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Spatiotemporal dynamics of urban expansion in 13 cities across the Jing-Jin-Ji Urban Agglomeration from 1978 to 2015

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A B S T R A C T

The newly implemented national policy "To build a world-class agglomeration of cities with the capital as the core" made the Jing-Jin-Ji Urban Agglomeration attract attention from both the scientific community and society. Here we quantified and compared the magnitude, rates, forms, and dynamics of urban expansion for 13 cities across the Jing-Jin-Ji Urban Agglomeration, and examined the relationship of urban patch structure and hierarchical structure of urban growth over the past four decades. We found that the rates and composition of urban expansion forms (i.e., infilling, edge-expansion and leapfrogging) varied considerably across cities and over time, due to national and regional policies, physical features and the urban administrative hierarchy. The overall annual urban expansion rate for the 13 cities was 5.5 ± 2.0% (mean ± standard deviation) between 1978 and 2015. Leapfrogging was the dominant urban expansion form in early period, edge-expansion took the leading role since 1990, and the contribution of infilling was generally less than 40%. Our results revealed that although three major cities (i.e., Tianjin, Beijing and Shijiazhuang) of the Jing-Jin-Ji Urban Agglomeration contributed 36.6% of the urban land area increase of this region, larger cities might not be better positioned for urban expansion. The urban expansion rates of cities were inversely related to city size in general from 1978 to 2015 with exception only from 2005 to 2010. Patch analysis showed that relationship between patch number and patch size derived previously at the national level can be applied to the Jing-Jin-Ji Urban Agglomeration despite the discrepancies in temporal scale and urban administrative hierarchy. This invariant self-organization of urban land patches during the urbanization process might provide insightful information guiding the design, planning, and management of sustainable cities in the capital urban agglomeration of China.

1. Introduction

Urbanization, characterized by demographic changes and urban land expansion, is the most drastic and irreversible form of land use, and its impacts far transcend city's physical boundaries (Grimm et al., 2008; Wu, 2014). The unprecedented urbanization has resulted in profound changes in landscape (Haas and Ban, 2014), biodiversity (He et al., 2014), biogeochemical cycles (Kaushal et al., 2014) and energy flow (Kennedy et al., 2015) at multiple spatiotemporal scales. More than 50% of the world's population now live in urban areas and this figure is projected to increase to about 75% by 2050 (United Nations, 2015) with the most increase in developing countries (Bloom, 2011). Cities are particularly vulnerable to increasing extreme climate and weather events (i.e., urban flooding, regional droughts and extreme heat waves) (Hu et al., 2016). Metropolitan areas of developing countries as the primary areas of urbanization, especially the capital regions, might experience severe environmental problems due to massive rural to urban migration and intensive anthropogenic activities. Therefore, understanding the rates, patterns, causes, and consequences of rapid spatial expansion of cities in developing countries is a formidable challenge in the 21st century (Cohen, 2006; Cobbinah et al., 2015).

China has experienced a rapid urbanization process in recent four decades since the implement of the "reform and opening-up" policy to promote economic growth (Chan, 2010; Wu et al., 2014). The urban administrative hierarchy of China consists of several levels, including provincial, prefectural, county, and township-level cities (Chan, 2010; Li et al., 2013). In contrast to developed countries, rapid urbanization in China is not only paralleled by economic growth but also significantly shaped by administrative means from government at all levels. And as a result, administrative levels in China's governments pose strong impact on urbanization process (Liu et al., 2012). Because cities with higher administrative status perform better socially and economically than those with lower status, the difference of local government's administrative status might contribute to the differences in the urbanization level among cities (Wu et al., 2015). Therefore, there is a need to investigate China's urbanization in the context of urban

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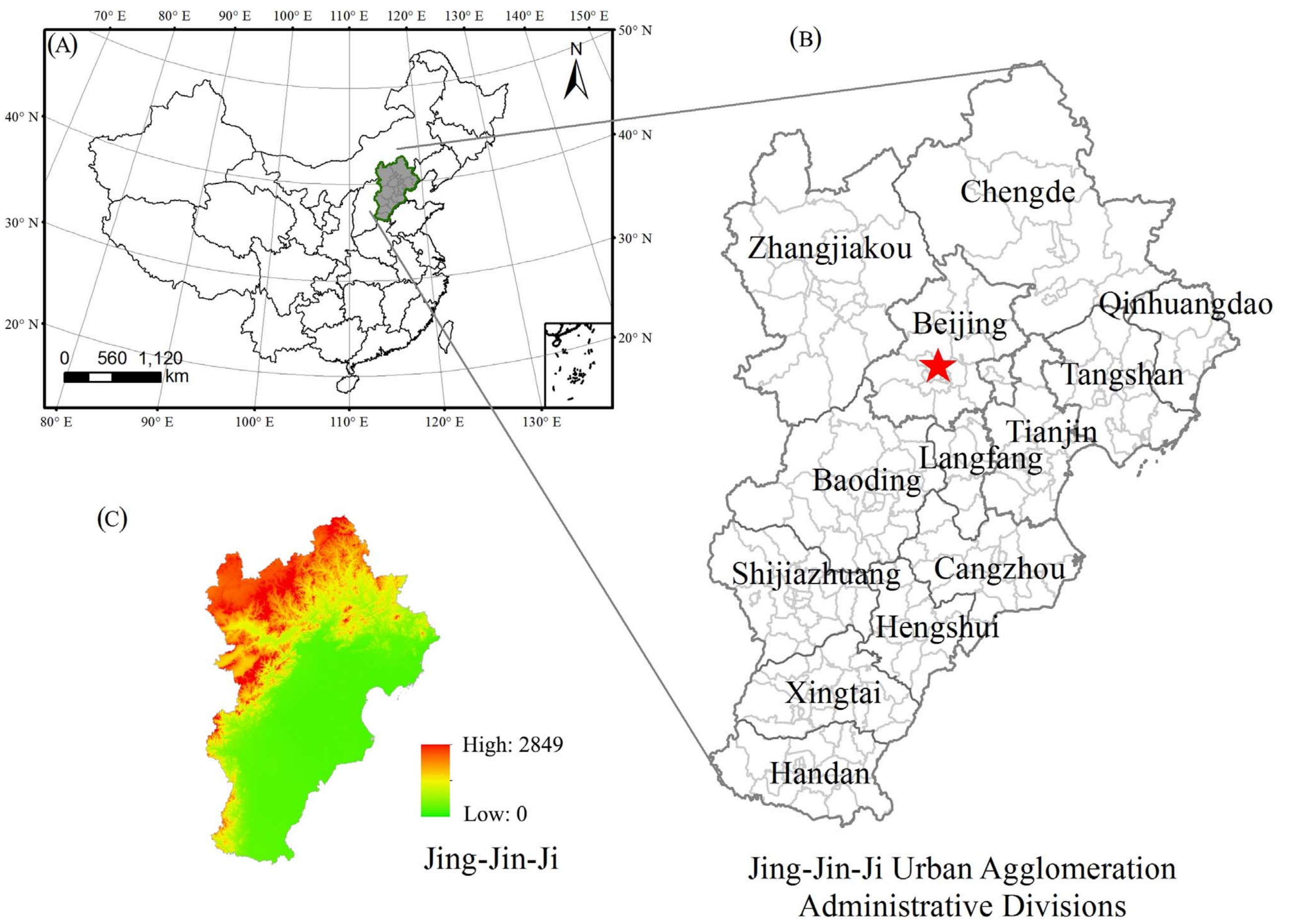

Fig. 1. The location and administrative divisions of the study area: (A) The study area in China, (B) The 13 cities in the Jing-Jin-Ji Urban Agglomeration, (C) Topography of study area.

administrative hierarchy for building robust knowledge and providing guidance for sustainable planning, designing, and managing of Chinese urban expansion. Previous studies found that larger cities might be better positioned than smaller ones for urban expansion owing to their higher ranks in the administrative hierarchy, and greater competiveness for land-use priority and resource exploitation (Schneider and Mertes, 2014; Zhang et al., 2014). Li et al. (2015) used spatial regime regression to examine the spatial effect of city hierarchy and found that in China between 1998 and 2008, cities ranked higher tend to expand more rapidly. However, Gibrat's law, the well-documented urban expansion theory, states that growth rate of cities are independent of city size (Eeckhout, 2004; Rozenfeld et al., 2008; Jiang and Jia, 2011). Recent studies found that during the entire period of 1978–2010, Chinese cities expansion in terms of urban growth rate showed an inverse relationship to city size, contradicting Gibrat's law (Zhao et al., 2015a). The emergence of various urban agglomeration development strategy and adjustment of city administrative divisions press the necessity to apply spatially explicit methods to understand the new urbanization in contemporary China (Li et al., 2015; Zhao et al., 2015a; Zeng et al., 2017).

The Jing-Jin-Ji Urban Agglomeration as the capital urban agglomeration of China has attracted much attention due to the newly implemented national policy "To build a world-class agglomeration of cities with the capital as the core" (Wu et al., 2015; Zhang et al., 2017). The administrative hierarchy of the Jing-Jin-Ji Urban Agglomeration is quite complete with a set of cities ranging from large (e.g. Beijing and Tianjin) to small. Therefore, the Jing-Jin-Ji Urban Agglomeration provides an ideal place for a synthetic understanding on the impacts of urban hierarchy systems; a comprehensive study on the urban growth characteristics of cities at all administrative levels of the Jing-Jin-Ji Urban Agglomeration will be of great significance to better understand the urban expansion model of China.

Compared to other important urban agglomerations of China (i.e., the Yangtze River Delta and the Pearl River Delta), there have been fewer spatially explicit studies on urbanization process of the Jing-Jin-Ji Urban Agglomeration (Xie et al., 2017). A comparative study of urbanization process in three major urban agglomerations of China revealed that from 1990 to 2010, the Jing-Jin-Ji Urban Agglomeration showed the highest magnitude and speed of urban growth (Haas and Ban, 2014). Using multi-temporal satellite data, Wu et al. (2015) quantified and compared magnitude of urban expansion in three major cities (i.e., Tianjin, Beijing and Shijiazhuang) of the Jing-Jin-Ji Urban Agglomeration from the late 1970s to 2010. Recently, Zhang et al. (2016) emphasized neighbor-city influence on intra-city urban expansion direction through comparing the spatiotemporal patterns of urban growth in Beijing, Tianjin and Tangshan from the 1970s to 2013. Most of those studies only included several more developed cities of this region or covered relatively short time periods, or not designed to investigate the impacts of the urban administrative hierarchy. Furthermore, spatial and temporal evolution of urban patch structure can reveal the metabolism and mechanism of city evolution and organization (Zhao et al., 2015a,b). Unfortunately, few studies have been conducted to examine patch characteristics (Dietzel et al., 2005; Li et al., 2013; Zhao et al., 2015a,b), let alone the convergence or divergence of urban patch structure in the context of urban administrative hierarchy. There is a dearth of multi-temporal spatially explicit research on the urban land growth, and the hierarchical structure of all major cities in the Jing-Jin-Ji Urban Agglomeration across recent four decades.

In this study, we mapped and quantified the magnitude, rates and spatial patterns of urban expansion for the Jing-Jin-Ji Urban

Agglomeration of China from the late 1970s to 2015 using multi-temporal Landsat Multispectral Scanner (MSS), Thematic Mapper (TM), Enhanced Thematic Mapper (ETM) and Operational Land Imager (OLI) satellite images. The objectives of this study were to (1) map the spatial and temporal dynamics of urban land covers of all major cities of the Jing-Jin-Ji Urban Agglomeration; (2) quantify and compare the rates, growth forms of urbanization in the Jing-Jin-Ji Urban Agglomeration; (3) examine the change of converged urban patch structure across time and space; and (4) investigate the impact of urban administrative hierarchy and the applicability of Gibrat's law in the region.

2. Data and methods

2.1. Study area

The Jing-Jin-Ji Urban Agglomeration is located in the northeastern part of mainland China and belongs to the Bohai Economic Rim (Fig. 1). The Jing-Jin-Ji Urban Agglomeration includes three provincial-level city: Beijing (the capital city of China and municipality), Tianjin (municipality) and Shijiazhuang (the provincial capital of Hebei); ten prefectural-level cities: Langfang, Baoding, Chengde, Zhangjiakou, Cangzhou, Tangshan, Qinhuangdao, Hengshui, Handan, Xingtai, each of which incorporates many districts and counties (Table 1). Our study area (i.e., its metropolitan area) includes Beijing and Tianjin, and all of the 11 cities in Hebei province surrounding them, covering an area of approximately 216,000 km^2. As one of the three most important urban agglomerations, this region is designated as the political, cultural, and economic center of China, with a population of approximately 110.5 million, contributing to 10.4% to China's GDP in 2014 rivaling Yangtze River Delta and the Pearl River Delta (Table 2). The climate of this region is humid continental with hot summers and cold winters. Since 2010, various national and local policies have been implemented to coordinate development of the Jing-Jin-Ji Urban Agglomeration and address subsequent environmental problems in urbanization process (Wang et al., 2013).

2.2. Remote sensing data and urban land cover classification

Cloud-free MSS (Multispectral Scanner), TM (Thematic Mapper), ETM+ (Landsat Enhanced Thematic Mappler Plus) and OLI (Operational Land Imager) satellite images were used to monitor urban land changes for the 13 cities over the past 37 years. The acquisition time of these images represent seven time periods of circa 1978, 1990, 1995, 2000, 2005, 2010 and 2015, corresponding to the rapid urbanization process of China since the critical national policy of "reform and opening-up" initialized in the late 1970s. Around 200 scenes of images with relatively high-quality were used to map the spatial extent of urban land for the 13 cities of the Jing-Jin-Ji Urban Agglomeration.

For all cities, we acquired images in summer as much as possible to effectively separate urban land from crop fields. For most of those 13 cities, several images have to be mosaicked to cover the whole administrative area of a city. When selecting images for mosaicking, we tried to use images with the date as close as possible (Table S1). We used official definition of the administrative area to cut the mosaicked images for each city using ERDAS Imagine version 9.2. Each selected image was geo-encoded, re-projected, histogram equalized and resampled to the resolution of 30 m. The coordinate system of Albers Conical Equal Area was used in this study.

We further coordinated Digital Elevation Models (DEM, downloaded from http://www.gdem.aster.ersdac.or.jp/search.jsp) and Normalized Difference Vegetation Index (NDVI, derived from the remote sensing images) to enhance the spectral and topographic heterogeneity and thus facilitate our following classification. The maximum likelihood classification (MLC) approach was used to classify the land covers into four types (i.e., cropland, urban land, water body, and other cover) (Zhao et al., 2006; Sun et al., 2015; Wu et al., 2015). The urban land consisted of all non-vegetative areas (e.g., roads and buildings), including transportation, industrial, commercial and residential space within the administrative boundary.

This study used the high-resolution images provided by Google Earth Pro to validate the classification results of all cities (Luedeling and Buerkert, 2008; Zhou et al., 2012). In addition, some of the local photos uploaded to the Panoramio website (http://www.panoramio.com/) were used to help distinguish different land cover types. Because of the lack of high-resolution images before 2009, this article uses Google Earth's satellite imagery for 2010 and 2015 to validate (1) classification products in 2010 and 2015 and (2) land cover unchanged area in the classification products from 1978 to 2010. For each city, three sets of 300 random points were selected based on the stratified sampling method in the 2010 and 2015 classification results and in the area where land cover was not changed between 1978 and 2010. The results show that the Kappa coefficients of all cities in 2010 and 2015 are larger than 0.77, the accuracy of classification results before 2010 is greater than 0.82 (Table S2), which can meet the accuracy requirements of land cover change evaluation (Foody, 2002).

Table 2
Socioeconomic data of three major urban agglomerations in China.

Urban Agglomeration	Area (10^4 km^2)	GDP (10^{12} RMB)[a]	% National GDP	Population (Million)[b]
Jing-Jin-Ji	21.6	6.6	10.5	110.5
Yangtze River Delta	21.17	12.7	20.0	150.0
Pearl River Delta	5.6	5.8	8.9	57.4

[a] 1 RMB approximately equals 0.15 US Dollar.
[b] Resident population.

Table 1
Urban hierarchical System of the Jing-Jin-Ji Urban Agglomeration.

Level	City	Per capita GDP (dollars)	Area (km^2)	Administrative divisions
Capital and Municipality	Beijing	16278	16411	16 districts
Municipality	Tianjin	17131	11946	15 districts 1 county
Provincial capital	Shijiazhuang	7907	15848	6 districts 17 counties
Prefectural	Tangshan	13148	13472	6 districts 8 counties
Prefectural	Langfang	7490	6429	2 districts 8 counties
Prefectural	Cangzhou	6978	13419	2 districts 14 counties
Prefectural	Qinhuangdao	6415	7812	3 districts 4 counties
Prefectural	Chengde	6218	39519	3 districts 8 counties
Prefectural	Handan	5377	12087	4 districts 15 counties
Prefectural	Zhangjiakou	5011	36797	4 districts 13 counties
Prefectural	Baoding	4389	22185	3 districts 22 counties
Prefectural	Hengshui	4206	8815	2 districts 10 counties
Prefectural	Xingtai	3763	12486	2 districts 17 counties

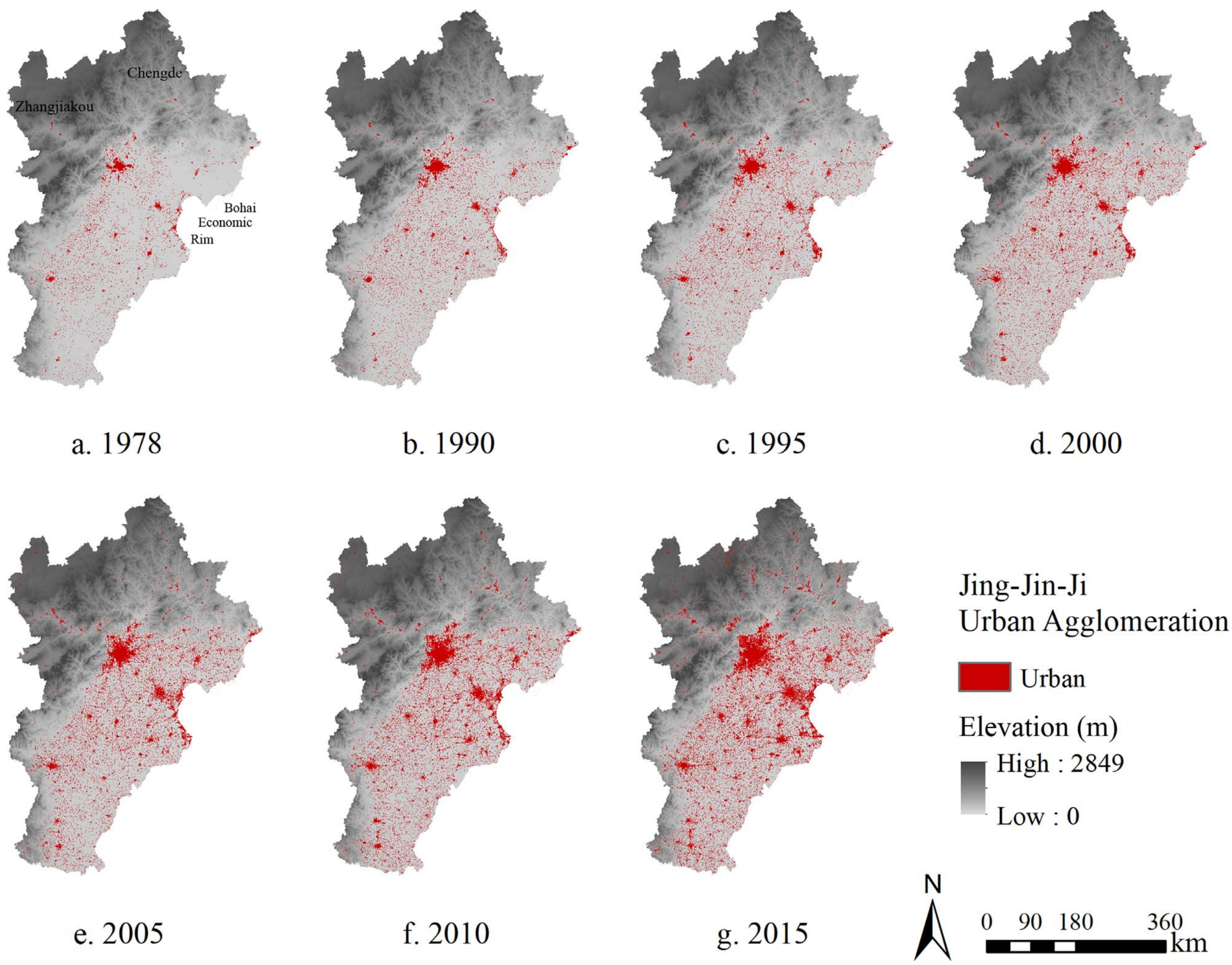

Fig. 2. Change of spatial extent of urban areas in the Jing-Jin-Ji Urban Agglomeration from 1978 to 2015. The background map shows the topography of China.

2.3. Rates and spatiotemporal analyses of urban expansion

The annual urban expansion rate (AER) of each city between six neighboring periods from 1978 to 2015 was computed using following equation:

$$\text{AER} = 100\% \times \left(\sqrt[d]{\frac{U_{end}}{U_{start}}} - 1\right) \quad (1)$$

where U_{start} is the urban area at the initial time, U_{end} is the urban area at the end time, and d is the time span of the period in years.

Urbanization may proceed by different urban growth modes at a given urban growth rate (Berling-Wolff and Wu, 2004). We classified urban growth into infilling, edge-expansion, and leapfrogging to examine urban expansion patterns and processes. To differentiate infilling, edge-expansion and leapfrogging, an urban expansion type (E) index (Zhao et al., 2015b) was calculated using following equation:

$$\text{E}= \frac{L_{\text{com}}}{P_{\text{new}}} \quad (2)$$

where P_{new} is the perimeter of a newly developed urban patch, and L_{com} is the length of common edge between the existing urban patch or patches and the newly developed urban patch. The urban expansion type will be defined according to the value of E ranging from 0 to 1: the new urban patch is infilling when $\text{E} > 0.5$, edge-expansion when $0 < \text{E} \leq 0.5$, and leapfrogging when $\text{E} = 0$ (Zhao et al., 2015b).

Zhao et al. (2015b) analyzed the composition and frequency distribution of urban patches through binning them into 13 patch size classes: 0–0.05, 0.05–0.25, 0.25–0.5, 0.5–1, 1–2, 2–5, 5–10, 10–20, 20–50, 50–100, 100–200, 200–500, and > 500 km^2 and calculated the area and perimeter of each urban land patch. They derived a relationship for calculating the number of patches given the patch size and the total urban land area for 32 major cities (including Beijing, Tianjin and Shijiazhuang) of China from 1978 to 2010 (Zhao et al., 2015b):

$$\text{N} = 0.0863 S^{-1.29} A^{0.977} \quad (3)$$

where S is the mean patch size (km^2) of each bin based on the above classification and N is the corresponding patch number of each bin; A stands for the total urban area of each city (km^2, excluding the bins with only one patch).

In this study, we attempt to apply the equation to test the data for Beijing, Tianjin and Shijiazhuang in 2015 since newly implemented series of policies might have affected the urban expansion process of these cities. We further explored the applicability of this equation for other 10 cities from the Jing-Jin-Ji Urban Agglomeration between the late 1970s and 2015 to examine whether an invariant scaling relationship between patch number, and patch size and total urban area across the urban administrative hierarchy exists.

2.4. Test of the impact of urban administrative hierarchy and size on urban expansion rate

Cities in this study fall into two levels in terms of urban administrative hierarchy: the higher level includes Beijing, Tianjin and Shijiazhuang and the lower level includes the ten prefectural cities of the Jing-Jin-Ji Urban Agglomeration. We used the Turkey HSD test to examine the difference between the two levels of cities in urban expansion rate, with significant difference ($\alpha = 0.05$) suggesting a significant impact of the administrative hierarchy on urban expansion.

On the other hand, cities with higher administrative ranks generally have larger city size and more urban land for urban expansion (Zeng et al., 2017). Therefore, we examined the relationship between the size and urban expansion rate to test whether the Gibrat's law holds at the regional level of the Jing-Jin-Ji Urban Agglomeration:

$$AER = kA_{start}^{\gamma} \quad (4)$$

where AER is the urban expansion rate, and k and γ are regression coefficients. In this study, we took logarithms of both sides of Eq. (4) and calculated the coefficient γ and its 95% confidence range. If the 95% confidence range of the coefficient γ did not include zero, we considered that the coefficient γ was significantly different from zero and thus Gibrat's law does not hold (Zhao et al., 2015a).

3. Results

3.1. Magnitude, rates, and spatial patterns of urban expansion

Fig. 2 illustrated the overall spatial extent of urban areas in the Jing-Jin-Ji Urban Agglomeration from the late 1970s to 2015. Hot zone of urban growth was around Bohai Economic Rim with two municipalities (i.e., Beijing and Tianjin) and two prefectural cities of Hebei (i.e., Tangshan and Cangzhou). Fig. 3 presents the areas and rates of urban expansion by city and time. The overall annual AER for the 13 cities was 5.5 ± 2.0% between 1978 and 2015. The temporal pattern and magnitude of urban growth varied across cities with different hierarchical level over the past 37 years. Beijing, Tianjin, and Shijiazhuang belong to the higher hierarchy level of this region and they added up to 49.6 percent of the total urban land area of the Jing-Jin-Ji Urban Agglomeration in the late 1970s and increased 6717.7 km^2 over the past 37 years, accounting for 36.6% of the total increased urban land area of this region. It is noticeable that Tianjin led the rapid urbanization of this region from the 1ate 1970s to 2015. The ecological barrier and tourism cities of the Jing-Jin-Ji Urban Agglomeration (i.e., Chengde, Zhangjiakou and Qinhuangdao) had small urbanized areas (28, 65 and 42 km^2, respectively) in the initial period. Although these cities had high AER (9.1%, 6.9% and 8.0%, respectively) from the late 1970s to 2015, they only contributed to 11.3% of the total increased regional urban land area. Four land-locked cities (i.e., Handan, Hengshui, Langfang, and Xingtai) displayed an average rate of urban growth during the past 37 years.

The rapid urbanization of the Jing-Jin-Ji Urban Agglomeration resulted from a combination of three urban growth types (i.e., infilling, edge-expansion, and leapfrogging) (Fig. 4). As urbanization continued, the relative proportions of three growth types in terms of patch number have experienced drastic changes from 1978 to 2015 (Fig. 5). In the initial period (i.e., 1978–1990), most cities were distributed toward the upper end of leapfrogging in the urban growth triangle, and edge-expansion became dominant thereafter. Infilling increased its shares substantially after the period of 1978–1990 and showed completely opposite trends of leapfrogging. The statistics associated with these three patterns are summarized in Table 3. The mean fraction of infilling was quite low (7.1%) in 1978–1990, giving way to edge-expansion and leapfrogging. Although the mean fractions of infilling fluctuated between 1990 and 2015, its coefficient of variation (CV) steadily decreased from 0.34 to 0.24. On the other hand, Table 3 illustrated the increasing role of edge-expansion in urban growth process of the Jing-Jin-Ji Urban Agglomeration since 1990, increasing from about 30% to 46% over time. In contrast, the weight of leapfrogging gradually

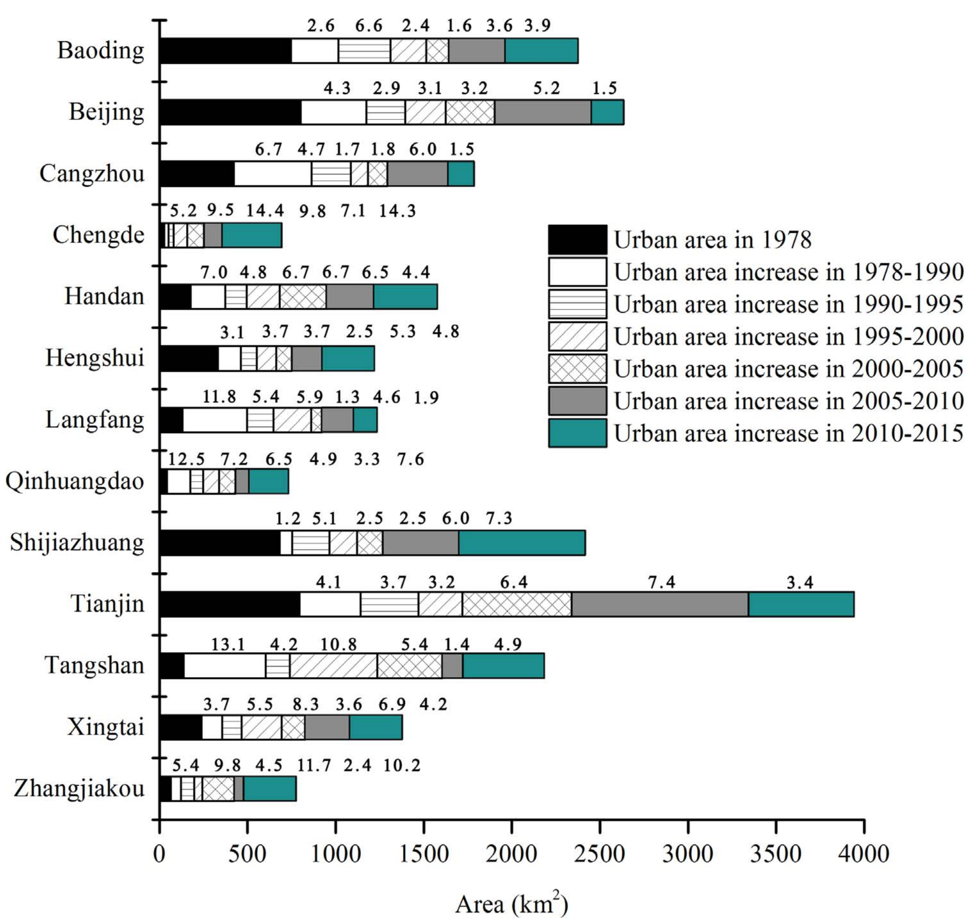

Fig. 3. The existing urban area in 1978 and growth of urban area (km^2) between six neighboring periods from 1978 to 2015 for 13 cities in the Jing-Jin-Ji Urban Agglomeration.

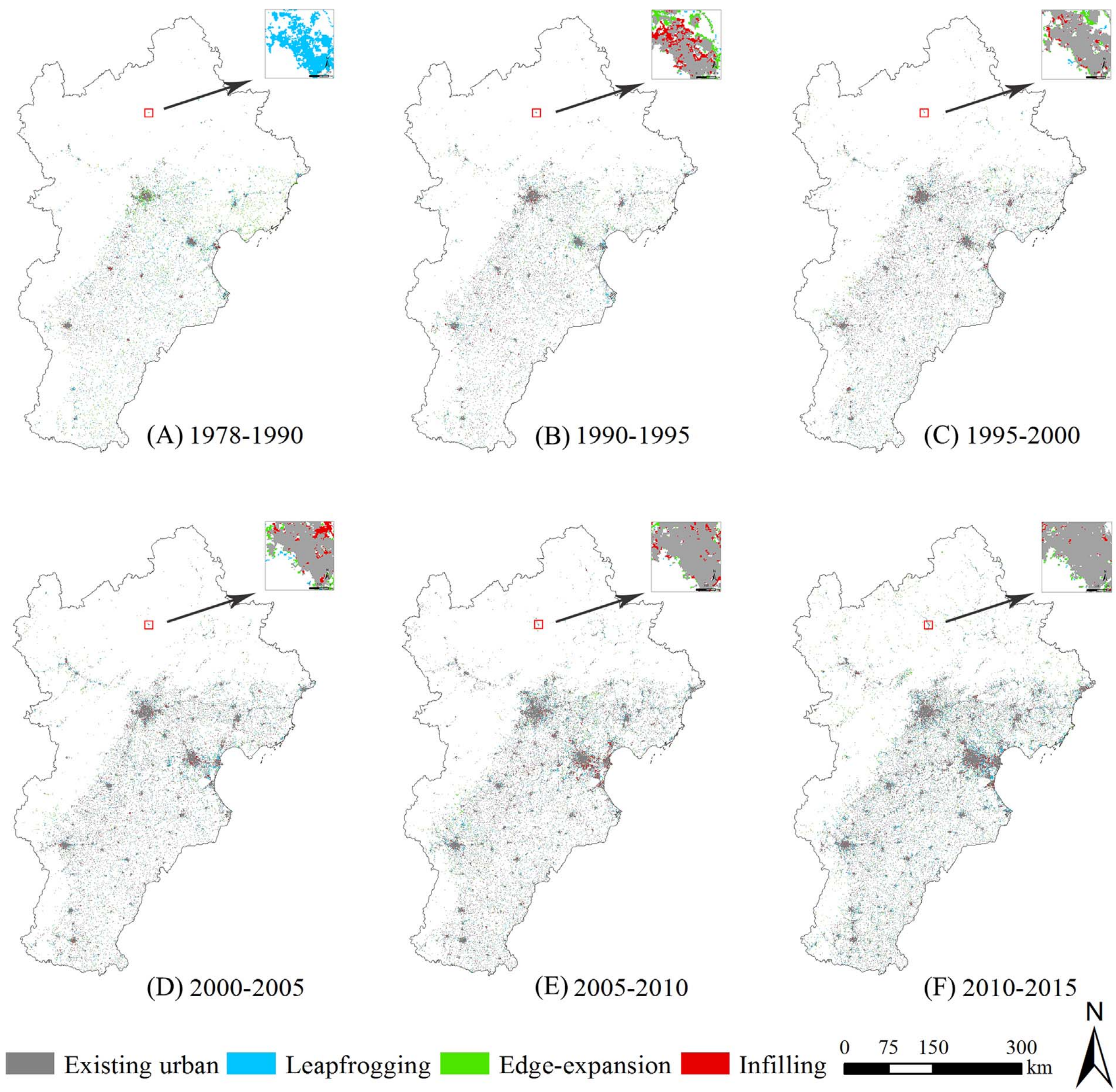

Fig. 4. Spatial distribution of three urban expansion types for the Jing-Jin-Ji Urban Agglomeration among six neighboring periods from 1978 to 2015.

decreased to about 24.4% during 2005–2010 and then rebounded to 33.3%. It is noticeable that after 2000, the spatial expansion patterns of Chengde and Zhangjiakou were significantly different from other 11 cities, both of which were composed of larger proportion of leapfrogging and smaller proportion of edge-expansion.

3.2. Characteristics of urban land patches

Patch analysis revealed that the patch size and its number in each city of the Jing-Jin-Ji Urban Agglomeration at a given time generally followed the "hockey-stick" log–log relationship (Fig. 6). The urban land patch with a frequency of one (i.e., the hockey stick's "blade" portion) usually refer to the urban center or core of a city and thus can reflect the expansion trait of a city's largest urban land patch. Beijing, Tianjin and Shijiazhuang had quite similar hockey-stick structure with apparent blade part and mostly overlapped sticks over the past 37 years. However, the other ten prefectural cities displayed slightly different structures of urban land patches. The hockey-sticks in 1978 for Tangshan and Qinhuangdao are obviously lower than other periods, which indicates that the urban land patches of the two cities increased considerably from 1978 to 1990, especially small size urban patches. Noticeably, characteristics of the smallest size bins for Chengde and Zhangjiakou differ from other cities with a gradually increasing trend at each given time. The other six prefectural cities shared roughly similar characteristics of urban land patches.

3.3. Relationship between patch number and size

We applied the Eq. (3) to test the data for Beijing, Tianjin and Shijiazhuang in 2015 since newly implemented series of policies might have affected the urban expansion process of these cities (Fig. 7). Surprisingly, the equation worked well ($p < 0.001$) which implied the invariance of the function. A slight overestimation of the number of urban patches was found for Tianjin and Shijiazhuang in 2015 (Fig. 7B and C), which was related to their magnitude of urban expansion and composition of urban growth types (Figs. 3 and 5). Our analysis also showed that the equation predicted remarkably well for those 10 prefectural cities in the Jing-Jin-Ji Urban Agglomeration (Fig. 8). Noticeably, the robustness of our equation increased steadily from the late 1970s to 2015 and the predicted and observed number of patches had

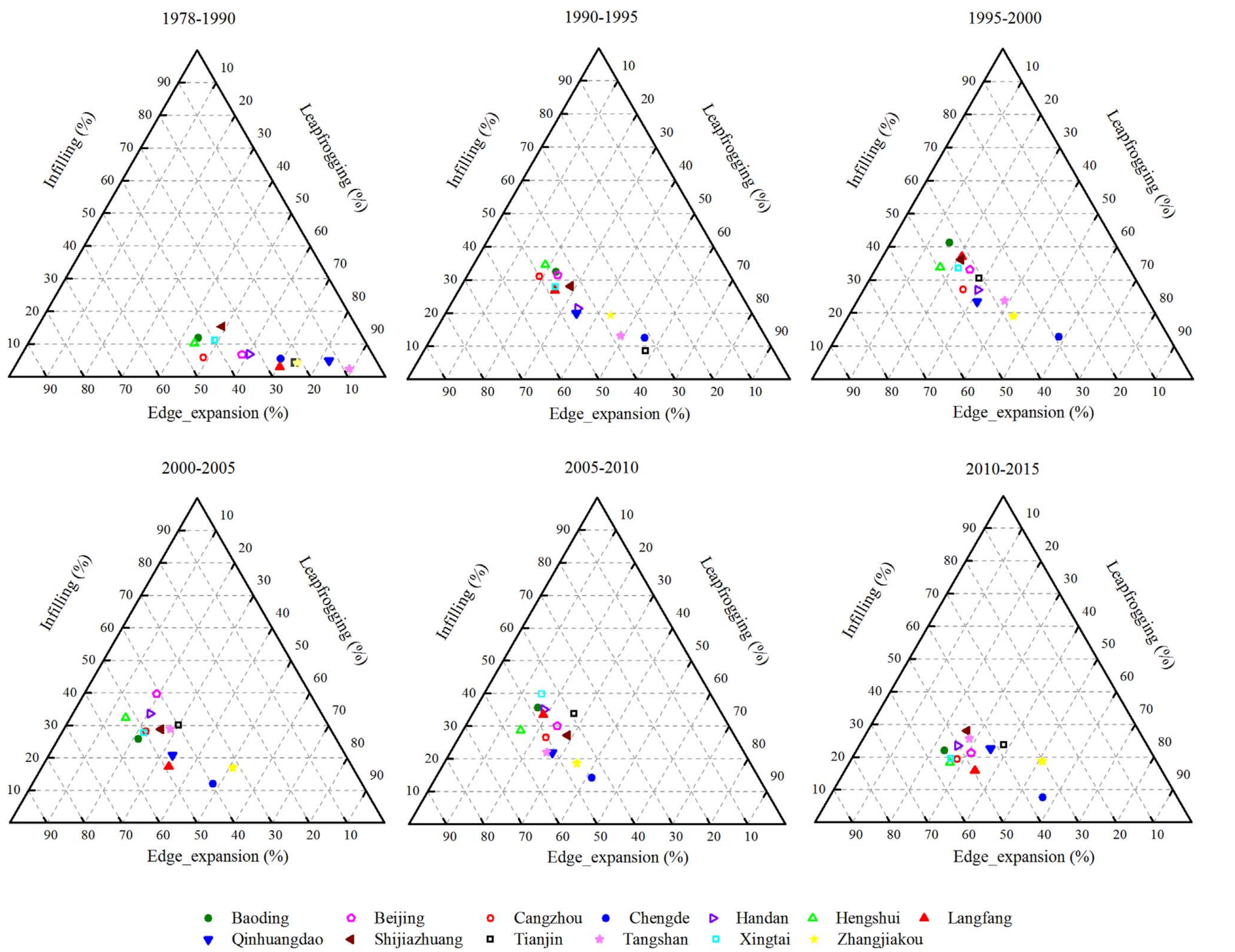

Fig. 5. Change of the proportional composition, calculated from number of patches, of the three growth types (i.e., infilling, edge-expansion, and leapfrogging) with city and time.

Table 3
The mean fractions (%) and coefficient of variation (i.e., mean divided by standard deviations) of the three urban growth types in terms of patch number across 13 cities during each time period.

	Infilling		Edge-expansion		Leapfrogging	
	Mean	CV	Mean	CV	Mean	CV
1978–1990	7.1	0.52	30.3	0.39	62.6	0.23
1990–1995	23.7	0.34	42.7	0.13	33.6	0.39
1995–2000	29.1	0.26	41.8	0.12	29.0	0.39
2000–2005	26.3	0.28	45.1	0.13	28.6	0.37
2005–2010	28.3	0.25	47.3	0.09	24.4	0.31
2010–2015	20.5	0.24	46.3	0.16	33.3	0.29

almost lain in 1:1 line since 1995 (Fig. 8A–G).

3.4. Relationship between urban administrative rank or size and urban expansion rate

The average urban expansion rates were 4.1% and 5.9% respectively for the provincial and prefectural cities in the administrative hierarchy. There was no significant difference in urban expansion rates between the two levels of cities ($\alpha = 0.05$). However, the difference was substantial ($p = 0.076$) and the expansion rate of prefectural cities was higher on average than that of provincial cities, opposite to the urban hierarchy theory (i.e., provincial cities expand faster than the prefectural ones because of power and resource accessibility).

Fig. 9 illustrates the temporal change of urban expansion rates against city size of all major cities in the Jing-Jin-Ji Urban Agglomeration and shows the 95% confidence ranges of the coefficient γ for each time period. Except 2005–2010, the 95% confidence ranges of the coefficient γ for each time period does not contain zero and γ is significantly lower than zero. The negative γ suggests that smaller cities expanded faster than larger ones, contradicting Gibrat's law and possibly the urban hierarchy theory. During the period 2005–2010, the relationship between expansion rate and city size became insignificant (the coefficient is not significantly different from zero). Therefore, Girat's law applies for the Jing-Jin-Ji Urban Agglomeration only in 2005–2010, but the urban hierarchy theory still does not hold. It is noticeable that during the entire period from 1978 to 2010, the 95% confidence bounds of the coefficient γ was $[-0.36, -0.22]$, contradicting Gibrat's law and the urban hierarchy theory.

4. Discussion

4.1. Urban expansion diversity of 13 cities

Over the past 37 years, all major cities of the Jing-Jin-Ji Urban Agglomeration experienced rapid urban expansion. However, the spatial and temporal patterns of urban expansion varied widely among cities. Therefore, it is of great importance to take account of intercity differences in making urban planning strategies to achieve the

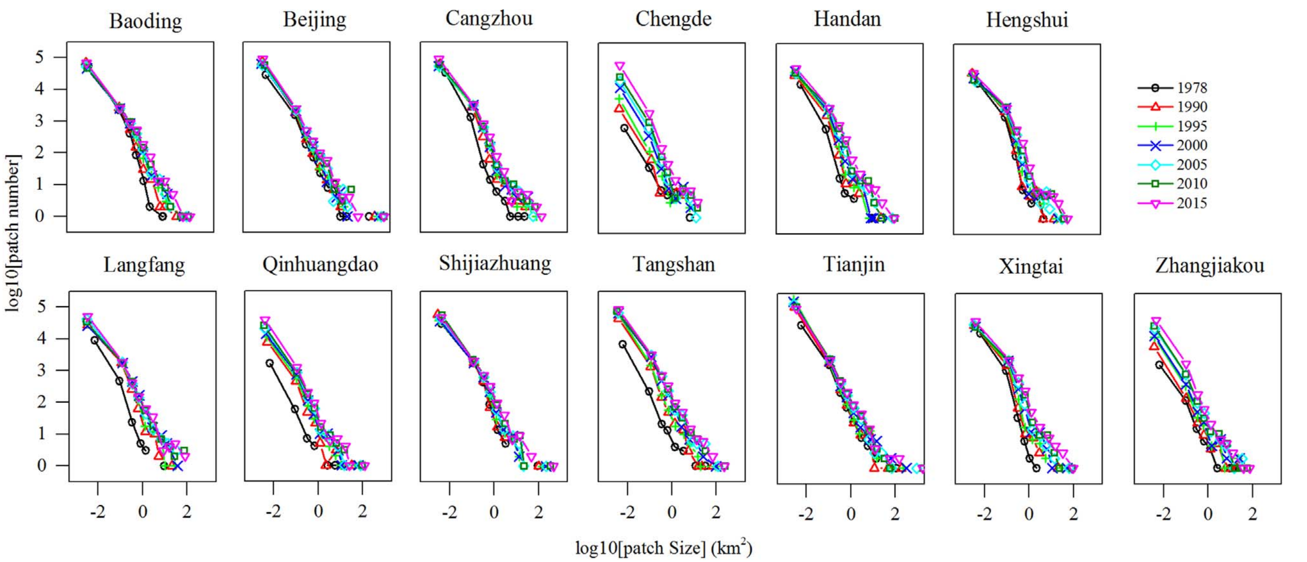

Fig. 6. The relationship between the number and size of patches across cities and time periods.

coordinated development goal of this region. Urban expansion rate and diversity are defined by multiple forces including various physical and administrative conditions. Chengde, Qinhuangdao, and Zhangjiakou are designated as tourist and ecological barrier cities for the entire region with relatively lower per capita GDP (Table 1). With substantially lower initial expansion rates compared to other cities of the Jing-Jin-Ji Urban Agglomeration, these three cities experienced increasing urban expansion rates during the recent decade (Fig. 3). Taking Chengde as an example (Fig. 4), physical conditions such as Bashang Plateau greatly constrained its urban expansion direction and urban expansion patches only concentrated in the plain area between mountains. Although the urbanization process of Chengde accelerated since 2010, the leapfrogging patches which accounts for the highest proportion of its urban expansion types still mostly distributed along the narrow intermountain plain of Yanshan Mountain Range. Comparatively, urban expansion of coastal cities (e.g. Cangzhou, Tangshan and Tianjin) on one hand enjoys the advantage of flat terrain (Fig. 2), and on the other hand have been promoted by the strategy of local city or Hebei Province to develop international trade, shipping, and logistics industry in coastal areas (Zhang et al., 2016).

4.2. Urban administrative hierarchy effect

The urban hierarchy theory states that, in China, a city with a higher administrative status is more likely to obtain more construction land quota for development and thus acquire higher potential for urban expansion and economic development (Zeng et al., 2017). However, our results revealed that cities with higher ranks in the administrative hierarchy might not be better positioned for urban expansion. Three major provincial cities (i.e., Tianjin, Beijing and Shijiazhuang) of the Jing-Jin-Ji Urban Agglomeration did contribute 36.6% of the urban land area increase of this region, but the urban expansion rates of were not the highest. In fact, the expansion rate was inversely related to city size during the entire study period (Fig. 9G). Before 2005, prefectural cities in general expanded faster than the above three cities with higher urban administrative ranks (Fig. 9A–D). In the only period when Gibrat's law held (i.e., 2005–2010), cities with higher administrative ranks (Fig. 9E) showed comparable fast expansion to the rates of smaller cities, which is consistent with previous study (Zhao et al., 2015a). The newly implemented strategy of "urbanization from below" which aims to "strictly control the growth of large cities, rationally develop medium sized cities, and vigorously promote the development of small cities and town" (Li, 2012) might have limited the further rapid expansion of Beijing and Tianjin (Fig. 9F). Furthermore, the new national policy "Integrated and coordinated development of Beijing, Tianjin and Hebei" have been issued to promote the future urbanization of Hebei Province (Zhang et al., 2017), as evidenced by the abrupt decrease of AER for Beijing and Tianjin, but continued increase for Shijiazhuang (the capital city of Hebei Province) and prefectural cities of Hebei Province (Figs. 3 and 9F). Therefore, when analyzing the

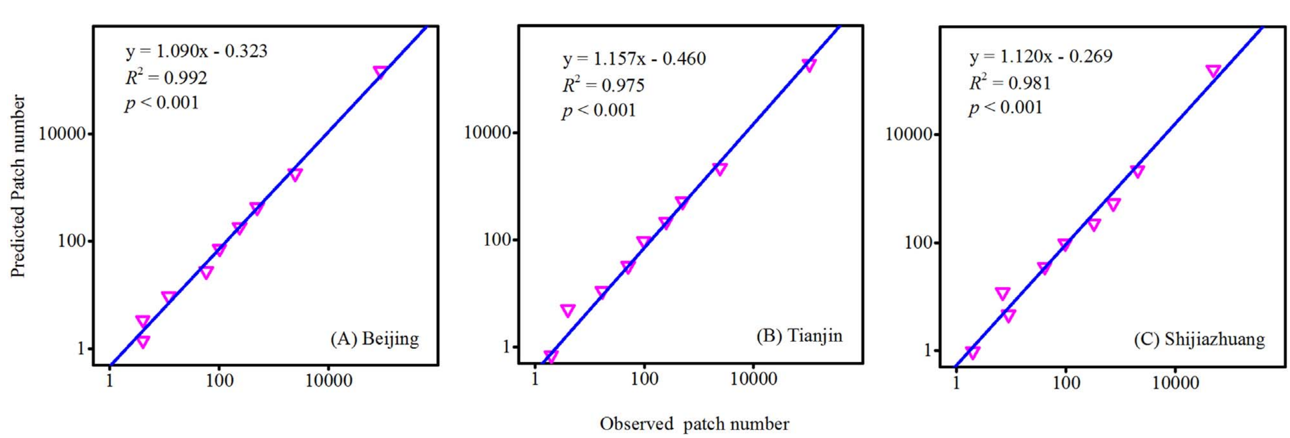

Fig. 7. Comparison of predicted and observed number of urban land patches for Beijing (A), Tianjin (B) and Shijiazhuang (C) in 2015 using $N = 0.0863S^{-1.29}A^{0.977}$ (where S is the patch size and A is the total urban area excluding the largest patch).

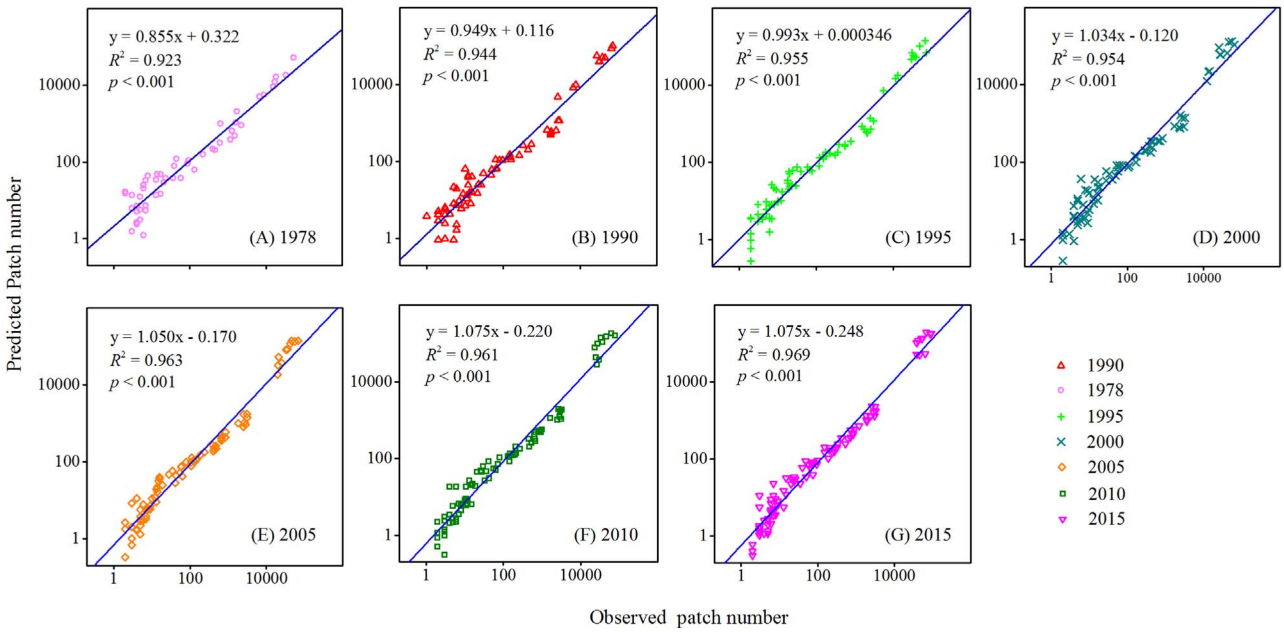

Fig. 8. Comparison of predicted and observed number of patches for a given patch size across 10 prefectural cities from the late 1970s to 2015. The equation used was the same as in Fig. 7.

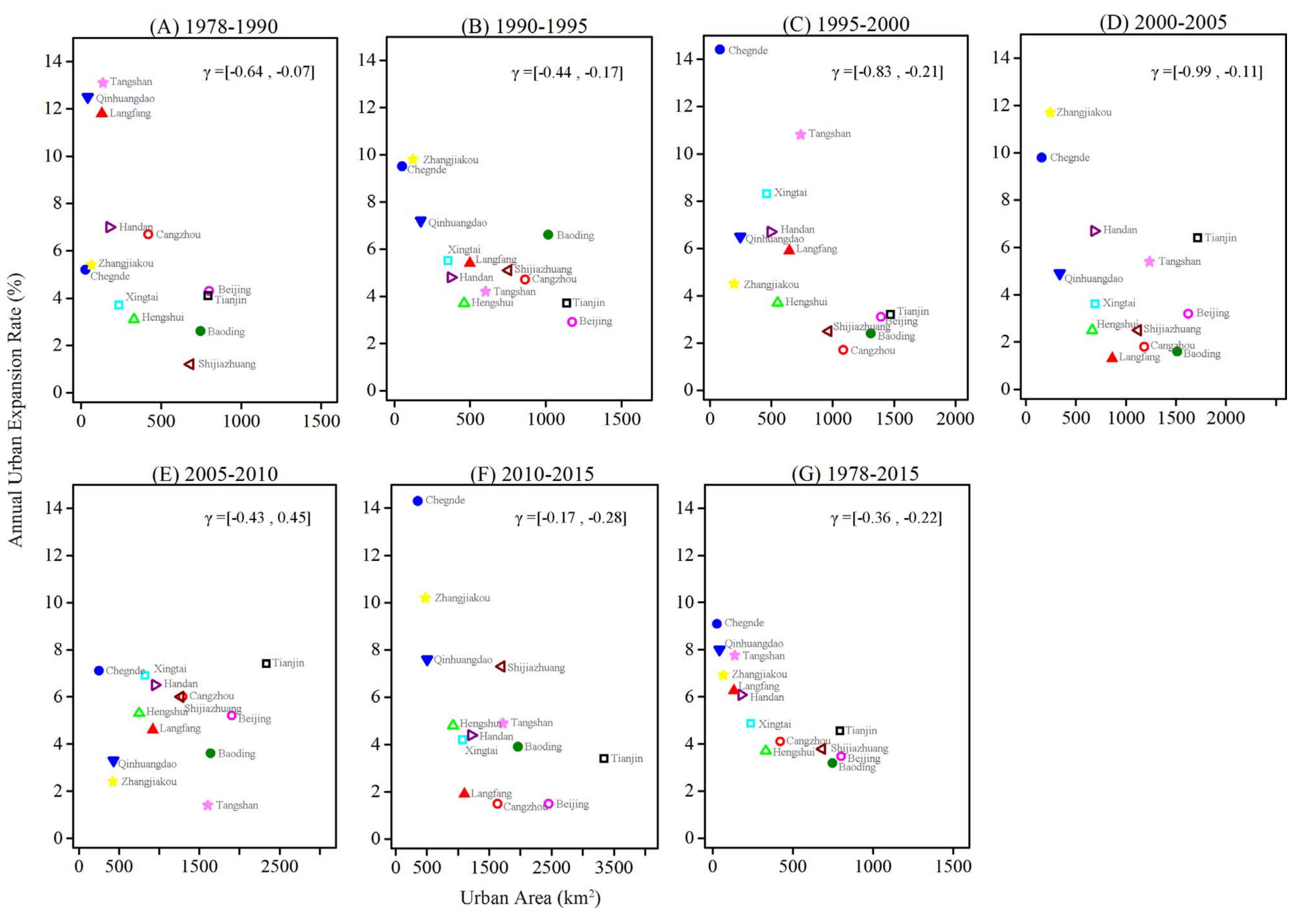

Fig. 9. The relationship between urban expansion rate and city size from 1978 to 2015. The values of γ is the 95% confidence range of the exponent of the power regression.

impact of urban administrative hierarchy on urban expansion rate, it is necessary to take the critical role of government planning policy into account at the same time for better understanding the organization evolution of cities in contemporary China (Li et al., 2015; Zhao et al., 2015a). To better understand the hierarchical effect of administrative level on urban expansion in China's urban agglomerations, we compared the hierarchy structure of the Jing-Jin-Ji Urban agglomeration with the Yangtze River Delta and the Pearl River Delta to shed light on possible drivers behind different urbanization situations in China's top three urban agglomerations. We found that adjustment to the urban

Table 4
Hierarchy structure of the Yangtze River Delta Urban Agglomeration and the Pearl River Delta Urban Agglomeration.

Level	City	Administrative divisions	
		1980s	Recent
		the Yangtze River Delta	
Municipality	Shanghai	12 districts 9 counties	15 districts 1 counties
Provincial capital	Nanjing	10 districts 5 counties	11 districts
Prefectural	Wuxi	4 districts 3 counties	5 districts 2 counties
Prefectural	Changzhou	4 districts 3 counties	4 districts 2 counties
Prefectural	Suzhou	4 districts 6 counties	5 districts 4 counties
Prefectural	Nantong	2 districts 6 counties	3 districts 5 counties
Prefectural	Yancheng	2 districts 7 counties	3 districts 6 counties
Prefectural	Yangzhou	2 districts 9 counties	3 districts 3 counties
Prefectural	Zhenjiang	2 districts 4 counties	3 districts 3 counties
Prefectural	Taizhou	1 districts 4 counties	3 districts 3 counties
Provincial capital	Hangzhou	6 districts 7 counties	8 districts 5 counties
Prefectural	Ningbo	5 districts 6 counties	6 districts 5 counties
Prefectural	Shaoxing	1 districts 5 counties	3 districts 3 counties
Prefectural	Huzhou	1 districts 3 counties	2 districts 3 counties
Prefectural	Jiazhou	2 districts 5 counties	2 districts 5 counties
Prefectural	Jinhua	1 districts 8 counties	2 districts 7 counties
Prefectural	Zhoushan	2 districts 2 counties	2 districts 2 counties
Prefectural	Taizhou	3 districts 6 counties	3 districts 6 counties
Provincial capital	Hefei	4 districts 5 counties	4 districts 5 counties
Prefectural	Wuhu	4 districts 3 counties	4 districts 4 counties
Prefectural	Maanshan	4 districts 1 counties	3 districts 3 counties
Prefectural	Tongluo	3 districts 1 counties	3 districts 1 counties
Prefectural	Anqing	3 districts 6 counties	3 districts 7 counties
Prefectural	Xuancheng	1 districts 6 counties	1 districts 6 counties
Prefectural	Chizhou	1 districts 3 counties	1 districts 3 counties
Prefectural	Chuzhou	2 districts 6 counties	2 districts 6 counties
		the Pearl River Delta	
Provincial capital	Guangzhou	6 districts 4 counties	11 districts
Special Economic Zone	Shenzhen	4 districts 1 counties	6 districts
Prefectural	Foshan	5 districts	5 districts
Prefectural	Dongguan	–	–
Prefectural	Zhongshan	–	–
Prefectural	Zhuhai	1 district 1 counties	3 districts
Prefectural	Jiangmen	2 districts 5 counties	3 districts 4 counties
Prefectural	Zhaoqing	2 districts 6 counties	2 districts 6 counties
Prefectural	Huizhou	1 district 4 counties	2 districts 3 counties

hierarchy of the Jing-Jin-Ji Urban Agglomeration has been far more lagged and the average number of counties for prefectural cities in the Jing-Jin-Ji Urban agglomeration is 12, much more than that of the Yangtze River Delta Urban Agglomeration and the Pearl River Delta Urban Agglomeration (Table 4). The decrease in the number of county-level cities and increase in the number of urban districts in the Yangtze River Delta and the Pearl River Delta over the past three decades might have fueled their urban development because the process of enlarging existing cities through establishment of new urban districts by annexing adjacent counties and county-level cities, part of the "territorial urbanization" concept proposed by Cartier (2011), can significantly fuel urban growth through infrastructure development and construction and more non-urban lands available to be urbanized promoting economic growth. Urban planners might refer to the development experience of the above two urban agglomeration about how to deal with the relationship between urban land expansion and administrative hierarchy in order to optimize the urban spatial structure of cities at all hierarchy levels for ensuring sustainable urban development strategies in the national capital region of China.

4.3. Phases of diffusion and coalescence in urban expansion

The urban expansion processes in the Jing-Jin-Ji Urban Agglomeration generally supported the temporal oscillation between the phases of diffusion and coalescence in the urbanization process hypothesized by Dietzel et al. (2005). In 1978–1990, numerous new patches, formed by leapfrogging urban expansion type, scattered throughout the Jing-Jin-Ji Urban Agglomeration, which can be identified as the diffusion phase. In the early stage of urbanization, hot zone of urban growth, mostly in the form of leapfrogging and edge-expansion, were mainly around the city centers (Fig. 4A and B). The year 1990 can be seen as the transforming point from diffusion to coalescence phase. In the coalescence period, connection between neighborhood urban patches were enhanced (Xu et al., 2007), which is evidenced by the drastic drop of leapfrogging and increase of infilling and edge-expansion in 1990–1995 and thereafter, leading to a compact landscape pattern. While the Jing-Jin-Ji Urban Agglomeration might embrace a new diffusion process, evidenced by the decrease of infilling and increase of leapfrogging in 2010–2015. After more than 30 years of rapid urbanization, the growing space of city's central area is less available and urban growth manifests through outward expansion like establishment of high-tech parks or special economic area thanks to the favorable provincial or local policy (Xu et al., 2007; Zhang et al., 2016). However, there is a clear deviation of Chengde and Zhangjiakou from other cities in the coalescence phase that the leapfrogging is the dominant type of urban growth during the whole urbanization process. These exceptions can be explained by following reasons. First, Chengde and Zhangjiakou was the least urbanized city in the region in the early stage of urbanization (Fig. 3) and thus there might be sufficient space left to leapfrogging urban development, and we may infer that they have not entered the typical phase of coalescent urban growth. Second, Chengde and Zhangjiakou were both cities with varied topography which could constrain edge-expansion urban expansion, the typical growth form in plain area. Third, Chengde and Zhangjiakou are both mountainous cities rich in natural amenities. Under the stimulation of collaborative development policies and with the advancement of technology such as road construction and building engineering, inner-city and inter-city highway of Chengde and Zhangjiakou increased, which might on one hand facilitate the tourism development of Chengde and Zhangjiakou, and on the other hand fire the investment of real estate on independent villas which have been increasingly popular in tourist cities of China.

4.4. Urban patch structure under urban administrative hierarchy

Our urban patch analysis verified that a converged urban patch structure and an invariant scaling relationship between patch size and its corresponding number (Zhao et al., 2015b) can be applied to capital municipality, municipality, provincial capital and prefectural cities independent of the ranks in the urban administrative hierarchy. A slight overestimation (Fig. 7) for Tianjin and Shijiazhuang might be related to the fact that Tianjin underwent urban expansion with almost the lowest annual growth rate whereas Shijiazhuang did experience its highest rate of urban expansion but most of this growth (more than 80%) was accomplished via the forms of edge-expansion and infilling that will not increase the number of patches, resulting in higher predictions than observations. One important reason for the relatively poor fitting (Fig. 8A) for the 10 prefectural cities in the late 1970s might be the strong governmental intervention on urban expansion. In addition, the resampling of MSS imagery from 60 m to 30 m resolution might lead to the number of patches higher than its true value and a resultant underprediction. The generality of converged urban path structure across the urban hierarchy systems in the Jing-Jin-Ji Urban Agglomeration implies that although cities are complex systems interwoven with physical, socioeconomic, political and planning properties and processes, they are invariantly self-organized in a way that can be easily understood and managed.

5. Conclusions

China has 23 urban agglomerations that are considered to possess the greatest potential for China's future economic development. Although the urbanization of the Jing-Jin-Ji Urban Agglomeration has been behind the Yangtze River Delta Urban Agglomeration and the Pearl River Delta Urban Agglomeration, the new policy of "To build a world-class agglomeration of cities with the capital as the core" will be likely to fuel the urbanization process of this region.

We quantified and compared the magnitude, rates, and forms of urban expansion, urban patch structure, and their dynamics for 13 cities across the Jing-Jin-Ji Urban Agglomeration from 1978 to 2015. The rates and forms of urban expansion varied considerably across cities and time due to national and regional policies, physical features and the urban administrative hierarchy. The overall annual urban expansion rate for 13 cities was 5.5 ± 2.0% between 1978 and 2015. For most cities, edge-expansion accounts for the highest proportion of urban expansion form except the early period when leapfrogging dominated. The diverged patterns of urban growth composition for two mountainous cities suggested that the influence of physical intrinsic features of the city on urban expansion could not be ignored in regional urban planning and management strategies. Three major cities (i.e., Tianjin, Beijing and Shijiazhuang) of the Jing-Jin-Ji Urban Agglomeration contributed 36.6% of the urban land area increase of this region. However, the urban expansion rate was generally inversely related to city size, contradicting Gibrat's law during the study period except 2005–2010. Therefore, we cannot draw the conclusion that in the Jing-Jin-Ji Urban Agglomeration, larger cities were better positioned for urban expansion than their smaller counterparts as the hierarchical theory implies. Considerable differences in urbanization level and urban growth trajectory were found for those 13 cities over the past 37 years. Beijing, Tianjin, Shijiazhuang and Baoding contributed to 45.4 percentage of the increased urban land area, with Tianjin leading the rapid urbanization of this region while Chengde, Zhangjiakou, and Qinhuangdao not only displayed distinct spatial patterns of urban expansion from other cities but also ranked in the bottom of urban growth rate.

Our results generally supported the applicability of converged urban patch structure across time and space, and an invariant scaling relationship between patch size and its corresponding number could be applied to capital municipality, municipality, provincial capital and prefectural cities despite the urban administrative hierarchy.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ecolind.2017.12.038.

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