

Similarities and differences of city-size distributions in three main urban agglomerations of China from 1992 to 2015:

A comparative study based on nighttime light data

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Abstract: Comparing the city-size distribution at the urban agglomeration (UA) scale is important for understanding the processes of urban development. However, comparative studies of city-size distribution among China's three largest UAs, the Beijing-Tianjin-Hebei agglomeration (BTHA), the Yangtze River Delta agglomeration (YRDA), and the Pearl River Delta agglomeration (PRDA), remain inadequate due to the limitation of data availability. Therefore, using urban data derived from time-series nighttime light data, the common characteristics and distinctive features of city-size distribution among the three UAs from 1992 to 2015 were compared by the Pareto regression and the rank clock method. We identified two common features. First, the city-size distribution became more even. The Pareto exponents increased by 0.17, 0.12, and 0.01 in the YRDA, BTHA, and PRDA, respectively. Second, the average ranks of small cities ascended, being 0.55, 0.08 and 0.04 in the three UAs, respectively. However, the average ranks of large and medium cities in the three UAs experienced different trajectories, which are closely related to the similarities and differences in the driving forces for the development of UAs. Place-based measures are encouraged to promote a coordinated development among cities of differing sizes in the three UAs.

Keywords: city-size distribution; comparative study; nighttime light data; rank clock; urban agglomeration

1 Introduction

City-size distribution has attracted long-term interests from researchers as it plays important roles in understanding the evolution of city sizes in an urban system and further optimizing the city sizes. According to previous studies, the size of cities in an urban system tends to follow a Pareto distribution (Batty, 2006; Gabaix *et al.*, 2004; Soo, 2014; Xu and Zhu, 2009;

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Anderson and Ge, 2005; Bosker *et al.*, 1999; Giesen and Sudekum, 2011; Tan *et al.*, 2014; Ye and Xie, 2012). In an urban agglomeration (UA), cities have close spatial, economic and communication connections with each other (Fang, 2015). The city-size distribution in a specific UA also follows the Pareto distribution (Duan *et al.*, 2009; Lu *et al.*, 2014; Sheng *et al.*, 2014; Tan *et al.*, 2014). However, the evolution of city-size distribution may vary over time among different UAs (Henderson and Venables, 2009; Xu and Zhu, 2009). Therefore, comparing the dynamics of city-size distribution among UAs might enrich our understanding of similarities and differences in this complex process.

The Beijing-Tianjin-Hebei agglomeration (BTHA), the Yangtze River Delta agglomeration (YRDA), and the Pearl River Delta agglomeration (PRDA) are the three largest UAs in China. During the last two decades, these three UAs played a leading role in the process of urbanization in China (Fang, 2015). They have experienced unprecedented and rapid urban development during the last 20 years. Specifically, the urban population increased from 14.1, 23.7, and 10.8 million in 1990 to 51.9, 74.3 and 46.4 million in 2010 in the BTHA, YRDA and PRDA, respectively (PCO, 1992, 2012). The GDP increased from 740, 1424 and 659 billion to 3969, 7003 and 3767 billion RMB yuan, respectively, in the three UAs (NBS, 1991, 2011). Currently, these three UAs occupy approximately 3% of the total land but account for 18% of the total population and 36% of the total GDP in China (CPG, 2014). More importantly, the New-type Urbanization Plan released by the Chinese government aimed to accelerate the development speeds of these UAs and develop them into world-class UAs (CPG, 2014). The new plan also emphasized a coordinated development of city size and city function in a UA. Therefore, a timely and accurate examination of city-size dynamics is necessary to generate development strategies for the three UAs.

Several recent studies explored the city-size distribution in these three UAs. For example, Sun and Lu (2014) evaluated the city-size distribution in the BTHA between 1995 and 2010. Tian *et al.* (2011) monitored the city-size distribution in the PRDA between 1983 and 2003. Gu *et al.* (2008) examined the city-size distribution in the YRDA from 1994 to 2005. However, comparative studies of UAs are rare. Most previous studies have used the non-agricultural population as a proxy for city size, but due to massive population migration, the non-agricultural population may significantly underestimate the real urban population in cities, particularly in these three UAs, which absorb a large number of migrant workers in China (Fan, 1999; Shen, 1995; Xu and Zhu, 2009). In addition, previous studies have mainly used the Pareto regression method to monitor the overall trend of city-size distribution from the top down without identifying the underlying changes in city size and rank from the bottom up.

Measuring city size based on nighttime light data provides an effective and comparable means to examine city-size evolution consistently over time and space. Generally, there are two types of data to measure city size, the population (e.g., non-agricultural population) data and the urban area data. Researchers have found that the non-agricultural population may underestimate urban residents (Xu and Zhu, 2009), especially in large urban agglomerations that attracts a large number of migrant workers (Huang *et al.*, 2016; Peng, 2011). In addition, the definition of non-agricultural population changed several times and may lead to incomparable results over time (Zhou and Ma, 2003). In comparison, the nighttime light data were collected by sensors with a consistent space platform and a continuous onboard design.

These data provide an alternative data source to non-agricultural population data to measure city size consistently and objectively (Elvidge *et al.*, 2009; Huang *et al.*, 2014). Several studies have adopted city size measured by nighttime stable light (NSL) data successfully to evaluate city-size evolution in China (Huang *et al.*, 2015; Small *et al.*, 2011; Small and Elvidge, 2013; Wu *et al.*, 2014). In addition, the rank clock method can explore the city-size distribution of a UA from the perspective of an individual city's rank changes (Batty, 2006). Combining the traditional Pareto regression with the rank clock method would facilitate the elucidation of the process of city-size distribution at both the aggregated and city levels (Huang *et al.*, 2015).

Our objective was to compare the dynamics of city-size evolution among the three UAs (i.e., the BTHA, the YRDA, and the PRDA) from 1992 to 2015. First, we explored the city-size distribution in the three UAs at the regional level based on the Pareto regression. Second, we examined the city rank dynamics among the three UAs for individual cities using the rank clock method. Finally, we discuss the potential reasons for the differences in city-size distributions among the three UAs qualitatively and provide corresponding policy suggestions.

2 Study area and data

2.1 Study area

We focused on the top three urban agglomerations in China, i.e., the BTHA, YRDA, and PRDA (Figure 1). The BTHA consists of 105 cities with a total area of $18.01 \times 10^4 \text{ km}^2$ (Table 1). In 2010, the total population in the BTHA was approximately 83.78 million, and the proportion of urban residents was nearly 60% (PCO, 2014). Beijing and Tianjin are the two core cities. The development target for the BTHA is to be the most innovative UA in China (Fang and Yu, 2016).

There are 75 cities in the YRDA, which has a total area of approximately $10.75 \times 10^4 \text{ km}^2$ (Table 1). In 2010, the total population of this UA was nearly 107 million, including an urban population of 74.55 million (70%). Currently, Shanghai is the core city of this UA (Fang and Yu, 2016). In the future, the YRDA aims to be a world-class region and the most competitive UA in China (Fang and Yu, 2016).

The PRDA encompasses 27 cities with a total area of $5.41 \times 10^4 \text{ km}^2$ (Table 1). In 2010, approximately 56 million people were living in this UA. More than 82% of the total population are urban residents (Table 1). The PRDA was the pioneer of China's economic reform and opening-up policy (Fang and Yu, 2016).

2.2 Data

In this study, we used three types of data: urban area, administrative boundaries and auxiliary data. The urban area data in China from 1992 to 2015 were produced by He *et al.* (2014) and Xu *et al.* (2016). The urban area in this dataset was extracted using NSL data, the normalized difference vegetation index (NDVI), the land surface temperature (LST), and the support vector machine classification method. The data have a spatial resolution of 1 km. The urban area data were validated by the results extracted from the Landsat TM/ETM+ images in a number of cities in China for 1995, 2000, 2005, 2012 and 2015. The average

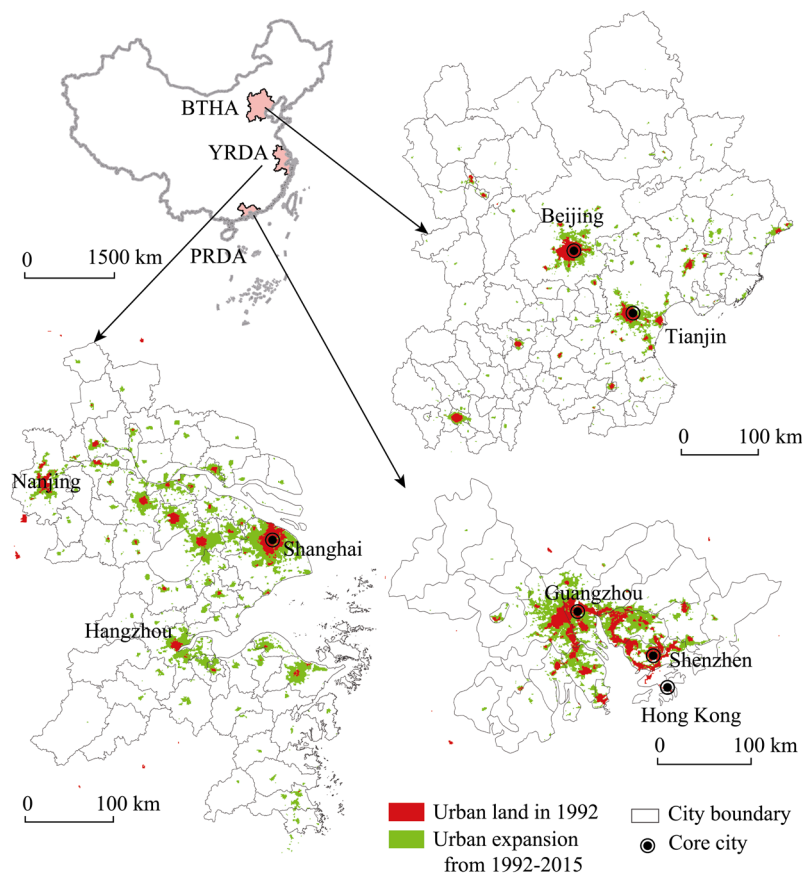


Figure 1 Urban expansion in China between 1992 and 2015
Note: Urban agglomeration abbreviations: BTHA (Beijing-Tianjin-Hebei agglomeration), YRDA (Yangtze River Delta agglomeration), and PRDA (Pearl River Delta agglomeration)

Table 1 Comparison of socioeconomic status among the three urban agglomerations in 2010

Urban agglomeration	Area ($\times 10^4 \text{ km}^2$)	Number of cities	Current core cities	Total population (million)	Percentage of urban population (%)	GDP per capita ($\times 10^4 \text{ yuan}$)
BTHA	18.20	105	Beijing, Tianjin	83.78	59.95	4.73
YRDA	10.75	75	Shanghai	106.51	69.75	6.58
PRDA	5.41	27	Guangzhou, Shenzhen, Hong Kong	56.13	82.72	6.71

Kappa and average overall accuracy of the data are greater than 0.60 and 92.6%, respectively. The average quantity disagreement and average allocation disagreement of data are below 2.3% and 5.9%, respectively. More details on the validation process can be found in He *et al.* (2014) and Xu *et al.* (2016). Based on the dataset, the time-series urban areas from 1992 to 2015 in the three UAs were extracted to evaluate the city-size evolution.

The administrative boundaries of the cities were obtained as Geographical Information System (GIS) files at a scale of 1:4,000,000 from the National Geomatics Center of China. For the auxiliary data, China's land use/cover datasets (NLCDs) for 1990 and 2010 with a spatial resolution of 1 km were obtained from the Data Sharing Infrastructure of the Earth

System Science at the Chinese Academy of Sciences. The NLCDs were produced based on the visual interpretation of Landsat images at a spatial resolution of 30 m (Liu *et al.*, 2014). The datasets were used to validate the results.

3 Methods

In this study, we used both the Pareto regression and the rank clock method to examine the city-size distribution in the three UAs. The two methods are complementary and the results can exhibit a whole picture of city-size distribution at the UA level as well as the city level.

3.1 Examining regional city-size distribution based on the Pareto regression

The regional city-size evolution was examined based on the Pareto regression method. This method was first proposed by Felix Auerbach, a German physicist, in 1913 (Xu and Zhu, 2009). It can be used to evaluate the distribution of city sizes (Eaton and Eckstein, 1997; Rosen and Resnick, 1980). The Pareto regression can be described as follows:

$$R_i = AS_i^{-\alpha} \quad (1)$$

where S_i refers to the size of city i (in this study, it is measured by the total urban land of a particular city). A refers to the size of the largest city. R_i refers to the number of cities with sizes no less than S_i . α represents the Pareto exponent (Li and Sui, 2013). The value of α ranges from 0 to positive infinity. To examine the city-size evolution over time or across countries empirically, the following formula is often used to compute the Pareto exponent (Soo, 2014; Ye and Xie, 2012):

$$\ln R_i = \ln A - \alpha \ln S_i + u \quad (2)$$

where u is the error term. A larger α suggests that the city-size distribution is more even, and vice versa (Xu and Zhu, 2009).

3.2 Analyzing the city rank dynamics based on the rank clock method

The rank changes among cities of different sizes were compared using the rank clock method. This method was first proposed by Batty (2006). In this method, a round disk is adopted to show the trajectories of individual cities' rank changes clockwise within a specific time period. The rank decreases from the center to the circumference. The circumference is divided into equal shares to correspond with the time interval. Turbulent changes in city rank over time can be identified visually and quantitatively using this method.

Based on this method, we calculated the mean value of the absolute rank shift (ARS, see equation 3) of all cities in each UA to compare the city-level rank fluctuations among the three UAs:

$$ARS_i = \sum_{t=1993}^{2012} |R_{i,t} - R_{i,t-1}| \quad (3)$$

where ARS_i is the absolute rank shift of city i in a particular UA and $R_{i,t}$ represents the rank of city i at year t . ARS measures the rank shift in terms of the absolute value and thus implies the magnitude of rank fluctuations during a particular period.

To further compare the differences in rank changes among the three UAs, we divided the cities within each UA into three categories according to city size and compared the changes

in the average ranks of the cities over time (see equation 4).

$$R_s = \sum_{i=1}^n R_{i,t} / n \quad (t=1992, 1993, \dots, 2015) \quad (4)$$

where R_s is the average rank of cities of s type (in this study, there were three types: small city, medium city and large city). n represents the number of cities of s type.

The cities in each UA were categorized as large, medium and small. Unlike the division based on population or urban population, there were no common criteria for categorizing city sizes by the extent of urban area. In addition, using absolute values for the division may lead to conflicting results among the three UAs. For example, using the extent of urban land in Shijiazhuang to distinguish large and medium cities in the BTHA may lead to no large city in the PRDA. Therefore, we adopted a method that not only considers the power-law distribution of city sizes in a UA, but also guarantees the consistency and comparability of criteria among the three UAs. Specifically, all cities of a UA were ranked by their sizes (i.e., extent of urban area) in 1992 in a descending order. Large cities accounted for approximately 50% of the total urban areas in each UA. Medium and small cities accounted for the remaining 40% and 10%, respectively. The final division agreed with common experience, i.e., the division by population.

4 Results

4.1 Similarities of city-size evolution in the three urban agglomerations

The city-size evolution exhibited two similar trends among all three UAs. First, in all three UAs, the city-size distributions became more even between 1992 and 2015 (Figure 2). Based on the Pareto regression, the largest increase in the estimated Pareto exponent occurred in the YRDA. The exponent increased from 0.53 in 1992 to 0.70 in 2015, with an annual average change of 0.007. By contrast, the smallest increase occurred in the PRDA. The increase in the Pareto exponent in the BTHA was 0.12, with an annual average change of 0.005.

Second, in all three UAs, the average rank of small cities exhibited a similar rising trend from 1992 to 2015 (Figures 3d, 3e and 3f). This finding indicates that the sizes of some small cities exceeded those of some medium cities in all three UAs. The rise in the average rank of small cities was the largest in the YRDA, followed by the PRDA and then the BTHA. Specifically, in the YRDA, the average rank of small cities rose from 37.00 to 36.45 because the ranks of four small cities, i.e., Kunshan, Jiangyin, Wujiang and Cixi, increased from 16, 12, 25 and 18 in 1992 to 8, 9, 10 and 11 in 2015, respectively. In BTHA, the average rank of small cities increased from 34.50 to

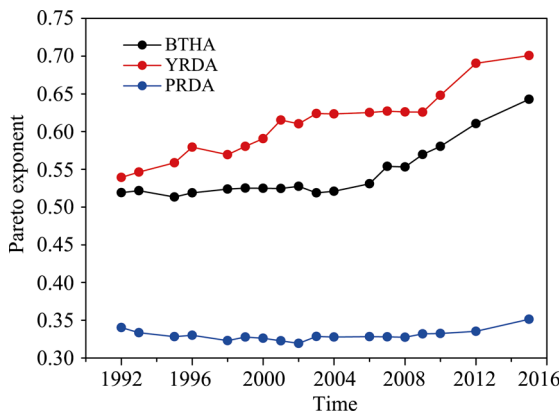


Figure 2 Temporal changes in the Pareto exponent among the three urban agglomerations from 1992 to 2015
Please refer to Figure 1 for an explanation of the abbreviations.

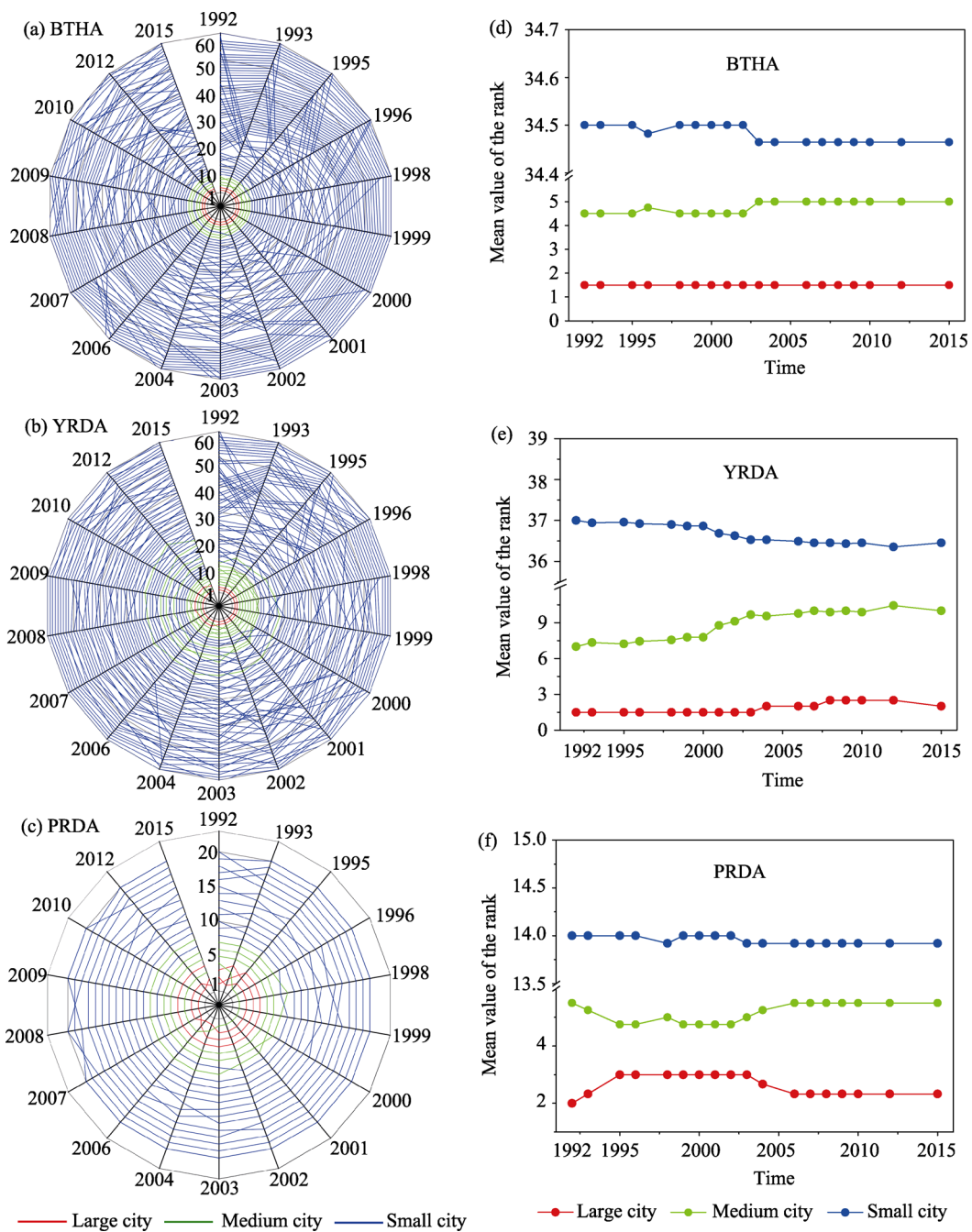


Figure 3 Comparison of rank fluctuations and the average rank for cities of differing sizes among the three urban agglomerations
Note: a-c: Rank clocks of individual cities within each urban agglomeration; d-f: Changes in the average ranks of cities of differing sizes

34.46, along with the rise in rank from 7 to 5 of Qinhuangdao. The average rank of small cities in the PRDA rose from 14.00 to 13.92 due to a rise in the rank of Jiangmen.

4.2 Differences of city-size evolution among the three urban agglomerations

The city-size evolution among the three UAs also exhibited two different trends. First, the city-rank fluctuations differed among the three UAs. The BTHA experienced the largest fluctuation, followed by the YRDA and then the PRDA. The mean values of absolute rank shift (ARS) were 42.35 in BTHA, 34.48 in the YRDA, and 4.60 in the PRDA. In the BTHA, Yutian had the largest rank fluctuation, with an ARS of 88. In the YRDA, Haimen exhibited the largest rank fluctuation, with an ARS of 74. In the PRDA, Taishan witnessed the largest rank fluctuation, with an ARS of 10.

Second, the medium and large cities exhibited distinct trajectories of ranks among the three UAs. In the BTHA, the average rank of large cities remained stable, whereas that of medium cities dropped. Specifically, the two large cities (i.e., Beijing and Tianjin) remained the top two locations, whereas the rank of a medium city (Baoding) fell from 5 to 7. By contrast, in the YRDA, the average ranks of both large and medium cities dropped. In this UA, the rank of a large city (Nanjing) was exceeded by those of two medium cities (Hangzhou and Suzhou), which resulted in the rank of Nanjing dropping from 2 to 4. Meanwhile, the ranks of four medium cities, Zhenjiang, Yangzhou, Nantong and Huzhou, were surpassed by some small cities, with the ranks of these cities dropping from 7, 8, 10 and 11 to 12, 19, 14 and 21, respectively. In contrast to the other two UAs, in the PRDA, the average rank of large cities dropped, whereas the average rank of medium cities did not change over time. In this UA, the rank of Shenzhen was surpassed by Dongguan and fell from 1 to 4. Overall, the average rank of medium cities remained stable.

5 Discussion

5.1 Nighttime light data provide an alternative measure for examining city-size distribution

Two approaches were used to validate the evolution of city-size distribution measured by the DMSP/OLS NSL dataset. The validation results confirmed that the distribution of city sizes can be measured by the NSL dataset objectively and consistently. First, the Pareto exponents estimated from the NSL dataset were compared to those extracted from the NLCDs during overlapping years (i.e., between 1990 and 2010). The Pareto exponents estimated from the two datasets displayed similar trends. Specifically, the Pareto exponents derived from the two datasets increased in the BTHA and the YRDA, whereas the estimated exponents decreased in the PRDA (Table 2). Second, the findings reported here were also in line with conclusions from previous studies. For instance, at the UA scale, previous studies have also found that the distribution of city sizes became more even in the BTHA (Wen and Thill, 2016) and the YRDA (Wang *et al.*, 2016) but more concentrated in the PRDA (Li *et al.*, 2007), respectively.

5.2 The driving forces for city-size distribution among the three urban agglomerations

The key factors that affect the development of a UA include political effects, the spatial linkage of industries, transportation networks, market mechanisms, technological advancement and investment (Fang and Yu, 2016). Based on existing research, we observed that the

dynamics of city-size distribution among the three UAs were closely related to the similarities and differences in the key factors driving the development of the three UAs (Table 3).

Table 2 Comparison of the Pareto exponents derived from various datasets

Region	Time	DMSP/OLS NSL dataset		NLCDs	
		Pareto exponent	R ² (%)	Pareto exponent	R ² (%)
BTHA	1990	0.52	83.12	0.71	95.61
	2010	0.61	95.77	0.78	95.81
YRDA	1990	0.54	96.68	0.83	97.28
	2010	0.69	95.28	0.90	96.84
PRDA	1990	0.34	87.59	0.49	85.62
	2010	0.33	78.68	0.46	90.08

Note: DMSP/OLS NSL (Defense Meteorological Satellite Program/Operational Linescan System), NLCDs (National Land use/Cover Datasets)

Table 3 Comparison of the major driving forces of city-size distribution dynamics among the three urban agglomerations

Region	City-size distribution dynamics		Major driving forces	
	Similarity	Differences	Similarity	Differences
BTHA		Rank of large cities: Stable Rank of medium cities: Down Rank of small cities: Up	Political effects exerted great impacts on city-size distribution, such as the stable rank of large cities in BTHA and the rising of small cities in YRDA and PRDA (Lu, and Fan 2010, Gu <i>et al.</i> , 2008).	
YRDA	Pareto exponent increased, indicating a more even distribution	Rank of large cities: Down Rank of medium cities: Down Rank of small cities: Up		Spatial linkage of industries encouraged the rising rank of small cities close to Shanghai (Luo and Shen, 2009)
PRDA		Rank of large cities: Down Rank of medium cities: Stable Rank of small cities: Up		Investment and transportation encouraged the rising ranks of small cities close to Hong Kong (Yeh and Xu, 2010, 2013; Xu & Anthony, 2009)

The evolution of the city-size distribution in the three UAs was influenced by a similar driving force, political effects. In the BTHA, the ranks of two large cities (Beijing and Tianjin) were stable and held the top two places during the studied period. One major reason for this position is that, as the national capital and a municipality that is directly under the control of the central government, Beijing and Tianjin have policy advantages and significant agglomeration effects (Wen and Thill, 2013). To guarantee the development of Beijing and Tianjin, the central government demanded that medium and small cities in this UA provide low-cost minerals, industrial materials, fresh water, and agricultural products to the two core cities and imposed restrictions on resource development, energy use, and industrial development in these medium and small cities (Lu and Fan, 2010).

In the YRDA and PRDA, political advantages also exerted great influence on the rising ranks of small cities. Specifically, the local government offered a number of preferential policies on taxation and financing to promote the development of township enterprises in small cities (Gu *et al.*, 2008). For example, in the YRDA, the development of township enterprises in certain small cities (e.g., Jiangyin, Kunshan and Wujiang) accelerated the increase in their city sizes, which exceeded the sizes of some medium cities (e.g., Nantong and

Yangzhou). Similarly, in the PRDA, “rural urbanization” driven by the growth of township enterprises has made small cities hotspots of regional economic development and urban expansion.

There were also differences in the driving forces for the city-size distribution among the three UAs. In the BTHA, political effects play a dominant role, whereas other factors have little influence. In the other two UAs, other factors also influenced the evolution of city-size distribution. In the YRDA, the evolution of city-size distribution was also influenced by the spatial linkage of industries. We observed that the ranks of large cities and medium cities in the northwestern part of the YRDA fell, whereas the ranks of small cities in the southeastern part of the YRDA increased. This pattern is attributable to the weaker intensity of spatial linkages between Shanghai and northwest cities compared to the intensity of the linkages between Shanghai and the southeast cities (Luo and Shen, 2009). The cities closer to Shanghai (e.g., Kunshan, Cixi and Wujiang) had the advantage of accepting industrial transfers from Shanghai, and their ranks rose accordingly.

In contrast to the other two UAs, the investment and transportation network in the PRDA played an important role in shaping its city-size distribution (Jin *et al.*, 2010). The ranks of small cities in the eastern part of the PRDA ascended, whereas the ranks of the medium cities in the west remained stable or declined. The differences in investment and transportation networks between small cities in the east and medium cities in the west might explain this phenomenon. Investments from Hong Kong are largely concentrated in the cities in the eastern part of the PRDA (Yeh and Xu, 2010), and the transportation network is less efficient and more expensive in the western part of the PRDA than the eastern part (Yeh and Xu, 2010). Therefore, the cities in the eastern part of this region (i.e., Dongguan and Huizhou) underwent rapid development, and their city-size ranks continued to rise.

5.3 Policy implications

Based on the analyses of the city-size evolution in each UA, we can advocate different measures to promote coordinated development among cities of different sizes. In the BTHA, accelerating the development of medium and small cities plays a key role in promoting the sustainable development of the urban system (Lu and Fan, 2010). Medium and small cities should take advantage of the “radiation effect” of Beijing and Tianjin to encourage the aggregation of population, capital, and industries. They should also optimize their industrial structure to promote the acceptance of industry transfers from Beijing and Tianjin. In the YRDA, attention should be paid to enhancing regional industrial coordinated development (Gu *et al.*, 2008). The spatial linkage of industries between cities in the northwestern part of the YRDA (e.g., Nanjing, Yangzhou and Zhenjiang) and the core city (i.e., Shanghai) should be strengthened by enhancing the development of complementary industries. In addition, the radiation effect of Nanjing to its surrounding cities (e.g., Yangzhou, Nantong and Huzhou) (Luo and Shen, 2009) should be enhanced to increase the spatial linkage of industries in this region. In the PRDA, accelerating the development of the medium and small cities in the western part of the urban agglomeration should be the priority for policy makers (Tian *et al.*, 2011). To achieve this goal, the transportation connections between these cities and Hong Kong must be improved via a number of measures, for instance, the construction of the

“Hong Kong-Zhuhai-Macau Bridge.”

5.4 Future work

There are some uncertainties in our study. First, the accuracy of city size extraction can be affected by the inherent limitation of the spatial resolution of the DMSP/OLS NSL datasets (Liu *et al.*, 2012). For example, the urban land of some cities failed to be extracted due to the low spatial resolution of 1 km, particularly in regions with weak nightlight (Liu *et al.*, 2012). Additionally, the urban area might be overestimated due to the “overglow” effect in nighttime images, particularly for large cities that have a high level of light intensity. Both the underestimation and overestimation of urban land may affect the value of the Pareto exponent. Second, we only qualitatively analyzed the potential reasons for the differences of the city-size dynamics among the three UAs based upon previous research.

In the future, the release of Visible Infrared Imaging Radiometer Suite (VIIRS) nighttime light datasets with finer spectral and spatial resolutions (Shi *et al.*, 2014), and newly developed method identifying the urban boundary (Peng *et al.*, 2016) should permit more accurate extraction of urban areas than the results in this study. In addition, we could use quantitative statistical approaches, such as principal component analysis and/or spatially explicit regression models (Zeng *et al.*, 2015; Peng *et al.*, 2015), to perform an in-depth comparison of the driving forces that underlie the changes in city-size distribution among the three UAs by simultaneously considering political, socioeconomic, locational, and physical factors.

6 Conclusions

Nighttime light data provide an effective and accurate means to examine city-size distribution at the UA scale. The Pareto exponents estimated from the nighttime light dataset were consistent with those extracted from the NLCDs during the overlapped years between 1990 and 2010.

The city-size distributions of the three largest UAs in China shared similar trends. First, the distributions of city size became more even among the three UAs from 1992 to 2015. The Pareto exponents increased by 0.17, 0.12, and 0.01 in the YRDA, BTHA, and PRDA, respectively. Second, the average ranks of small cities rose in all three UAs. Meanwhile, the city-size distribution among the three UAs exhibited different degrees of rank fluctuation, especially for large and medium cities.

The evolution of city-size distribution among the three UAs was affected by a similar driving force, the influence of preferential policies. However, the city-size distributions in the YRDA and the PRDA were affected by additional factors, including the spatial linkage of industries, investment, and transportation networks. Thus, in order to develop a more coordinated UA following the New-type Urbanization Plan released by the Chinese government, place-based measures should be used to promote the coordinated development among cities of differing sizes in the three UAs in the future.

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