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Investigating the Synergistic Evolution Mechanism of Multi-Scale Cities: A Case Study of Three Urban Agglomerations in Eastern China

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Abstract: Urban growth has evolved from cities to metropolitan areas and urban agglomerations, exhibiting a multi-scale pattern. Urban scaling law can reflect the nonlinear relationship between urban indicators and population size, which is very important for urban planning through analyzing the evolution of urban system characteristics. However, existing studies mainly focused on scalar law within countries, neglecting the multi-scale synergistic evolution of complex urban systems. The purpose of this study is to investigate the scalar relationship between urban indicators and population size at multiple scales from the perspective of individual cities, metropolitan areas, and urban agglomerations, using data from 45 cities in three urban agglomerations in eastern China. Based on the urban scaling law, local spatial autocorrelation model is used to analyze and explore the collaborative evolution of multiple scales. Results show that from the perspective of time evolution, the three urban agglomerations exhibit greater scaling effects than metropolitan areas, with a scaling exponent (β) greater than 1 for urban indicators including economy, land, infrastructure, ecological pressure, and innovation. From the perspective of spatial differences, the spatial development gap between the metropolitan area scale and the urban agglomeration scale is relatively small compared with the city scale. In addition, the Beijing–Tianjin–Hebei urban agglomeration (BTH) mainly displays the synergistic development of the dual-core structure of Beijing and Tianjin. The Yangtze River Delta (YRD) exhibits significant disparities between its cities, resulting in a low degree of overall synergy. In contrast, the Guangdong-Hong Kong-Macao Greater Bay Area (GBA) leads in terms of synergistic evolution. This study is crucial to help understand the development of urban systems at different scales and to support regional planning and the achievement of coordinated development.

Keywords: scaling law; multi-scale; co-evolution; metropolitan area; urban agglomeration

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1. Introduction

Since the 20th century, rapid urbanization and globalization have given rise to mega-cities and megacities worldwide, with metropolitan areas, urban agglomerations, and contiguous areas of large cities emerging in various locations. These developments have brought about significant changes to the urban landscape, resulting in the formation of a complex multi-level spatial structure [1–4]. Over the past 40 years of reform and opening up, China's city scale has continued to increase, and urbanization rates have risen, with three of China's representative urban agglomerations forming in the eastern region, the Beijing-Tianjin-Hebei urban agglomeration (BTH), the Yangtze River Delta (YRD), and the Guangdong-Hong Kong-Macao Greater Bay Area (GBA) [5]. Understanding how different scales of cities can synergistically evolve in time, space, and organization during rapid urbanization is crucial for regional sustainable development.

Cities are complex systems with characteristics such as self-organization and nonlinearity [6,7]. Metropolitan areas and urban agglomerations established by numerous cities aggregate a significant quantity of resources in a restricted space, such as population, capital, technology, and innovation, and have a high economic volume and radiation capacity, as well as the same qualities as complex systems [8–10]. The first stage of the urban development system is characterized by substantial agglomeration in the center city, a high degree of industrial and population agglomeration in the first city, and a siphon effect throughout the region [11]. During the second stage, the regional center gradually spreads and becomes polycentric, leading to the development of urban systems in subsidiary cities within the region, eventually establishing metropolitan areas within a commuting circle of one hour [12]. In the third stage, the region's first metropolitan area will continue to grow, while the second metropolitan area's population growth rate will outstrip it, increasing the population of the region's small and medium-sized cities which are smaller in population and area compared to major cities. Relying on a well-developed infrastructure network, an urban agglomeration with one megacity as the core and at least three metropolitan areas or large cities as the basic units is gradually formed, which is characterized by a relatively compact space and a highly integrated economy. In summary, cities transition from urban areas to metropolitan areas and urban agglomerations through the tangible material exchange, connected transportation infrastructure networks, and intangible flow spaces intertwined between cities [13,14]. The evolution of urban space reflects the multidimensional, multilevel, and multifactorial structure of the urban system [15]. Analyzing the evolution process of urban systems to summarize the laws and patterns of urban development is the foundation for achieving sustainable cities.

At present, the research content and methods of the evolution process of cities, metropolitan areas, and urban agglomerations are constantly enriched. From a research perspective, studies on cities tend to focus more on changes in spatial relationships among elements and the evolution of geographical space. In contrast, research on metropolitan areas and urban agglomerations tends to be more concerned with centralization, networking, and the structure of different layers within the regions [16–21]. Wang et al. calculated the centrality indices of six major urban agglomerations in China based on population and economic use of the ordinal scale rule [22]. In terms of indicators and research methods, indicators have diversified from population and economic indicators to land, innovative technology, and ecological environment indicators, and network analysis methods, GIS-based spatial analysis, remote sensing, and landscape indices are useful for studying the evolution of urban agglomerations [23–27]. Although there have been many studies on spatial evolution, there is still a lack of research on the synergetic evolution of cities at multiple scales.

In recent years, the theory of urban scaling laws has provided new insights into the evolution of urban systems, based on common approaches to the evolution of urban systems [28,29]. Scaling laws can help reflect the characteristics of urban functions and the development status of urban systems [30–33], which is used to assess the balance of development of urban indicators and urban sustainability [34–36]. The basic formula of urban scaling law is $Y = Y_0 N^{\beta}$, where Y is an urban index, N is population size, and β is scaling exponent. The scaling exponent represents the nonlinear relationship between urban index and urban population size [37,38]. Scholars have conducted extensive research on urban scaling laws, which have been supported by a wealth of empirical evidence covering various urban indicators in many countries, including GDP, land use efficiency, urban crime, environmental pollution, social interactions, and urban form (Table 1). Most scaling law studies have focused on short-term data and city scales, and have lacked exploration of the multi-scale coordinated evolution of complex urban systems, which hinders the investigation of the dynamic changes in complex urban systems [39,40].

Table 1. Studies related to urban scalar laws.

Authors	Country	Sample Size	Urban Features
Bettencourt, L.M.A., et al. [29]	US, European Union, China	MSAs, LUZs, UAUs	New patents, inventors, private R&D employment, total wages, total electrical consumption, total housing, GDP, total employment, gasoline stations, and road surface
Arcaute, E., et al. [41]	UK	8850 wards of England and Wales	Patents
Fragkias, M., et al. [42]	US	942 urban 'core based statistical areas'	CO_2 emissions
Schläpfer, M., et al. [43]	Portugal, UK	nationwide communication records	social connectivity
Bettencourt, L.M.A. and Lobo, J. [44]	Europe	102 cities	GDP, urbanized area, employment, patents
Jiao, L., et al. [45]	China	289 prefecture-level cities	Urban land use efficiency
Prieto-Curiel, R., et al. [46]	Africa	Nearly 6000 urban agglomerations	Urban form
Cottineau, C., et al. [47]	France	Urban units and Metropolitan areas	Land use, commuting flows, commuting flows, jobs by sector, infrastructures, hospitals, and length of roads
Keuschnigg, M., et al. [48]	Sweden	Sweden's 75 labor market areas	Wage income
Arvidsson, M., et al. [49]	Europe and the US	cities in Sweden, Russia, and the United States	interconnectivity, productivity, and innovation

Thus, this study establishes a multi-scale perspective based on the urban scaling law, and explores the co-evolution of urban systems in the BTH, YRD, and GBA. The main objectives include: (1) To verify multi-scale urban scaling law, and to reveal the temporal changes and spatial differences of the scaling exponents of urban indicators at different scales; (2) to comparatively analyze the evolution process of multi-scale urban scaling law; (3) to analyze the process of regional co-evolution through spatial autocorrelation analysis of scaling exponents for urban indicators in three urban agglomerations. The BTH, YRD, and GBA are of great strategic significance to national economic development. This study innovatively deepens the dynamic analysis of urban system evolution from a multi-scale perspective based on the urban scaling law, and examines the balance and efficiency of the development of these three important urban agglomerations, which serves as a theoretical basis for proposing development suggestions.

2. Materials and Methods

2.1. Study Area and Data

BTH, TRD, and GBA are the most economically developed regions in China, known for their high-density and high-urbanization areas with well-established urban systems, including 10 metropolitan areas and 45 cities (Figure 1). Due to the differences in the definition of the concept and spatial scope of metropolitan areas and urban agglomerations in relevant studies at home and abroad, this study relies upon China Metropolitan Area Development Report 2018, Yangtze River Delta Urban Agglomeration Development Plan and Outline of the Guangdong-Hong Kong-Macao Greater Bay Area Development Plan.

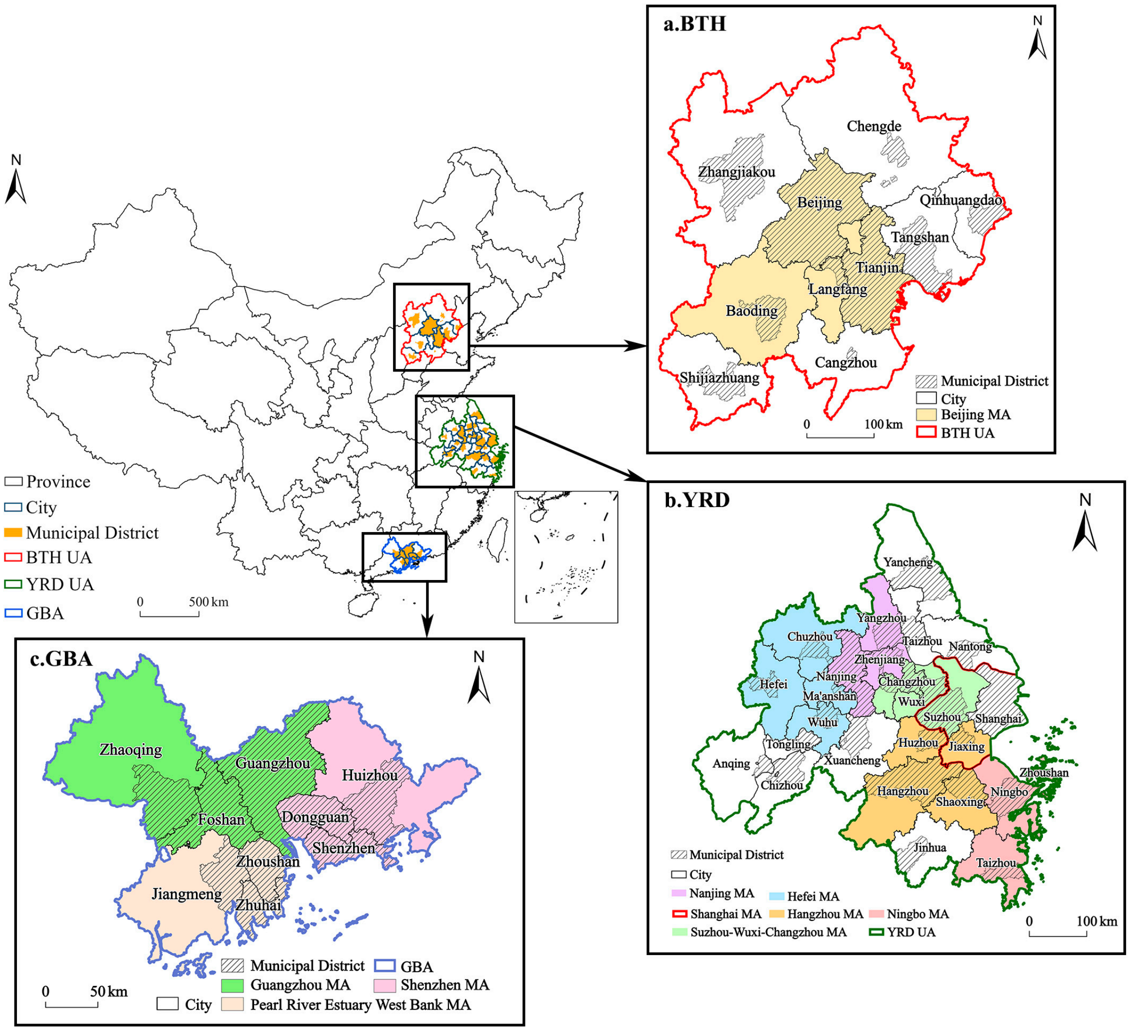

Figure 1. Study Area.

Due to the high urbanization rate in municipal districts, they are more representative of the "urbanized areas". Therefore, the statistical scope of urban indicators is defined as municipal districts. This study collects data on population and urban indicators for urban areas above prefecture level contained in the three major urban agglomerations from China Urban Construction Statistical Yearbook (1999–2018) and China Urban Statistical Yearbook (2000–2019). Considering that urban indicators need to represent the urban development dimension, we selected 12 urban indicators, including economic development (GDP), land use (built-up area, green coverage area of built-up area, area of green space), infrastructure (length of urban roads, area of urban roads, length of water supply pipelines, total collections of public libraries, number of beds in hospitals and health centers), environmental pressure (annual quantity of wastewater discharged, house garbage collected and transported), technological innovation (number of invention patent applications). We chose these specific indicators because they are widely used in urban studies and provide a comprehensive understanding of different aspects of urban development. For instance, the GDP is an important economic indicator that reflects the overall economic performance of a city or region. The built-up area, green coverage area of built-up area, and area of green space provide insights into the land use pattern and the extent of urbanization. The length of urban roads, area of urban roads, and length of water supply pipelines are indicators of infrastructure development. The total collections of public libraries and number of beds in hospitals and health centers can reflect the level of development of public infrastructure and social welfare. The annual quantity of wastewater discharged, house garbage collected, and transported are important indicators of the environmental pressure caused by urban development. As cities grow and populations increase, there is often a corresponding increase in the production of waste and wastewater, which can have negative environmental impacts if not properly managed. Therefore, monitoring the amount of wastewater and waste produced by a city is crucial in assessing its environmental sustainability. Technological innovation is a key driver of economic growth and social progress, and cities with higher levels of technological innovation tend to be more competitive and attractive to businesses and skilled workers. Therefore, measuring the number of invention patent applications is a useful indicator for evaluating a city's innovative capacity and potential for future growth. China's regional statistics are based on administrative divisions, and GDP is deflated using GDP data from China Urban Statistical Yearbook for municipal districts, with 2000 as the base year. We removed data that had changed abruptly due to administrative division changes and corrected data using local statistics yearbooks, resulting in a sample of 45 cities in three major metropolitan agglomerations. Due to missing data, Hong Kong and Macau are excluded from the scope of this study.

2.2. Urban Scaling Law

Bettencourt et al. introduced Kleber's law into urban research and proposed the urban scaling law, which represents the nonlinear relationship between urban indicators and urban population [38]. Urban scaling law has been widely used in geography and sociology. For example, some scholars have compared the differences in regional development and provided development suggestions by analyzing the geographical spatial differentiation characteristics of scaling exponents for urban indicators [45]. In sociology, some scholars have found that human networks and productivity exhibit a heavy-tailed distributions in the urban scaling law, revealing the inequalities that urban residents benefit from during the process of urban expansion [49]. The formula is as follows:

$$Y_i(t) = Y_0 N_i(t)^{\beta} \quad (1)$$

where $Y(t)$ represents the measurement of various indicators (GDP, built-up area, etc.) within the city; i represents different cities within the whole urban system; $N(t)$ is the urban population size at time t; Y_0 is the normalized constant; β is the scaling exponent.

We take logarithms on both sides of Equation (1) and get:

$$log Y_i(t) = log Y_0 + \beta log N_i(t) \quad (2)$$

Urban indicators can be classified into three categories according to the scaling exponent β: (1) sublinear indicators ($\beta \approx 0.85 < 1$) show a sublinear relationship with urban population size, mainly including urban indicators related to infrastructure construction (length of roads, etc.), where the rate of increase of indicators is smaller than the rate of increase of the population; (2) linear indicators ($\beta \approx 1$) show a linear relationship with the urban population, mainly including indicators related to individual demand (number of houses, household water consumption, etc.); (3) super linear indicators ($\beta \approx 1.15 > 1$) show a superliner relationship with the urban population, mainly including urban indicators related to economy and social interaction (GDP, knowledge output, etc.), reflecting the increasing return to scale effect of urban indicators [29].

2.3. Research Method of Multi-Scale Co-Evolution

Spatial autocorrelation models include global spatial autocorrelation and local spatial autocorrelation, which measure and test patterns of spatial association. Global spatial autocorrelation explores the average degree of association of an attribute value across the study area, while local spatial autocorrelation reflects the degree of association and distribution pattern of an attribute value in one regional unit with the same attribute value in neighboring regional units. From city to metropolitan area and then to urban agglomeration, evolution is a complex process, which is influenced by many factors such as economy, politics, and technology. Urban scaling law provides a simplified method to understand multi-scale co-evolution by analyzing the impact of city size on urban indicators at city, metropolitan, and urban agglomeration scales. Based on the urban scaling law, this study discusses the co-evolution of city-metropolitan circle-urban agglomeration and pays attention to the correlation between the development level of urban indicators and the development level of urban indicators in neighboring cities. Therefore, the local Moran's I index is used for analysis. The formula is as follows:

$$Local\ Moran's\ I_{ij} = \frac{n(\beta_{ik} - \overline{\beta_k})\sum_{j=1}^{n}\omega_{ij}(\beta_{jk} - \overline{\beta_k})}{\sum_{j=1}^{n}(\beta_{jk} - \overline{\beta_k})^2} \quad (3)$$

where β_{ik} represents the scaling exponent of urban indicator k for city i, n represents the number of cities, ω_{ij} is the spatial weight, and the spatial weight matrix is created by K-nearest neighbors. Through the Moran scatter plot to achieve a more intuitive LISA plot on the map, spatial association mode of local autocorrelation can be divided into four types, HH(LL) indicates that the high-value (low-value) unit is also clustered around the high-value (low-value) unit; HL indicates that the high-value unit is surrounded by low-value cells; LH indicates that the low-value cell is clustered around the high-value unit.

3. Results

3.1. Multi-Scale Urban Scaling Law

3.1.1. City Scale

Figure 2 showed that the relationship between urban GDP and population from 2000 to 2018 was super-linear (β > 1), which was in line with the theoretical expectation. From 2000 to 2009, β value of GDP increased from 1.07 to 1.14, indicating the effect of urban economic agglomeration increased. After 2009, β value of GDP began to decline to decrease until 1.05 in 2018, with the stable play of the economic agglomeration effect. City economic development did not rely on innovation-driven. From 2000 to 2014, the number of patent applications for inventions showed a super-linear relationship with population, but the number of patent applications for inventions showed a nearly linear relationship with the population since 2015, indicating a weakening of the urban talent agglomeration effect and a stable rate of technological innovation in cities.

The scale economy of land use has been more significant because built-up area has been always sub-linearly related to the population (β < 1). β value of the built-up area increased from 0.88 to 0.90 from 2000 to 2009, and the comparative advantages of land use economies of scale in large cities gradually weakened. Since then, β value of the built-up area decreased, falling to the lowest value of 0.82 in 2018, indicating a strengthening trend of land use scaling. In terms of ecological green space, β value of green coverage area of built-up area was stable between 0.84 and 0.98, while β value of green space area is between 0.94 and 1.10. β value related to green space was generally greater than β value of built-up area, indicating that although land resources are in short supply in urban construction and the trend of land use intensification is strengthened, greening work has been still paid attention to and implemented in place.

The supply of urban infrastructure such as roads, water supply, and medical treatment lagged behind the population growth, resulting in significant pressure on public service provision and management. In recent years, urban road occupancy per capita has decreased and traffic congestion has intensified. From 2000 to 2011, owing to the long-term construction of water supply pipelines by the government, the water supply system realized the full coverage of the urban system, and the length of water supply pipelines was approximately linear with urban population ($\beta \approx 1$). However, with urban expansion, construction of water supply pipeline gradually lagged behind the growth rate of population from 2012 to 2018, which was manifested in the sublinear relationship between the length of water supply pipes and the population ($\beta < 1$). From 2001 to 2018, β value of the number of beds in medical and health institutions decreased from 1.00 to 0.79, the relationship with urban population changed from linear to sublinear, reflecting the current situation of the overall shortage of urban medical resources. In response to this situation, the investment of urban public resources and medical resources should be increased in the future.

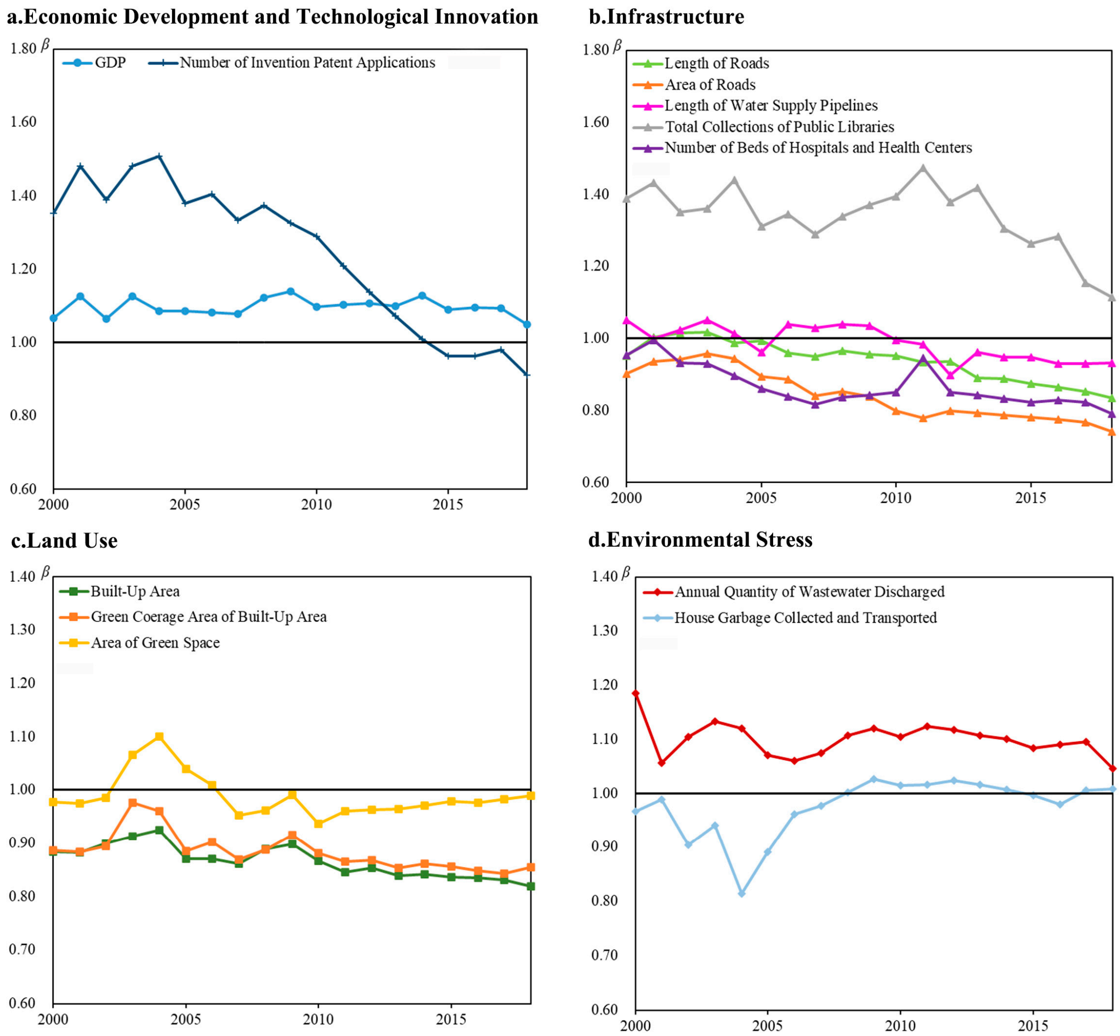

Figure 2. Changes in scaling exponents of city-scale elements from 2000 to 2018.

In the horizontal comparison of cities, the GDP scaling exponent of 43 cities was greater than 1, indicating that most cities showed strong agglomeration effect of economic output (Figure 3). The exception was that the GDP of Dongguan and Xuancheng was sublinearly related to population. The reason was that Dongguan's labor-intensive industries developed and its population attraction increased. However, its current industrial structure restricts the city's economic development and scientific and technological innovation; Dongguan's number of invention patent applications scaling exponent was the smallest ($\beta = 1.63$). Based on labor force gathering, Dongguan should drive industrial upgrading by innovation and highlight the advantage of industrial cluster. The huge population has also brought problems such as traffic jams, insufficient education, and medical resources, β value of urban infrastructure indicators in Dongguan was all at a low level. Unlike Dongguan, Xuancheng's economic development had a poor foundation, its urbanization was lagging and its GDP growth was stunted.

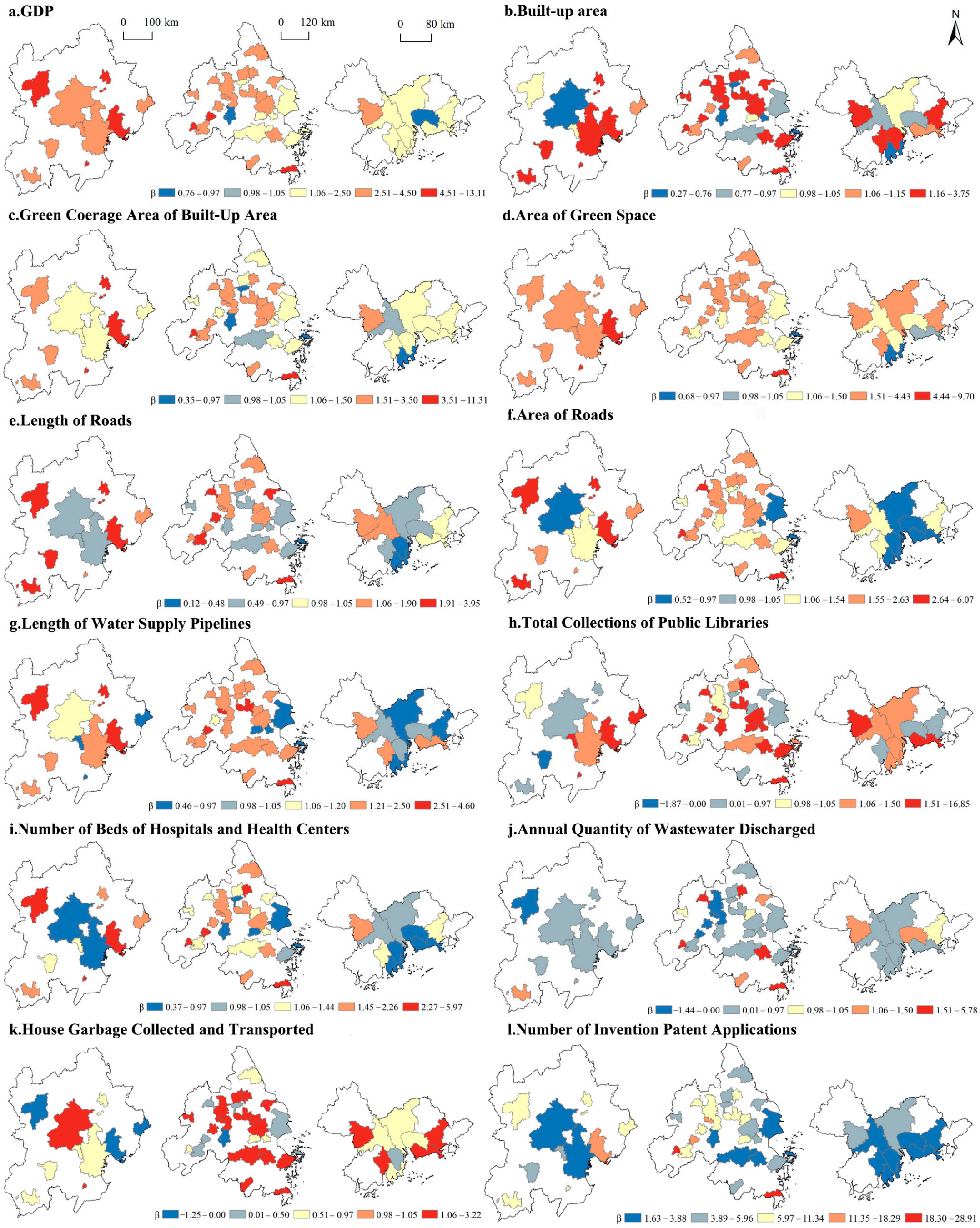

Figure 3. Spatial distribution of scaling exponents of city scale elements.

We found that land use in large cities tended to be more intensive, as shown by the sublinear relationship between built-up area and population ($\beta < 1$) in Beijing, Shanghai, Hangzhou, and Guangzhou, and the approximately linear relationship between built-up area and population ($\beta \approx 1$) in Dongguan and Shenzhen. The greening level of 43 cities has been greatly improved with super-linear relationship between green area and population in the built-up areas, which indicates that cities have been paying more and more attention to the construction of ecological civilization. Due to its good foundation of ecological environment, there was little pressure on green space construction. There was a sublinear relationship between green area in built-up areas and population of Zhuhai (β = 0.52) and Zhoushan (β = 0.35). Meanwhile, we found that β value of roads area and length, beds in medical institutions are generally low in large cities. Therefore, traffic jams and medical resource shortages have been more likely to occur in large cities, such as Beijing, Zhuhai, Shenzhen, Shanghai, Guangzhou, and Dongguan. The number of invention patent applications and population in 45 cities showed a super-linear relationship, which fully demonstrated the effect of talent aggregation.

3.1.2. Metropolitan Area Scale

To summarize the temporal change pattern at the metropolitan area scale, we calculated the scaling exponent of each urban indicator from 2000 to 2018 (Figure 4). We found that GDP of metropolitan areas had a sublinear relationship with population, with β value increasing from 0.82 to 0.93. It showed that the metropolitan area as a whole was gradually mature, but it was still in a state of diseconomy of scale.

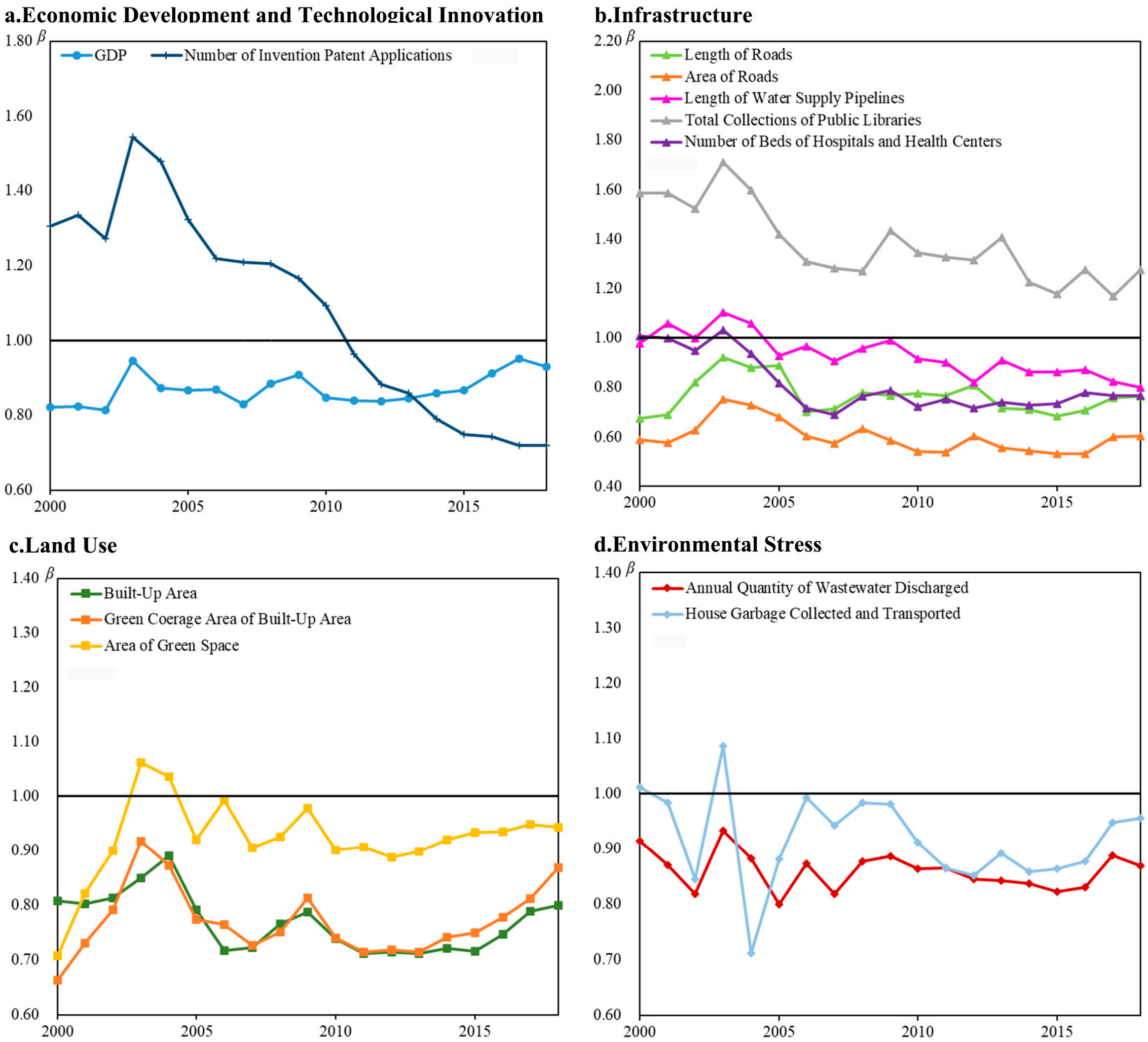

Figure 4. Changes in scaling exponents of metropolitan scale elements from 2000 to 2018.

Similar to economic trends, various infrastructure has gradually improved, but in recent years it has fallen behind the population growth. β value of road length increased from 0.67 in 2000 to 0.77 in 2018, indicating that the road construction has been gradually strengthened and the road network structure has been improved at metropolitan area scale. From 2000 to 2004, β value of water supply pipeline length increased from 0.98 to 1.06, which showed the construction speed of urban water supply pipelines was approximately equal to the population growth speed in metropolitan areas. However, the relationship between the length of water supply pipeline and population became sublinear after 2005 (β = 0.93). Continuously, β value of water supply pipeline length decreased to 0.80 in 2018, and the pressure of water supply increased in metropolitan areas. β value of the number of beds in medical institutions fluctuated between 0.94 and 1.03 from 2000 to 2004, which showed an investment of medical resources matched the population growth. But it showed the same trend as the water pipeline, β value of number of beds in medical institutions decreased from 0.82 to 0.77 from 2005 to 2018. The investment of medical services lagged behind the population growth, and medical resources was increasingly strained.

By horizontally comparing scaling exponents of urban indicators at metropolitan area scale (Table 2), we found that the strength of the economic agglomeration effect of metropolitan areas has been strongly correlated with transportation. Ten metropolitan areas, with β value of GDP ranging from 1.22 to 4.04, while the length of roads, area of roads, and population in most metropolitan areas have a linear or super-linear relationship. Scaling exponents of GDP (β = 4.04), road length (β = 1.80), and road area (β = 2.40) of Nanjing metropolitan area were the largest, while scaling exponents of GDP (β = 1.22) and road area (β = 1.86) of Shenzhen metropolitan area were the smallest. Innovation plays an important role in the economic development of metropolitan areas, the relationship between the number of patent applications and population in all metropolitan areas was super-linear. Scaling exponent in Suzhou-Wuxi-Changzhou metropolitan area was the largest (β = 7.32). The main reason is that Suzhou, Wuxi, and Changzhou had a solid industrial base and carried out more collaborative innovation cooperation in the fields of equipment manufacturing, electronic information, high-end textiles, and biomedicine, which ensured the quality and quantity of innovative inventions.

Table 2. Scaling exponents of urban indicators at metropolitan area scale.

Metropolitan Area (MA)	Economic Development	Land Use			Environmental Stress	
	GDP	Built-Up Area	Green Coverage Area of Built-Up Area	Area of Green Space	Annual Quantity of Wastewater Discharged	House Garbage Collected and Transported
Beijing MA	3.48	1.02	1.59	2.00	0.82	1.09
Pearl River Estuary West Bank MA	1.74	0.98	1.00	1.22	0.58	0.77
Shenzhen MA	1.22	1.06	1.26	1.15	0.78	0.80
Guangzhou MA	2.53	1.02	1.29	1.99	0.71	0.71
Shanghai MA	2.47	1.09	1.62	1.61	0.39	0.69
Suzhou-Wuxi-Changzhou MA	3.59	1.71	2.06	2.19	1.06	1.91
Hangzhou MA	2.35	1.02	1.26	1.77	0.74	1.24
Hefei MA	2.98	1.27	1.54	1.86	0.53	1.36
Nanjing MA	4.04	1.75	1.93	2.07	−0.03	1.52
Ningbo MA	2.74	1.14	1.74	1.97	1.13	1.37

Metropolitan Area (MA)	Infrastructure					Technological Innovation
	Length of Water Supply Pipelines	Length of Roads	Area of Roads	Total Collections of Public Libraries	Number of Beds of Hospitals and Health Centers	Number of Invention Patent Applications
Beijing MA	1.41	0.94	1.43	0.99	0.84	4.65
Pearl River Estuary West Bank MA	1.2	0.58	0.86	1.29	1.02	3.35
Shenzhen MA	1.12	0.96	0.96	1.36	0.64	2.09
Guangzhou MA	1.02	1	1.09	1.32	1.09	4.23
Shanghai MA	1.08	1.02	1.3	0.55	0.85	4.28
Suzhou-Wuxi-Changzhou MA	2.06	1.39	2.1	2.09	1.78	7.32
Hangzhou MA	1.54	1.04	1.43	1.4	1.29	4.29
Hefei MA	1.93	1.19	1.85	0.91	1.39	6.72
Nanjing MA	1.84	1.8	2.4	1.18	1.6	7.25
Ningbo MA	1.81	0.96	1.39	2.92	1.4	6.1

We found that land use was relatively less tense at the metropolitan scale compared to the city scale. The built-up area of metropolitan areas in the northern YRD grew faster than population growth rates, such as Nanjing metropolitan area (β = 1.75), Suzhou-Wuxi-Changzhou metropolitan area (β = 1.71), and Hefei metropolitan area (β = 1.27). The built-up area of other metropolitan areas had a linear relationship with population in general ($\beta \approx 1$). However, the medical resources at the metropolitan area level are affected by the core cities. For example, the number of medical beds in Shanghai metropolitan area, Shenzhen metropolitan area, and Beijing metropolitan area was sub-linearly related to population ($\beta < 1$), mainly because the medical resources in the core cities (Shanghai, Shenzhen, and Beijing) were too tight.

Water-rich and industrially developed metropolitan areas have greater pressure for wastewater treatment. Only annual quantity of wastewater discharged and population of Ningbo metropolitan area (β = 1.13) and Suzhou-Wuxi-Changzhou metropolitan area (β = 1.06) showed a super-linear relationship. Two regions had abundant water resources and developed industries, resulting in more wastewater discharged. In contrast, scaling exponent of wastewater discharged in other metropolitan areas shows a sub-linear relationship with population with less pressure on sewage treatment.

3.1.3. Urban Agglomeration Scale

Table 3 showed that the scaling exponents of GDP, built-up area, green space, length and area of roads, length of water supply pipelines, beds of hospitals, and invention patent applications in GBA are all lower than those of BTH and YRD. In terms of economic development, β value of GDP in GBA is the smallest (β = 1.74), and the agglomeration effect of economic output is relatively weak. Meanwhile, β value of GDP in BTH is the largest (β = 3.88) with a strong economic output agglomeration effect. Thanks to strong education, technological innovation resources, and industrial economy and education foundation, β values of invention patent applications in BTH (β = 5.34) and YRD (β = 5.59) were significantly higher than β value of GBA (β = 2.95) with rich innovation.

Table 3. Scaling exponents of urban indicators at urban agglomeration scale.

Urban Agglomeration (UA)	Economic Development	Land Use			Environmental Stress	
	GDP	Built-Up Area	Green Coverage Area of Built-Up Area	Area of Green Space	Annual Quantity of Wastewater Discharged	House Garbage Collected and Transported
BTH UA	3.88	1.17	1.76	2.30	0.82	0.85
GBA	1.74	1.05	1.28	1.43	0.70	0.80
YRD UA	3.22	1.41	1.82	2.02	0.53	1.18

Urban Agglomeration (UA)	Infrastructure					Technological Innovation
	Length of Water Supply Pipelines	Length of Roads	Area of Roads	Total Collections of Public Libraries	Number of Beds of Hospitals and Health Centers	Number of Invention Patent Applications
BTH UA	1.52	1.11	1.73	1.12	1.07	5.34
GBA	1.09	0.93	1.02	1.37	0.82	2.95
YRD UA	1.64	1.19	1.87	1.01	1.40	5.98

In terms of land use, built-up area and population of BTH (β = 1.17) and YRD (β = 1.41) showed a super-linear relationship, with the built-up area expanding faster than population growth. The built-up area of GBA had an approximately linear relationship with population (β = 1.05), and the land urbanization matched the population urbanization. Meanwhile, sufficient land resources guaranteed greening construction, as evidenced by β value of green coverage area of built-up area and area of green space in BTH and YRD being greater than GBA.

The length and area of roads in BTH and YRD had a super-linear relationship with population. However, β values of length and area of roads in GBA were 0.93 and 1.02, respectively. The per capita road occupancy was relatively low, and residents' transportation is relatively congested in GBA. β value of water supply pipelines length in GBA (β = 1.09) is better in water saving than that in BTH (β = 1.52) and YRD (β = 1.64). In terms of medical infrastructure, β value of beds of hospitals and health centers in GBA was the smallest (β = 0.82), and the scale economy of medical resources in GBA was the most significant, which indicated that the medical resources in GBA were relatively tight.

3.2. Comparative Analysis of Evolution Process of Multi-Scale Urban Scaling Law

By comparing and analyzing the changes in scaling exponents of urban indicators at urban agglomeration, metropolitan area, and city scale from 2000 to 2018 (Figure 5), we found that β value of all urban indicators in metropolitan areas was basically smaller than β value of cities, indicating that urban agglomeration failed to exert strong scale effects and metropolitan area system was still in the cultivation and formation stage without reaching maturity. Especially in terms of economic development, β value of GDP at city scale was stable between 1.05 and 1.13, but β value of GDP is less than 1 at metropolitan area scale. However, β value of GDP at urban agglomeration scale increased overall and changed from sublinear to linear and super-linear with population. Through these years of development, urban agglomerations realized the role of urban resource agglomerates and achieved greater economies of scale.

The built-up area of city scale and metropolitan area scale had a sublinear relationship with population. The coordination between land expansion and population growth of city and metropolitan area was weak. Scaling exponent of urban agglomerations exceeded that of cities and metropolitan areas, and the rate of land expansion gradually caught up with the rate of population growth after 2011.

The scaling exponent of road length and road area in urban agglomerations was greater than that of cities and metropolitan areas, and it had a super-linear relationship with population. Transportation and infrastructure, for example, can enable physical connectivity, accelerate the circulation of factor resources among cities, and form a unified factor and product market. A single city faced the dilemma of medical resource scarcity and unbalanced distribution, and the integration of many cities into a unified service network by urban agglomerations was conducive to improving resource linkage efficiency and distribution rationality. As a result, the scaling exponent of the number of beds in medical and health institutions in urban agglomerations was greater than in cities and immature metropolitan areas, and it had a super-linear relationship with population.

Innovation in science and technology is the endogenous driving force for the synergistic development of urban agglomerations. From 2000 to 2018, the relationship between invention patent applications and population of cities and metropolitan areas shifted from super-linear to linear and sub-linear, respectively, which proves that the isolation and isolation of cities are not conducive to the development of science and technology [50]. However, on a larger spatial scale, the number of invention patent applications in urban agglomerations had a super-linear relationship with the population, and technology exchanged between cities became increasingly common. Cities in the region gradually evolved from fighting alone to collaborative innovation, indicating the maturity of urban agglomerations.

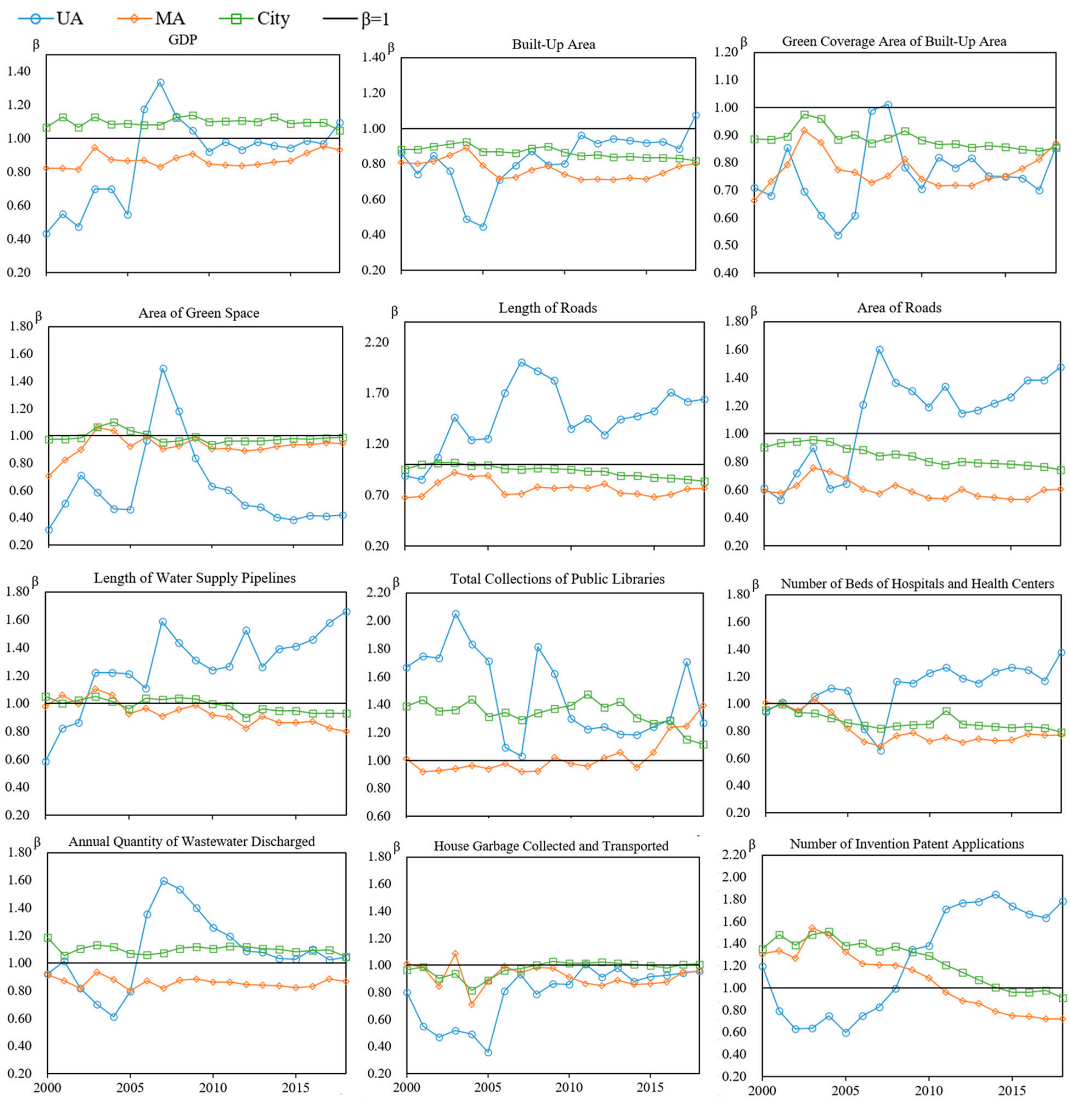

Figure 5. 2000–2018 changes of scaling exponents of urban agglomerations, megalopolises, and urban scaling exponents.

The scaling exponents of GDP, built-up area, green area, road area, road length, number of innovations and inventions, total collections of public libraries, and beds in hospitals and health centers in the BTH were all greater than those of the Beijing metropolitan area (Figure 6), indicating that the scale agglomeration effect of the BTH was stronger than that of the capital metropolitan area. The scaling exponent of wastewater discharged in the BTH was the same as that of the Beijing metropolitan area (β = 0.82), and the scaling exponent of house garbage collected and transported was smaller than that of the Beijing metropolitan area. The ecological pressure of the BTH was less than that of the Beijing metropolitan area, and the ecological collaborative governance has achieved remarkable results. Except for house garbage collected and transported, the scaling exponents of other urban indicators in Beijing were smaller than those of the Beijing metropolitan area, indicating that the scale agglomeration effect of the Beijing metropolitan area was stronger than that of Beijing. Since the BTH only included the Beijing metropolitan area, and the scaling exponents of most urban indicators were larger than the Beijing metropolitan area, it can be concluded that for an urban agglomeration that only included a single metropolitan area, the scale effect became stronger as the scale expanded.

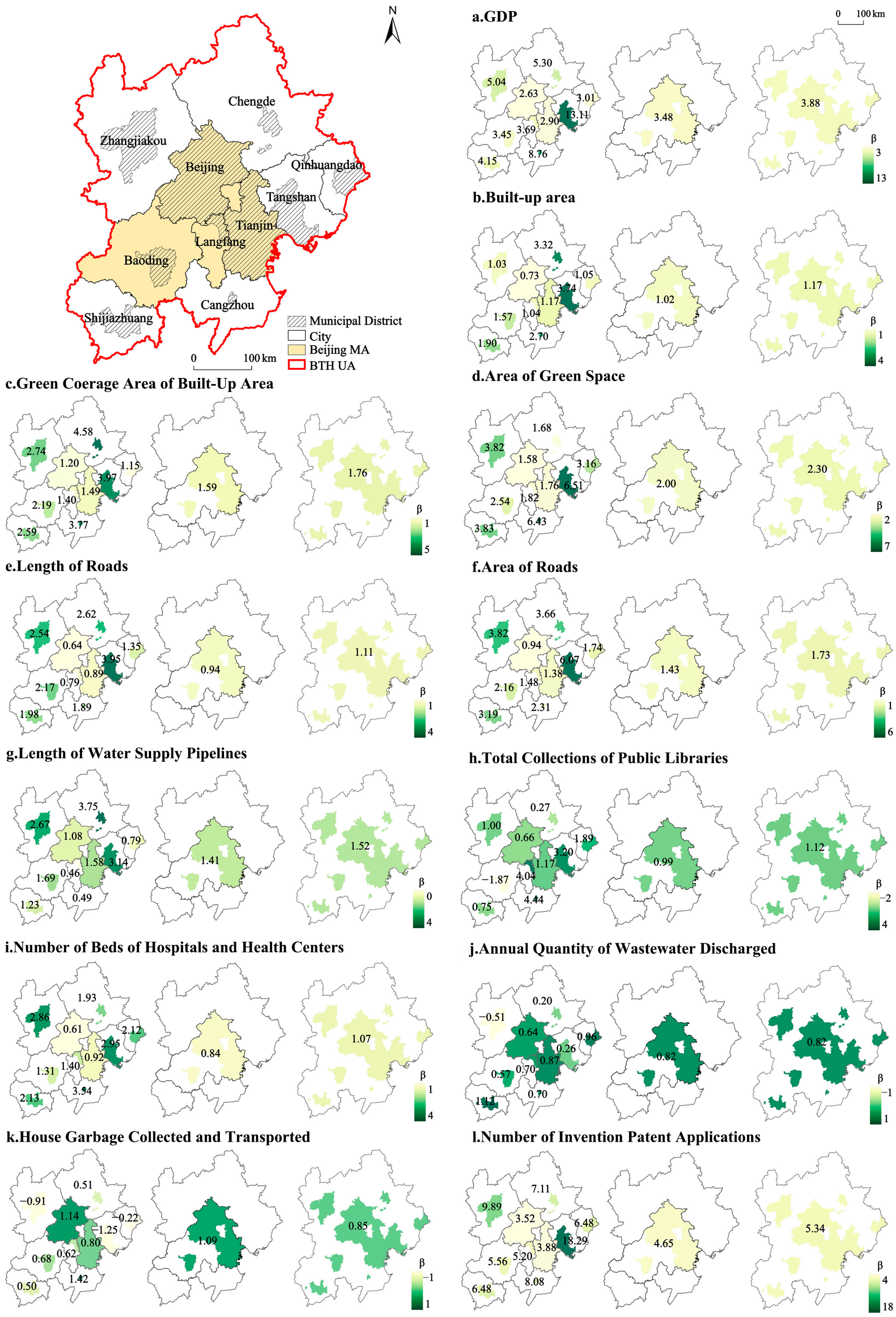

Figure 6. Spatial distribution of scaling exponents in urban agglomeration, metropolitan area, and city scales in BTH.

The YRD contained six metropolitan areas, and the evolution of the metropolitan areas showed obvious spatial differences (Figure 7). In addition to the volume of household garbage collected and transported, the scaling exponents of GDP, built-up area, green area, length of water supply pipelines, length of roads, area of roads, beds of hospitals and health centers, collections of public libraries, and number of invention patent applications in the YRD were all less than Nanjing metropolitan area and Suzhou-Wuxi-Changzhou metropolitan area. The scale effect of the Nanjing metropolitan area and the Suzhou-Wuxi-

Changzhou metropolitan area were stronger than that of the YRD. The scale effect of the YRD in terms of economic development, land use, road construction, and technological innovation was stronger than that of the Shanghai metropolitan area, Ningbo metropolitan area, Hangzhou metropolitan area, and Hefei metropolitan area.

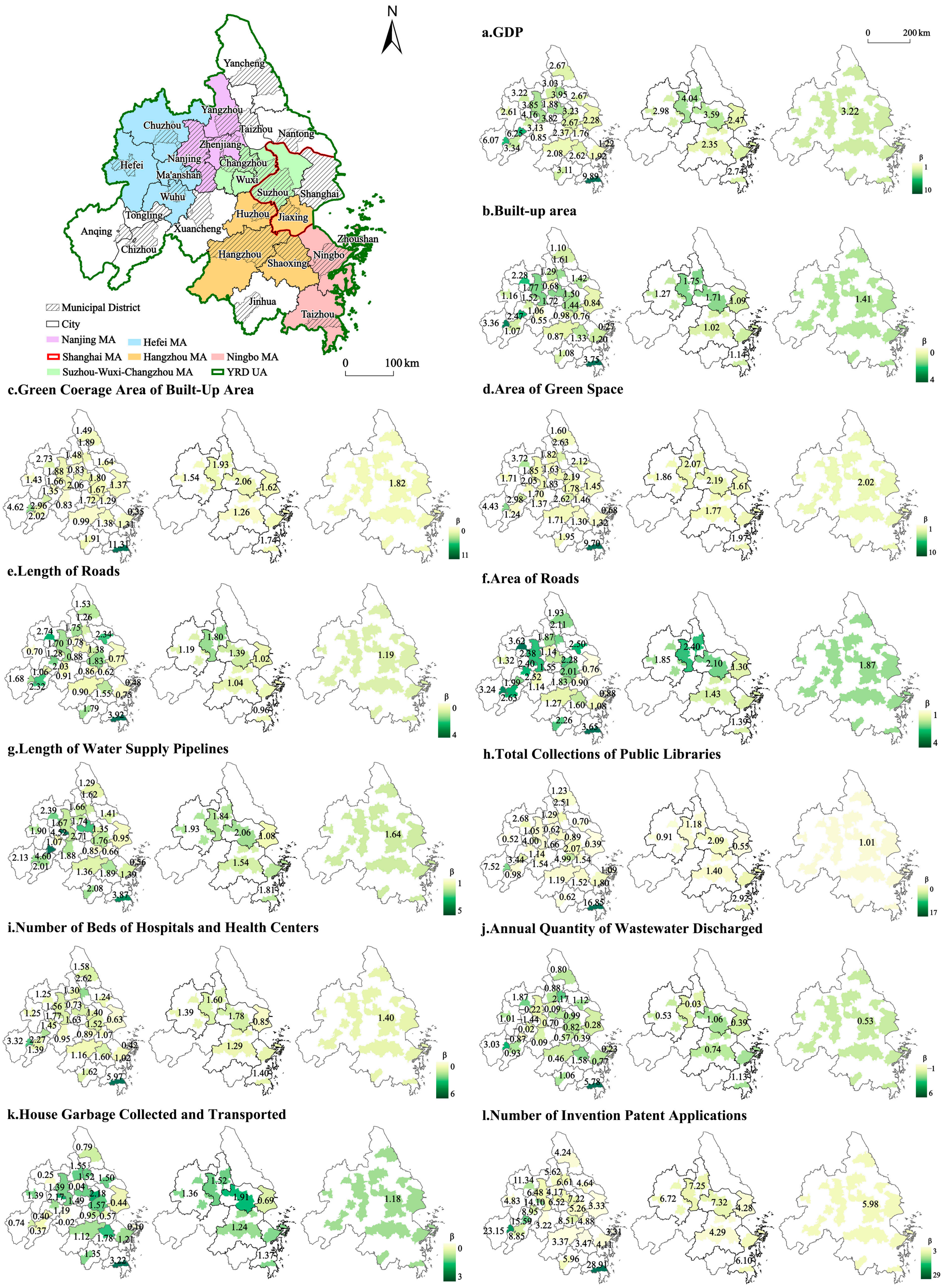

Figure 7. Spatial distribution of scaling exponents in urban agglomeration, metropolitan area, and city scales in YRD.

The GBA includes three metropolitan areas, and each metropolitan area presented different characteristics in the evolution of different urban indicators (Figure 8). For example, the scaling exponents of GDP, length of roads, area of roads, green area, number of patent innovation applications, collections of public libraries, and beds of hospitals and health centers in the GBA were smaller than those of the Guangzhou metropolitan area. The economic development, road construction, greening construction, public services, and innovation of the Guangzhou metropolitan area were significantly ahead of the overall level of the GBA. The scaling exponents of water supply pipeline and beds in hospitals and health centers in the GBA were smaller than those of the Pearl River Estuary West Bank metropolitan area, indicating that the construction of water supply pipeline length and the supply of medical resources were stronger than those in the GBA. At the same time, except for GDP, the scaling exponents of various urban indicators in the Shenzhen metropolitan area were very close to those of the GBA. It can be said that the development of the Shenzhen metropolitan area was the epitome of the GBA.

3.3. The Co-Evolution Process of Urban Scaling Law

Urban scaling law is a powerful summary of the change of urban indicators with city scale [39]. Based on the K-nearest neighbor matrix, we calculated the local Moran Index of the scaling exponent of 12 urban indicators, obtained the spatial evolution patterns of different urban indicators (Figure 9), and analyzed the regional co-evolution process. In BTH, the low-high concentrations of the scaling exponent of GDP, road area, and road length were found in Beijing, Tianjin, and Qinhuangdao, while the high-high concentrations were found in other cities. The dual-core structure of Beijing and Tianjin was stable, but it lacked the radiation-driving effect on the economic development of the surrounding cities, which had a certain impact on the coordinated development. At the same time, the production development drove the transportation infrastructure construction and established the convenient transportation connection. The area of built-up and area of green space in Baoding belonged to the low-high concentration, while Tianjin belong to the high-high concentration. This showed that the urban land expansion was co-evolving with a gap. In terms of ecological pressure, house garbage collected and transported in Beijing belonged to the high-low concentration. As the core city of population and economic aggregation, Beijing has always borne greater ecological pressure. The ecological optimization of the BTH urban agglomeration focuses on solving the "big city disease" of Beijing.

In the YDR, scaling exponent of GDP low-low gathered in Shanghai and Shaoxing, most of the city's GDP scaling exponent space was not relevant. As the core city of Shanghai stimulated the development of the surrounding city, the radiation ability weakened. The economic development of YRD was on a large scale. There was less collaboration and exchange between cities, and competition was greater than cooperation. The integrated development of metropolitan areas needs to be strengthened. In addition, the city location difference, imbalance of economic development level, and the construction of infrastructure and other issues also increased the difficulty of co-evolution. The development of the YRD in the future needs to attach great importance to the overall regional linkage, deepen city exchanges and cooperation, and narrow the gap between regions.

In the GBA, Zhaoqing was a high-low β value aggregation area of GDP, built-up area, public green area, road area, road length, water supply pipe length, and number of beds in medical institutions. Zhaoqing, which was originally more backward, has actively integrated into the GBA by initially building a three-dimensional transportation network, optimizing the business environment, introducing enterprises from Guangzhou and Shenzhen, developing green energy industry with ecological advantages, and building a livable and quality living city. Other cities are low-low β value agglomerations of GDP, green area, road area, road length, water pipeline length, number of beds in medical institutions, and invention applications. We found that the development of GBA was holistic and coordinated, and developed in a steady and low state of synergy in terms of economy, ecological green areas, transportation and pipeline infrastructure, and medical services.

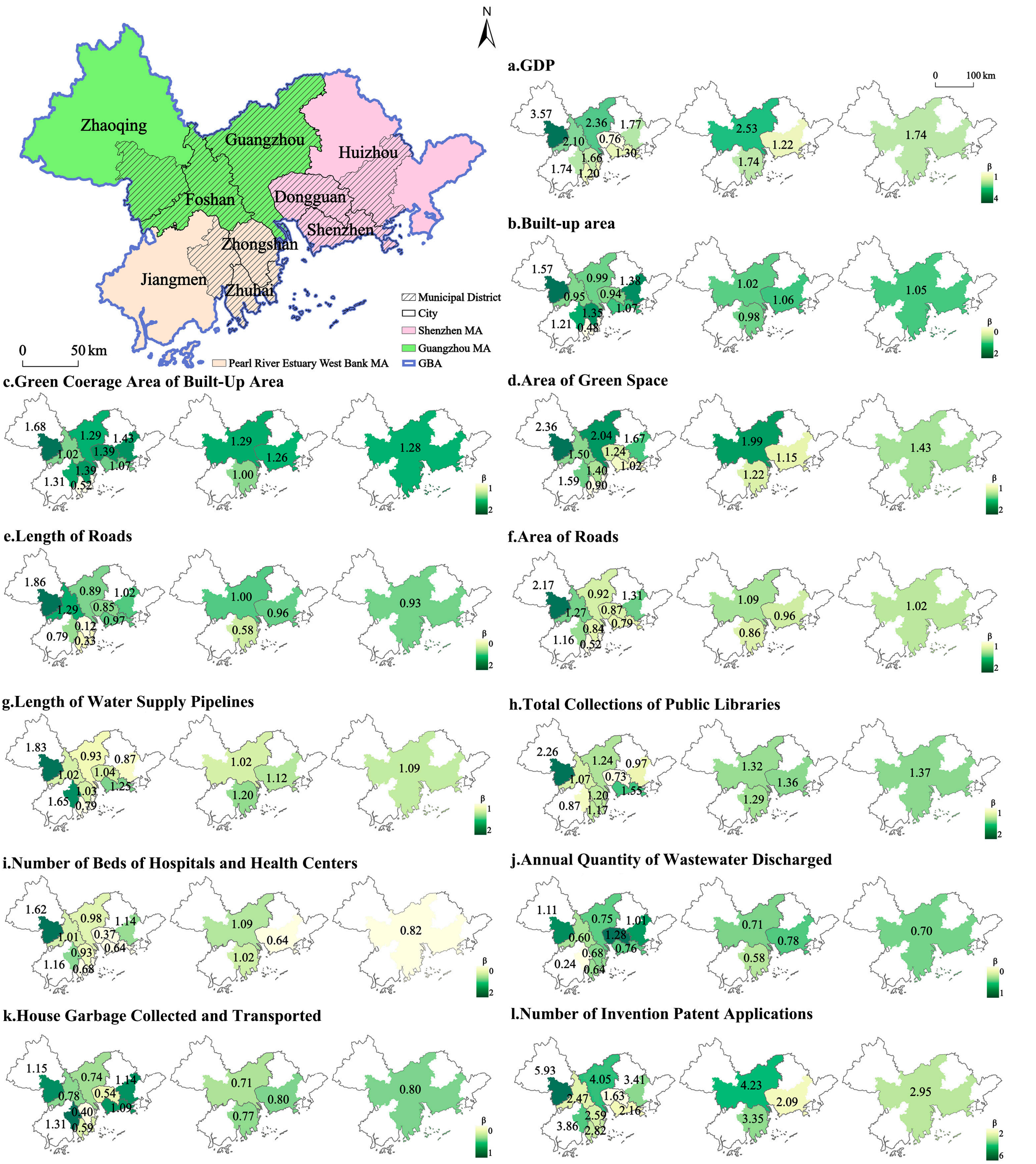

Figure 8. Spatial distribution of scaling exponents in urban agglomeration, metropolitan area, and city scales in GBA.

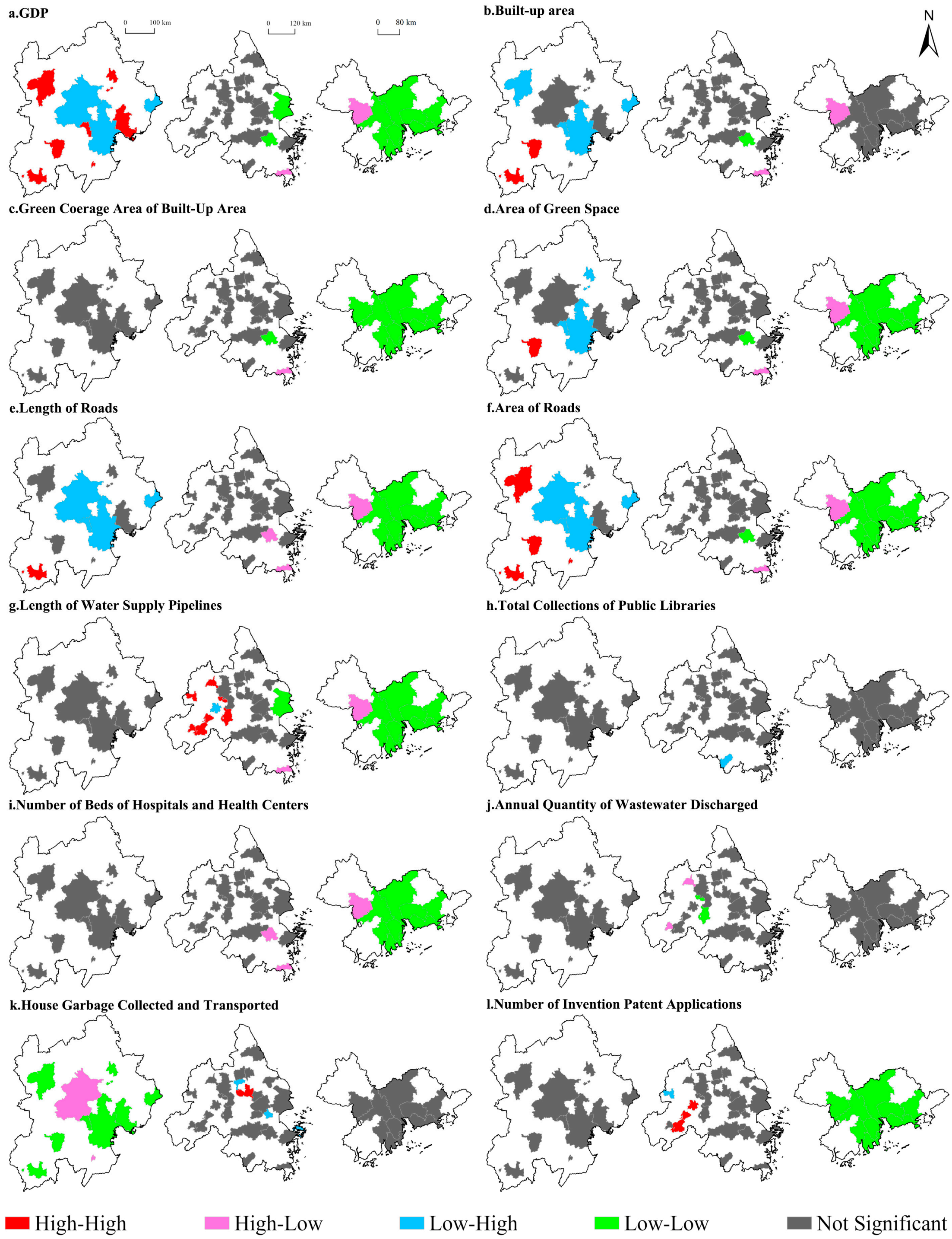

Figure 9. Lisa's aggregation graph of city index scaling exponent.

4. Discussion

Based on the BTH, YRD, and GBA, this study explored the scaling law of urban population and urban indicators from the perspective of city, metropolitan area, and urban agglomeration. The results of previous studies showed that the scaling exponent of urban built-up area, road area, road length, number of beds in medical and health institutions was less than 1, and the scaling exponent of GDP and patents applied for was more than 1 [29]. We found that the scaling exponent of urban indicators in large cities has been more in line with the theoretical expectations. The scaling exponents of urban indicators in metropolitan areas were mainly influenced by the core cities. For example, the number of medical beds in Shanghai metropolitan area, Shenzhen metropolitan area, and Beijing metropolitan area was sub-linearly correlated with the population, because the core cities of metropolitan areas (Shanghai, Shenzhen, and Beijing) were too tight in medical resources ($\beta < 1$). There was an excessive concentration of medical and health resources in municipalities directly under the central government, while resources in lower-level cities, especially prefecture-level cities, were relatively insufficient. This has led to people in lower-level cities frequently traveling to higher-level cities to obtain high-quality medical and health resources, exacerbating the problem of relatively insufficient per capita medical and health resources in higher-level cities [51].

Previous studies have shown that, at the city scale, the same urban indicators exhibit fundamental differences in temporal and spatial scaling [52]. Our research found that this conclusion also applied to the metropolitan and urban agglomeration scales, but as the scale increased, the magnitude of the temporal variation of the scaling exponent increased, while the spatial differences gradually decreased. For example, the scaling exponent of GDP at city scale was stable over time between 1.07 and 1.14, while the inter-city variability ranges from 0.76 (Dongguan) to 13.11 (Jiangmen). The scaling exponent of GDP for metropolitan areas fluctuated between 0.81 and 0.95 over time, and the inter-metropolitan area variability ranged from 1.22 (Shenzhen metropolitan area) to 4.04 (Nanjing metropolitan area). The scaling exponent of GDP at the urban agglomeration scale fluctuated between 0.43 and 1.34 over time, and the inter-urban agglomeration variability ranged from 1.74 (GBA) to 3.88 (BTH). The differences in temporal changes at different scales indicated that metropolitan areas and urban agglomerations were at a high development stage, and the spatial differences at different scales indicated that the economic development of individual cities was relatively unstable, while metropolitan areas and urban agglomerations possess more sharing and coordination of industries, resources, and markets, and their economic development was relatively stable, emphasizing the need for regional synergistic development [15,53].

The temporal change in the scaling exponent described the evolution process of the urban system. From a holistic perspective, the GDP scaling exponent of the metropolitan area was lower than the theoretically expected value, and the economies of scale have not been fully utilized. This may be because the urban hierarchy and division of labor system within the metropolitan area have not been fully established, resulting in a weak circle structure. The competition for urban resources is greater than cooperation, and the ability of metropolitan areas to resist risks is weak, and high-quality development of metropolitan areas has not been fully promoted. The planning and construction focus of many metropolitan areas is on the core city, resulting in a low degree of integrated development of the metropolitan area and a fragmented development between the central city and the peripheral regions. The urban system is currently in the stage of cultivation and formation and has not reached a mature state. At the same time, the development speed and maturity level of urban agglomerations were faster. As the connections between cities in urban agglomerations strengthen, the efficiency of resource integration improves, and the economies of scale of the economy, land, transportation, public services, and innovation resources were raised to a higher level. The construction of metropolitan areas should not only pursue a large area and coverage of cities, but should accurately define the scope, concentrate resources to exert economies of scale and promote urbanization and integrated development. The research area in this study was based on the administrative boundaries of the officially designated metropolitan areas and urban clusters, which may not be the most functional and efficient combination of cities. Therefore, for metropolitan areas and urban agglomerations, how to define the most efficient development scale is a question we need to consider in the future.

Although this study analyzes the co-evolution of urban systems from a multi-scale perspective based on existing data, but there are still limitations. First, existing urban statistical data are based on the statistics of administrative units. The lack of statistical data on urban physical space and functional characteristics cannot scientifically and accurately reflect the real situation of the city, which is not conducive to meaningful urban spatial division. In the future, multiple sources of high-resolution spatial data that can reflect urban entities should be used for research. Second, the evolution of metropolitan areas and urban agglomerations needs to consider the interaction between cities, and the co-evolution of urban systems needs to extend to flows and networks, which is also important for exploring the scaling law, further research is needed to consider the flow of elements between urban systems.

5. Conclusions

Urban scaling law, as one of the models for studying urban science, reflected the regularity of urban evolution to a certain extent. This study found that land use tends to be intensive in big cities, and the problems of traffic jams and medical resource supply were more likely to occur ($\beta < 1$). The metropolitan area was in a state of diseconomy in scale, but the development has been gradually maturing. The road factor of urban agglomerations was larger than that of cities and metropolitan areas, and had a super-linear relationship with population, indicating that a perfect transportation network system was an important foundation for the development of urban agglomerations. The synergistic evolution of the GBA was steadily advancing, but medical resources were relatively scarce ($\beta = 0.82$). The degree of synergistic evolution of Beijing and Tianjin in the BTH was high, with Beijing facing greater ecological pressure. The YRD had difficulties in overall synergistic evolution due to the wide area of the region, a large number of internal cities and metropolitan areas, and the large gap in development bases. It is necessary to pay more attention to the construction of road infrastructure, strengthen inter-city exchanges, and promote the synergistic development of the economy, infrastructure, innovation, and other elements.

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