urban area with a steep slope and its largest urban patch has always been developed from the original urban core and been well ahead of its second largest urban core, in response to its mononuclear concentric urbanization pattern. Tianjin exhibited no clear gradient in urban area with its largest urban patch being extremely large since 2005 resulting from the combination of the original urban core and Binhai New Area in response to its double-nucleated urban form. Shijiazhuang presented a gradient in urban area with a gentle slope and its largest urban patch, developed from the original urban core which also absorbed some small growth points during urbanization process in response to its point urbanization. Furthermore, the relationship between urban form and landscape connectivity, which is critical to urban ecosystem's stability and integrity (Gobattoni, Pelorosso, Lauro, Leone, & Monaco, 2011; Magle, Theobald, & Crooks, 2009), can be inferred from our results based on the existing literature. For example, Tannier, Foltete and Girardet, (2012) concluded that the planning rule of "proximity to existing roads" improves the landscape connectivity when compared with the rule of "proximity to built and open spaces", which implied that the connectivity of Beijing was higher than Shijiazhuang. In addition, the double-nucleated polygon line pattern contributes to improve the connectivity of Tianjin. However, it should be noted that the urban ecological connectivity is complex and should be investigated more deeply in order to compare across cities. The urban fragmentation metrics cannot be used to fully assess the ecological connectivity of the region (Gobattoni et al., 2011; Tannier et al., 2012).

Within-city variability of landscape for three cities were observed as well. Although urban percentage increased for all three cities during the study period, it had different increasing magnitude in different directions and at different distances within each city, indicating hotspots of urbanization changed with urban planning or policy in specific periods. Although landscape fragmentation varied first and then all decreased for three cities, it may keep stable or even increasing for a certain part of each city during the entire study period, and time for the most drastic fragmentation differed with direction and distance, demonstrating the relative dominance of urban growth types varying within city over time, which may be adjusted according to urban planning, policy or other factors. Therefore, a general understanding on landscape metrics at regional or city level may fail to uncover detailed landscape dynamics under the impact of urban expansion.

5. Conclusions

Urban expansion, which has affected ecosystem functioning and services at local to global scale, is projected to have aggravating impacts on landscape in the future. With development of RS and GIS as well as landscape analysis approaches, many studies have been conducted on spatiotemporal patterns of urban expansion, especially on Chinese cities. However, comparative study integrated with regional, city and within-city scale analyses on urbanization induced landscape change is relatively limited. In this study, we quantified and compared spatiotemporal patterns of both urbanized area and urban expansion in three main cities of the Jing-Jin-Ji Urban Agglomeration at multi-levels, using spatially explicit Landsat RS data with high consistency and temporal frequency over the past 30 years, which is both timely and necessary.

From 1980 to 2010, Beijing, Tianjin and Shijiazhuang all have experienced rapid urbanization with average annual urban growth rate of 3.7%, 4.7% and 3.2%, respectively. Our results revealed a considerable regional disparity in the Jing-Jin-Ji Urban Agglomeration measured by urban expansion magnitude and speed, suggesting more optimized urban planning strategies need to be adopted in this area. Beijing, Tianjin and Shijiazhuang have presented a mononuclear polygon urban expansion pattern, a double-nucleated polygon-line urban expansion pattern, and a sectorial point urban expansion pattern, respectively, as a consequence of their respective topographic constraints as well as urban planning and policy. Urban expansion in Beijing depended largely on ring roads, Tianjin's urban expansion was mainly fueled by dramatic development of Binhai New Area, and point spontaneous northward urban growth in Shijiazhuang was influenced by the expansion of Beijing and Tianjin. Landscape responses to urban expansion varied with time and scale investigated and a comprehensive understanding on landscape dynamics under the impacts of urban expansion needs to be performed at multi-scales.

Infilling urban growth type is generally associated with a compact urban form and outlying with a dispersed one. Our results indicated that the dominant urban growth type shifting from outlying to infilling in the Jing-Jin-Ji Urban Agglomeration came in an increasing order in time from Beijing (1990), Tianjin (1995) to Shijiazhuang (2000). Although it is beyond our scope with this study to address whether a compact urban form has more merits than a dispersed one, we believe each city should reach a balance between urban intensification and extensification according to its own development mode to maximally benefit both urbanites and the environment.

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