SPATIAL LINKAGE AND URBAN EXPANSION: AN URBAN AGGLOMERATION VIEW

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ABSTRACT:

Urban expansion displays different characteristics in each period. From the perspective of the urban agglomeration, studying the spatial and temporal characteristics of urban expansion plays an important role in understanding the complex relationship between urban expansion and network structure of urban agglomeration. We analyze urban expansion in the Yangtze River Delta Urban Agglomeration (YRD) through accessibility to and spatial interaction intensity from core cities as well as accessibility of road network. Results show that: (1) Correlation between urban expansion intensity and spatial indicators such as location and space syntax variables is remarkable and positive, while it decreases after rapid expansion. (2) Urban expansion velocity displays a positive correlation with spatial indicators mentioned above in the first (1980-1990) and second (1990-2000) period. However, it exhibits a negative relationship in the third period (2000-2010), i.e., cities located in the periphery of urban agglomeration developing more quickly. Consequently, the hypothesis of convergence of urban expansion in rapid expansion stage is put forward. (3) Results of Zipf's law and Gibrat's law show urban expansion in YRD displays a convergent trend in rapid expansion stage, small and medium-sized cities growing faster. This study shows that spatial linkage plays an important but evolving role in urban expansion within the urban agglomeration. In addition, it serves as a reference to the planning of Yangtze River Delta Urban Agglomeration and regulation of urban expansion of other urban agglomerations.

1. INTRODUCTION

With ongoing urbanization, the urban agglomeration featuring hierarchical structure and network organization in certain geographical area has been gradually formed all over the world. Urban growth within the urban agglomeration has taken place both vertically through population or build-up land growth of cities and horizontally by adding new cities (Fan, 1999). Meanwhile, urban expansion of an urban agglomeration is no longer the isolated development of individual city, but the coordinated development among various cities in an increasingly interconnected way. At present, China is paying more attention to urban spatial strategic planning with urban agglomeration as the main form. From the perspective of the urban agglomeration, studying the regularity and mechanism of urban expansion plays an important role in deciding spatial planning of urban agglomerations. The general trend of city-size distribution of an urban agglomeration or urban group develops toward either convergent or divergent, and this trend can be revealed through Zipf's law on city-size distribution and Gibrat's law on the growth of city size (Tang et al., 2016; Kalra et al., 2015; Soo, 2014). For cities in the western countries, urban growth exhibits a transition from sequential growth to parallel growth of cities over long periods of time in Canada (Sheng et al., 2016). For cities in the Yangtze River Delta Urban Agglomeration (YRD), it exhibited a random growth pattern before 2000 and conformed to Gibrat's law, i.e., the growth rate did not depend on initial size, and parallel growth pattern after 2000.

The analysis of urban expansion is generally limited to a single city or isolated analysis of urban growth of each city within a certain region (Liu et al., 2010; Mundia et al., 2010; Liu et al., 2014; Jiao, 2015; Jiao et al., 2015; Wu et al., 2015; Zhao et al., 2015; Liu et al., 2016), while few researches study urban expansion from the viewpoint of interaction among cities in the past. Previous studies have shown that factors such as location, road network are the driving forces behind urban expansion (Lu et al., 2013; Feng et al, 2014). It can quantitatively compute the spatial linkage among cities by analyzing location of city and connectivity of road network. Location of each city is measured by its accessibility and spatial interaction intensity with core cities. Wu (2013) argues that regional central cities would impact and promote the development of surrounding cities (Wu et al., 2013). Sohn (2012) argues that the distance to regional core city will influence the population growth of surrounding cities (Sohn, 2012). Spatial interaction intensity measures the radiation effect of core city to other cities (Guan et al., 2014). The gravity model is an effective method to measure the spatial interaction intensity (Yang et al., 2014). Road network connects cities within the urban agglomeration into an organic whole, and space syntax model reveals the connectivity of road network; Road network is playing an increasingly important role in the process of urban sprawl (Li et al., 2014; Iacono et al., 2016). Jiang (2000) puts forward space syntax model to quantitatively analyze the urban spatial morphology (Jiang et

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al., 2000). This method is widely used in road network analysis of a single city (Liu et al., 2015), as well as the connectivity of road network of the urban agglomeration (Zhu, et al., 2011). At present, few researches study urban expansion based on spatial linkage, but with urbanization accelerating, studies about regularity and mechanism of urban expansion from the perspective of the urban agglomeration are more in line with the present situation.

YRD is one of the six largest urban agglomerations in the world with the highest level of economic development and density of cities in China. It first enters the process of rapid urbanization and its urban expansion is particularly fast. This paper takes YRD as a study area and analyzes the correlation between spatial linkage and urban expansion based on location and road network. It aims to offer some references for studying urban expansion of other urban agglomerations from the viewpoint of spatial linkage in the future.

2. MATERIALS AND METHODS

2.1 Study Area

Located in the east of China, the study area, Yangtze River Delta Urban Agglomeration (YRD), is at latitudes between 27°03′ and 35°07′N and longitudes between 117°09′ and 122°06′ E, covering an area of 25.12×10^4km^2. According to China Urban Agglomeration Development Report (Liu et al., 2014), YRD includes Shanghai, cities at prefecture level or above in Jiangsu and Zhejiang province, Hefei, Wuhu, Huainan, Ma'anshan, Chuzhou in Anhui province (totaling 30 cities). This paper aims to analyze the temporal and spatial relationship between urban expansion and spatial linkage, particularly linkage through road network. While the road network between Zhoushan and other cities was not opened until 2009, hence Zhoushan is not included in the study area.

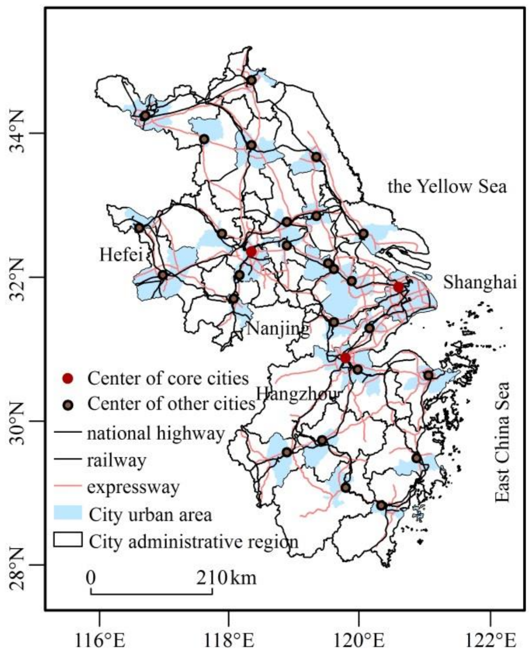

Figure 1. Study area

2.2 Data Preparation

Research data included build-up land area, population and main road network of urban agglomeration. Based on supervised classification method, urban build-up land had been extracted from the Landsat TM/ETM+ remote sensing images in 1980, 1990, 2000 and 2010 with a spatial resolution of 30 m. Urban population used population data in 2010 obtained through the sixth China's population census. Road network included railway, expressway and national highway, because these road networks serve to bridge each city within an urban agglomeration. Road network data in 2010 was obtained from OpenStreetMap and served as a foundation to get road network data in 1990 and 2000 through revision of road network data of 2010 according to their opening time.

2.3 Methodology

2.3.1 Urban Expansion Indicators: Three indicators were used to calculate the urban expansion level in main urban area: average annual increase (AI), average annual growth rate (AGR) of build-up land and average annual degree of expansion (AE) of build-up land in each period (with ten years as a period, namely, Ⅰ(1980-1990), Ⅱ (1990-2000), Ⅲ (2000-2010)). AI (km^2/year) directly estimates the average annual increase of the build-up land area, revealing the differences of expansion level of the same city in different periods. AGR(%) compares the variations of the expansion speed of different cities in the same period. AE(%) is the percentage of build-up land increase in the main urban area, which compares the expansion intensity of build-up land in different periods. It is defined as Equation (1~3):

$$AI=(A_{\mathrm{end}}-A_{\mathrm{start}})/n \tag{1}$$

$$AGR=(A_{\mathrm{end}}-A_{\mathrm{start}})/(A_{\mathrm{satrt}}\times n)\times100\% \tag{2}$$

$$AE=(A_{\mathrm{end}}-A_{\mathrm{start}})/(A_{\mathrm{urban}})\times100\% \tag{3}$$

where A_{end} = build-up land area in main urban area by the end of a period
A_{start} = build-up land area in main urban area at the start of that period
A_{urban} = total area of main urban area;
n = time span (year)

2.3.2 Gravity Model: Gravity model estimates both distance decay effect and Newton's law of universal gravitation, and calculates spatial interaction intensity between two cities, which is defined as Equation (4~5):

$$F_{ij}=K_{ij}\sqrt{P_iG_i\,P_jG_j}\,/\,R_{ij}^2 \tag{4}$$

$$K_{ij}=G_i/(G_i+G_j) \tag{5}$$

where F_{ij} ((RMB·pop·10^8)/km^2) = spatial interaction intensity between city *i* and city j
G_i and G_j = GDP of the main urban area of city
P_i and P_j = population of the main urban area of city
R_{ij} = the sum of railway and expressway network distance between city *i* and city j
K_{ij} = weight

2.3.3 Space Syntax Model: Space syntax variables indicate the accessibility of road network, the degree of spatial connection and so on. The connection value represents the local connectivity of the network axis, and compositive ability value and global integration value indicate the global connectivity of

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the axis. The axis with higher local connectivity generally has higher global connectivity as well. Road networks connect each city within the urban agglomeration are mainly railway, expressway and national highway. As to different types of road networks, we calculate total connection value, compositive ability value and total global integration value of each city by divisional statistics function.

C_i (Connectivity value) is the connection value of each road, indicating the connectivity ability of a certain axis (road) i in the whole topological network. It is defined as Equation (6~7):

$$C_i = K \tag{6}$$

$$CC_j = \sum_{i=1}^{n} C_i \tag{7}$$

where K = the number of roads directly linked to the road i
CC_j= total connectivity ability of the axis within city, j indicating the sum of the connectivity value of roads in each city

CA_i (Compositive Ability) represents the spatial linkage between a city and all other cities, that is, the relationship between the local and the global. The accessibility of a city is not only related to the total connection value, but also to the average depth (Chen et al., 2005). It is defined as Equation (8~10):

$$CA_j = CC_j / D_j \tag{8}$$

$$D_j = \sum_{i=1}^{n} MD_i / n \tag{9}$$

$$MD_i = \sum_{j=1}^{n} d_{ij} / (n-1) \tag{10}$$

where CC_j = total connection of urban axis of city j
D_j = mean depth value of urban axis, that is, the average of the mean depth of each road i within city j
n = the number of axis
MD_i = average depth value, representing the average value of the shortest distances from each node to all other nodes respectively
d_{ij} = the shortest distance between any two nodes

TGI_j (Total Global Integration) represents the degree of accumulation and dispersion between a city and other cities, its value equal to the sum of GI_i within a city. GI_i (Global Integration) positively reflects the concentration degree of axis i with other axes within a system. They are also the reflections of relationship between the local and the global. It is defined as Equation (11~15):

$$RA_i = 2 \times (MD_i - 1)/(n-2) \tag{11}$$

$$RRA_i = RA_i / S_n \tag{12}$$

$$S_n = 2 \times \{n[\log_2((n+2)/3) - 1] + 1\}/(n-1)/(n-2) \tag{13}$$

$$GI_i = 1/RRA_i \tag{14}$$

$$TGI_j = \sum_{i=1}^{n} GI_i \tag{15}$$

where n = the number of axial lines of each city, depth can be normalized into Relative Asymmetry i (RA_i), and further normalized into Real Relative Asymmetry i (RRA_i) to eliminate structural interference
S = a datum RA of Ideal Diamond Structure applicable to various systems (Yang et al., 2015)

2.3.4 Standardized Value of Space Syntax Variable: The standardized values of space syntax variables (total connection value, compositive ability and global integration) were obtained through min-max normalization process. Take city's total connection value as an example, which is defined as Equation (16~17):

$$CC_i = (v_j / \sum_{j=1}^{3} v_j) \cdot CC'_{ji} \tag{16}$$

$$CC'_{ji} = (CC_{ji} - (CC_j)_{\min}) / ((CC_j)_{\max} - (CC_j)_{\min}), \quad j=1, 2, 3 \tag{17}$$

where CC_i = standardized value of total connectivity of city i
CC_{ji} = total connectivity of road network j (1-expressway, 2-national highway, 3-railway) of city i and CC'_{ji} is the corresponding standardized value
$(CC_j)_{max}$ = the maximum of the total connectivity of road network j of all cities
$(CC_j)_{min}$= the minimum of the total connectivity of road network j of all cities
V_j = the average speed of road network j

In the same way, the calculation formulas of compositive ability and total global integration of each city were obtained.

2.3.5 Weighted Distance Index: We calculated the distance from each city to core cities based on expressway network and railway network separately, and then added up the two kinds of distances for each city. The weighted distance index of each city was obtained by Min-max standardization. It is defined as Equation (18~19):

$$d_j = \sum_{i=1}^{3} w_i \cdot \frac{(d_{ij} - (d_{ij})_{\min})}{(d_{\max} - (d_{ij})_{\min})} \tag{18}$$

$$w_i = \frac{1}{2} \cdot \frac{GDP_i}{GDP_1 + GDP_2 + GDP_3} + \frac{1}{2} \cdot \frac{pop_i}{pop_1 + pop_2 + pop_3}, \quad i=1, 2, 3 \tag{19}$$

where d_j = the weighted distance index of city j (non-core cities)
d_{ij} = the sum of railway and expressway network distance from city j to core city i(1-Shanghai, 2-Nanjing, 3-Hangzhou)
$(d_{ij})_{min}$ the minimum road network distance from city j to core city i in the YRD
d_{max} = the maximum road network distance between city j and each core city in YRD
w_i = weight of core city i
GDI_i = GDP and pop_i is the population of core city i

2.3.6 Zipf's Law and Gibrat's Law: Zipf's law describes the dynamics of city-size distribution, reflecting the temporal characteristics of city size distribution. Zipf's law of city-size distribution is also known as rank-size distribution law, which is defined as Equation (20~22):

$$P(size > S_i) = a / S_i^{\alpha}\text{, i=1, 2, …, n} \tag{20}$$

$$\ln rank_i = A - \alpha \ln S_i\text{, i=1, 2, …, n} \tag{21}$$

$$\ln(rank_i - 0.5) = A - \alpha \ln S_i\text{, i=1, 2, …, n} \tag{22}$$

where a = a constant to be estimated
α = Pareto distribution coefficient met by city-size distribution
$rank_i$ = rank of city i with city's rank sorted in a descending order
S= size of a city, measured by urban build-up land area

Rank-size distribution law was shown in Eq. (21). The study of Gabaix (Gabaix, 2007) showed that Eq. (22) can be the most effective estimation of Pareto distribution coefficient. When α is equal to 1, then spatio-temporal dynamics of city-size distribution conforms to Zipf's law. If α increases over time, then city-size distribution evolution shows a scattered trend with small and medium-sized cities developing faster. If α decreases over time, then city-size distribution evolution presents a convergent trend with large cities expanding faster.

Gibrat's law indicates that the growth rate of a city is independent from its current size. Gibrat's law in an urban system can be tested by Equation (23~24):

$$S_{i,t} / S_{i,t-1} = \alpha S_{i,t-1}^{\beta-1} \varepsilon_{it} \tag{23}$$

$$\ln S_{i,t} = \ln\alpha + \beta \ln S_{i,t-1} + \ln\varepsilon_{it} \tag{24}$$

where $S_{i,t}$ = the size (build-up land area in main urban area) of city i in year t
$\varepsilon_{i,t}$ = the random error with mean 1 and variance σ^2 (a constant irrespective of $S_{i,t-1}$)
β = the influential effect of city's current size to its growth rate

If Gibrat's law holds, then β =1, indicating that urban growth is independent from its current size. β >1 indicates that bigger cities expand faster than smaller ones, while β <1 demonstrates smaller cities expand faster than bigger ones.

3. RESULTS

3.1 The Correlation between Urban Expansion and Location

We evaluate the location of cities by analyzing their accessibility to and spatial interaction intensity from core cities. The accessibility to core cites can be calculated by network distance between each city and core cities. The gravity model is used to calculate spatial interaction intensity with core cities. The former focuses on the distance to core cites to analyze city's location, and the latter considers city's scale effect apart from distance. Location of city was quantitatively analyzed by combining these two factors.

The determination of regional core cities is based on the following indicators: GDP and population in main urban area during the study period (1980-2010), the status of city in the road network within the urban agglomeration calculated through space syntax variables. Shanghai, Nanjing and Hangzhou are the top three cities in YRD in terms of indicators mentioned above. Besides, Shanghai, Nanjing and Hangzhou are all regional political centers. Thus we employ these three cities as regional core cities in YRD in this study.

3.1.1 The Correlation between Urban Expansion and Accessibility to Core Cities

Weighted distance index depicts the accessibility to core cities, which measures the location of city within the urban agglomeration. Cities had been classified into six grades evenly in accordance with the value of the weighted distance index in descending order, with five cities in the first five grades respectively and four cities in the last grade, which was shown in Table 1.

Grade	*WDI*	Included Cities	Main urban area in 1980 (km^2)
1	0.81	Shanghai, Suzhou, Jiaxing, Huzhou, Wuxi	166.10
2	0.68	Changzhou, Hangzhou, Shaoxing, Zhenjiang, Nanjing	123.04
3	0.53	Ma'anshan, Yangzhou, Chuzhou, Wuhu, Ningbo	55.31
4	0.44	Taizhou(Jiangsu), Jinhua, Nantong, Hefei, Quzhou	59.65
5	0.31	Taizhou(Zhejiang), Yancheng, Suqian, Lishui, Huainan	63.54
6	0.13	Wenzhou, Xuzhou, Huaian, Lianyungang	93.03

Table 1. Classification result according to weighted distance index (*WDI*)

Grade 1 identifies the highest spatial interaction intensity received from core cities, while grade 6 the lowest. *WDI* is the mean value of cities' weighted distance index of each grade.

	AI (km^2)	*AGR* (%)	*AE* (%)
WDI(1990)	0.345	0.297	0.307^{*}
WDI(2000)	0.576^{**}	0.372^{**}	0.614^{**}
WDI(2010)	0.315	-0.210	0.391^{*}

Table 2. Spearman's rank correlation coefficient between *WDI* and urban expansion indicators

*, ** and *** denote significance at 0.1, 0.05 and 0.01 level, respectively.

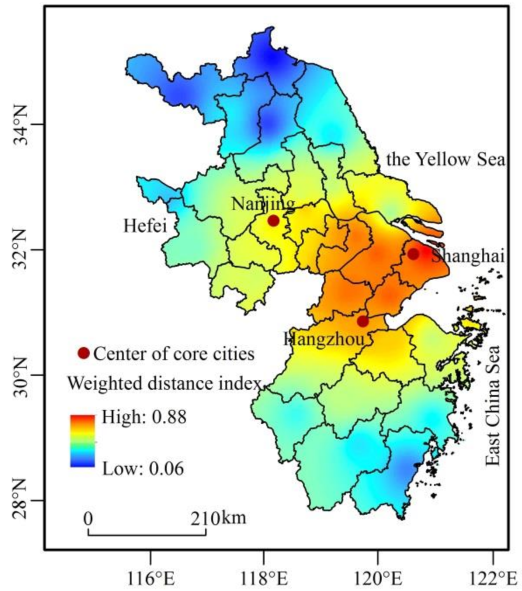

Figure 2. The spatial interpolation of weighted distance index

Weighted distance index indicates the closeness to the core cities of YRD, ranging from 0.06: close to core cities to 0.88.

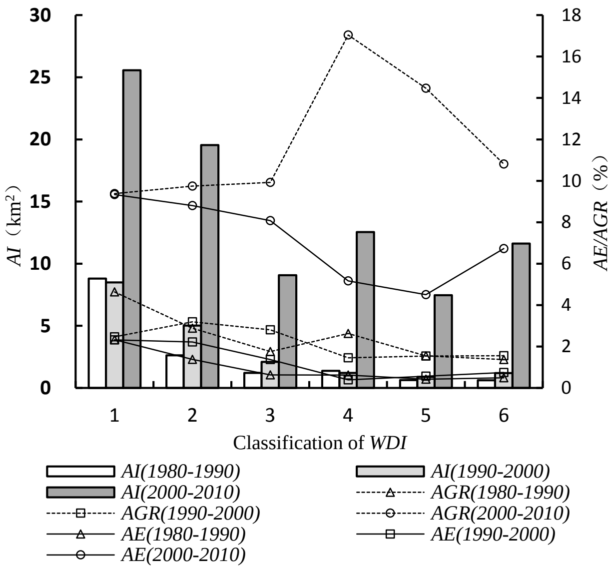

Figure 3. The relationship between road network distance to core cities and urban expansion

Cities had been classified into six grades evenly in accordance with the value of the weighted distance index(*WDI*) in descending order, with five cities in the first five grades respectively and four cities in the last grade.

Figure.2 implies weighted distance index of each city based on network distance and gets spatial interpolation map of weighted distance index through IDW (Inverse Distance Weighted) method. A closer examination of Figure.3 reveals cities near regional center have higher urban expansion intensity (AI and AE). This trend, however, was fluctuated for cities far from regional center in the third period. Because of the limited scope of influence and radiation radius of regional core cities, this positive correlation between urban build-up land expansion intensity and road network distance to core cities was not obvious for cities in the periphery of urban agglomeration. Table.2 shows that rank correlation coefficient between accessibility to core cities and urban expansion indicators is highest in the second stage (1990-2000). The overall pattern of urban development experienced two main transformations after 1990s. First, the scale and number of big city increased a lot under the influence of economic convergence and external expanding effect. Second, the sound development of metropolis significantly promoted the growth of its adjacent small and medium-sized cities, instead of causing many urban headaches (Wang, 2015). Rank correlation coefficient reduced in the third stage, which showed that the influence of core cities on urban expansion of other cities moderated in rapid expansion stage. The velocity of urban expansion, generally, decreased with the decline of spatial accessibility in the first and second stages, while cities in the fringe of YRD region expanded faster in the third stage. Core cities significantly affected the urban expansion of its surrounding cities in the initial stage, but its influence weakened with the course of urbanization aggravating.

3.1.2 The Correlation between Urban Expansion and Spatial Interaction Intensity from Core Cities

The spatial interaction intensity from core cities (Shanghai, Nanjing and Hangzhou) were calculated based on gravity model with the statistical data in 2010. The total force received by each city is the sum of the spatial interaction intensity from each core city. Cities except core cities had been classified into five grades evenly in accordance with the magnitude of total force in descending order. There were five cities in the first five grades and six cities in the fifth grade. Classification results were displayed in table 3.

Grade	F ((RMB·pop·10^8)/km^2)	Included Cities
1	21.09	Suzhou、Wuxi、Changzhou、Ningbo、Hefei
2	3.80	Zhenjiang、Ma'anshan、Yangzhou、Jiaxing、Shaoxing
3	1.59	Huzhou、Wuhu、Nantong、Xuzhou、Wenzhou
4	0.45	Taizhou(Jiangsu)、Taizhou(Zhejiang)、Huaian、Yancheng、Jinhua
5	0.19	Chuzhou、Huainan、Suqian、Quzhou、Lianyungang、Lishui

Table 3. Classification result according to spatial interaction intensity

Grade 1 identifies the highest spatial interaction intensity received from core cities, while grade 5 the lowest. F is the mean value of cities' spatial interaction intensity of each grade.

	AI(km^2)	AGR (%)	AE (%)
SI (1990)	0.442^{*}	0.312	0.495^{*}
SI (2000)	0.740^{**}	0.402^{*}	0.708^{**}
SI (2010)	0.551^{**}	-0.106	0.584^{**}

Table 4. Spearman's rank correlation coefficient between SI and urban expansion indicators

*, ** and *** denote significance at 0.1, 0.05 and 0.01 level, respectively.

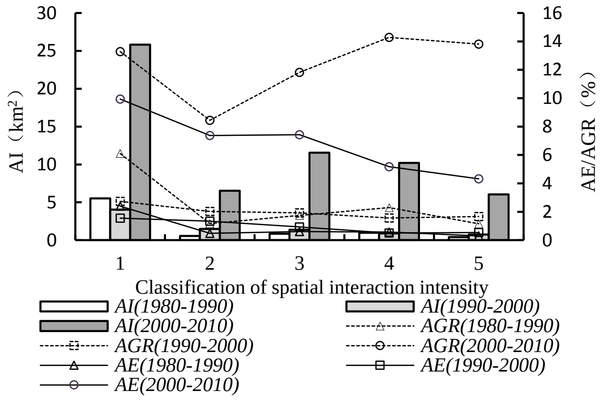

Figure 4. The relationship between spatial interaction intensity and urban expansion

Cities except core cities had been classified into five grades evenly in accordance with the size of the total spatial interaction intensity in descending order. There were five cities in the first five grades and six cities in the fifth grade.

Figure.4 shows the correlation between spatial interaction intensity with core cities and urban expansion. In general, it displayed a positive correlation between spatial interaction intensity with core cities and urban expansion intensity. The higher the interaction force was, the larger the build-up land expansion city had. Rank correlation coefficient (Table 4) between the speed of urban expansion and spatial interaction intensity is significantly positive only in the second period. Although cities in the first grade (adjacent to core cities) had the highest interaction force and expanded at the fastest pace, smaller cities expanded faster for cities in other grades. Rank correlation coefficient between location and urban expansion indicators was highest in the second stage, the third stage taking second place, followed by the first stage. During the early period of reform and opening-up, network organization within the urban agglomeration had not yet been formed and urban expansion of each city was isolated from one another. Urban development pattern began to transform and big cities significantly stimulated the growth of their surrounding small and medium-sized cities. Urbanization enters high-speed developing period after 2000, the influence of core cites on urban expansion of lower-rank cities is lesser than that of adjacent higher-rank cities.

3.2 The Correlation between Space Syntax Indicators and Urban Expansion

Space syntax indicators were calculated through Axowoman in ArcGIS software and Figure.5 displayed the classification results of connection value and global integration value of road network in YRD. The classification result of connection value showed that cities along the Nanjing-Shanghai-Hangzhou line had higher connection values and local accessibility. The global integration value showed that core cities in YRD had higher global integration and were convenient to access other cites within the urban agglomeration. Both local and global connection of road network showed that the accessibility of road network was higher in the central region of YRD. In addition, kernel density analysis was conducted based on space syntax variables, and point with the highest kernel density value in each city was taken as its traffic center.

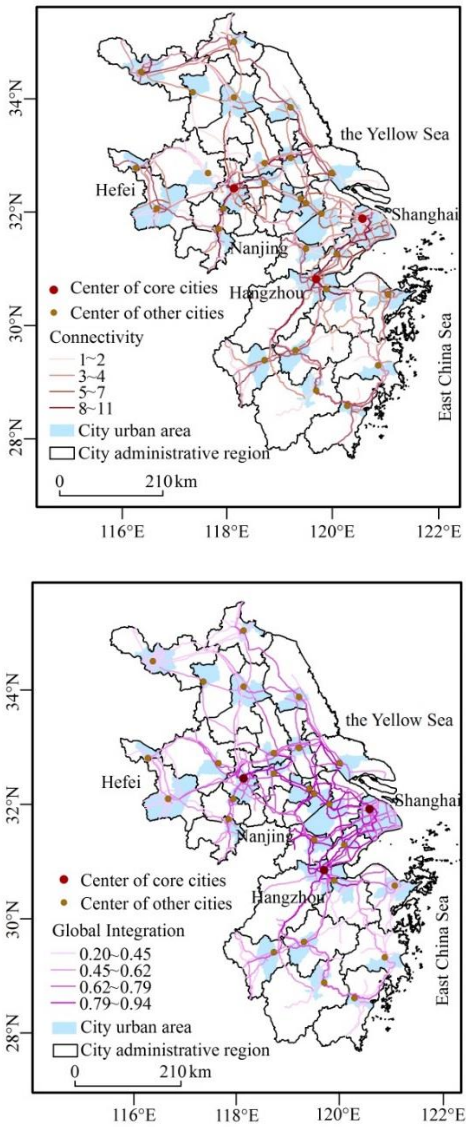

Figure 5. Classification results of space syntax model of road network

The weighted space syntax value of each city was obtained based on the space syntax value and the weight set according to the speed of different types of road networks. According to Highway Engineering Technical Standards of the People's Republic of China (JTGB-2006) and the practical conditions of the roads in YRD, the average speeds of different kinds of roads in each period were set as shown in Table 5. The weights of different kinds of road networks were obtained based on the average velocity of corresponding road (the influence of expressway was not considered before 1990 because the first expressway opened in 1988).

Year	National highway	Railway	Expressway
1990	60	50	—
2000	70	100	110
2010	80	140	120

Table 5. Average velocity of road network in the YRD (km/h)

— means there was no expressway in China before 1990.

Factors like total connection value, compositive ability and total global integration depicted a city's status in the road network of the urban agglomeration, quantitatively describing the accessibility to other cities through road networks within the urban agglomeration. Standardized results of the indicators mentioned above were in [0, 1] after min-max normalization. Bivariate Pearson correlation analysis was conducted among standardized space syntax variables and results showed that Pearson correlation coefficient was above 0.96 and significant, i.e., space syntax variables were mutually replaceable. Bivariate Pearson correlation analysis was conducted between standardized space syntax variables and urban expansion indicators. Results showed that correlation coefficient between total global integration and urban expansion indicators was the largest in each period. Therefore, we use total global integration to calculate accessibility of road network of each city. Results were shown in Table 6.

	AI (km^2)	AGR (%)	AE (%)
TGI1990	0.744***	0.328*	0.574**
TGI2000	0.860***	0.482**	0.870***
TGI2010	0.850***	-0.254	0.373*

Table 6. Correlation analysis result between TGI and construction land expansion indicators

*, ** and *** denote significance at 0.1, 0.05 and 0.01 level, respectively.

It exhibited a significantly positive correlation between *TGI* and build-up land expansion indicators, with exemption for the correlation between *TGI* and *AGR* in 2010. Pearson correlation coefficients showed that *TGI* had the highest correlation coefficients with *AI*, followed by *AE*, and *AEG* was the lowest.

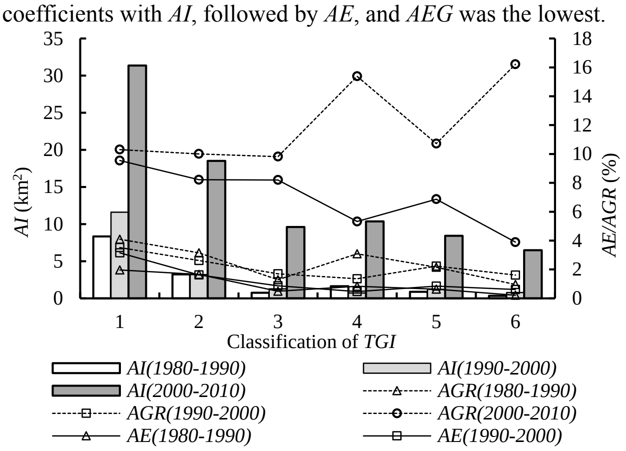

Figure 6. The relationship between traffic network and urban expansion

All cities had been classified into six grades evenly in accordance with the value of the standardized index of TGI in descending order. There are five cities in the first five grades respectively and four cities in the last grade. TGI was the highest for cities in the first grade, stronger accessibility of road network. On the contrary, TGI was the lowest for cities in the sixth grade.

Figure.6 depicted that, first, the value of *AI*, *AGR* and *AE* didn't vary much between the first stage (1980-1990) and the second stage (1990-2000), but changed a lot during the third stage (2000-2010). In 2000, Policies about national urbanization transformed from strictly controlling urban size and rationally developing small and medium-sized cities in 1989 into speeding up the process of urbanization and adhering to coordinated development among different cities (Fang et al., 2015). The urbanization rate had exceeded 30% in 2000, and YRD entered a stage of accelerated urbanization with higher speed of urban expansion. Second, rank correlation coefficient between road network accessibility and urban expansion intensity was significantly positive, and in the second and third stages it was significantly greater than that in the first stage, which showed under the background of rapid urbanization, urban expansion intensity and traffic network linked more closely. Third, rank correlation coefficient between the speed of urban expansion and road network accessibility is significantly positive only in the second period. However, cities with a lower grade in the whole road network (located in the periphery of the urban agglomeration) expanded faster in the third stage.

3.3 Convergence Analysis of Urban Expansion

Results mentioned above showed that along with urbanization, cities located in the periphery of urban agglomeration expanded faster in the third stage (2000-2010). The hypothesis of parallel growth of urban expansion has then been put forward and convergence analysis of city-size evolution was calculated through Lorenz curve, Zipf's law and Gibrat's law. Figure.7 depicted that the differences of city size was enlarging during the first and second stage, but it was narrowing in the third stage, which was in line with the convergence trend from 2000 to 2010. This trend also conforms to pole-axis theory, whose formation was attributed to spatial agglomeration and spatial dispersion. It displayed first spatial convergence and then spatial divergence (Lu, 2002). Figure.8 showed that cities in the upper and middle tail grew faster in early study period, while cities in the middle and lower tail expanded more quickly in the late study period. Figure.9 showed that the alteration of city-size distribution in YRD was obvious. With the nuclear density curve constantly moving to the right, it indicated that the overall scale of cities in YRD was expanding. Meanwhile, the kurtosis of kernel density curve was on the decrease and the shape of the curve was gradually evolving from left-skewed distribution to normal distribution in 2010. It indicated that small and medium-sized cities developed increasingly faster during the study period and the gap among different cities further narrowed.

Year	α(R^2)	Period	β(R^2)
1980	1.157***(0.86)		
1990	1.116***(0.86)	1980-1990	1.006***(0.94)
2000	1.073***(0.88)	1990-2000	1.041***(0.98)
2010	1.219***(0.91)	2000-2010	0.853***(0.90)

Table 7. Parameters and statistics of the Zipf's and Gibrat's model of cities in YRD

α is the Pareto exponent to analyze city size distribution, and β is the exponent of Gibrat's law. *, ** and *** denote significance at 0.1, 0.05 and 0.01 level, respectively.

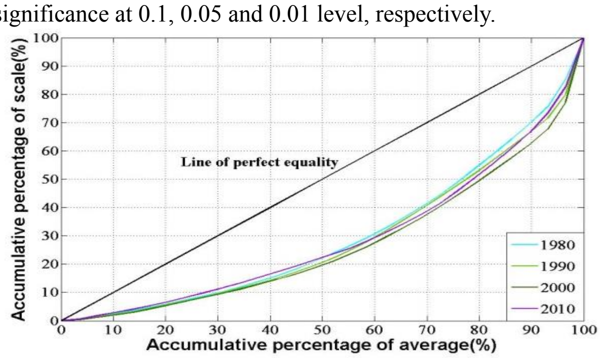

Figure 7. Lorenz curve of city size

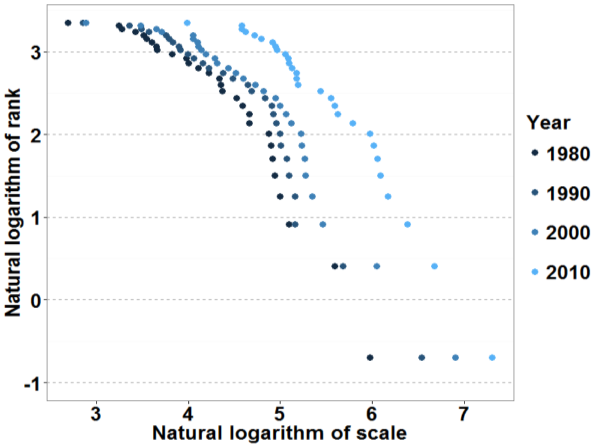

Figure 8. Rank-size distributions of cities in YRD

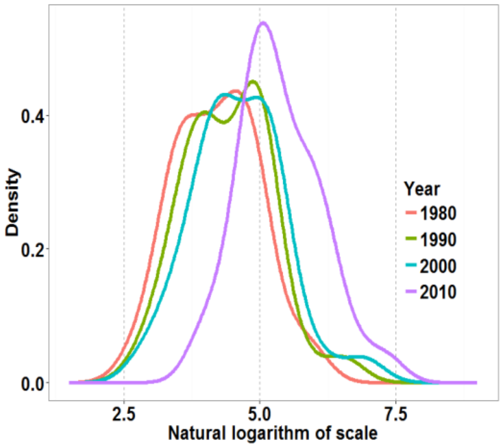

Figure 9. Kernel density estimates

OLS results in Table 7 depicted that build-up land size evolution in YRD did not meet the Zipf's law, only Zipf coefficient of city-size evolution in 2000 close to 1 while others not. α in each year was greater than 1, which indicated that build-up land scale distributed dispersedly and small and medium-sized cities were larger than expected of Zipf's law. Results of Gibrat's law showed that city-size evolution in YRD conformed to Gibrat's law in the first and second stages, indicating that the growth rate did not depend on initial size. But it did not hold in the third stage with smaller cities reaching a higher annual growth rate of build-up land. To sum up, urban expansion of cities in YRD was convergent in the third stage with smaller cities developing faster.

4. DISCUSSION

From the perspective of urban agglomeration, dynamic correlation between spatial linkage and urban expansion was analyzed based on location and road network. Overall, urban expansion was moderate and slow in the first and second phases. Urbanization accelerated in the third phase, with higher intensity and speed of urban expansion than the level before 2000.

Strong linkage with the core cities, such as accessibility and spatial interaction intensity, would promote the expansion of neighboring cities. But core cities had certain spheres of influence, and there was no positive correlation between urban expansion intensity and accessibility to core cities beyond this range. Along with the urbanization process in depth, the influence of regional core cities on other cities' urban expansion weakened. Considering the size of city such as GDP and population, the correlation between urban expansion intensity and spatial interaction intensity from core cities was positive. Core cities played a significant role in promoting the growth of surrounding cities after the overall urban development pattern had transformed in 1990s, when location, linkage with regional core city, became most closely related to urban expansion. Apart from cities near core cities expanding at the fastest pace after entering rapid development stage, smaller cities developed with a higher speed and therefore it presented a convergent trend.

With the course of urbanization accelerating, the correlation between the connection of road network and urban expansion intensity increased firstly and then decreased, indicating the improvement of road network within the urban agglomeration playing a firstly enhanced and then weakened role in the process of urban expansion. During the third stage when urban expansion entering rapid development stage, the impact of road network on urban expansion transformed from positive into negative. Meanwhile, cities with lower connectivity in the whole road network and located in the periphery of urban agglomeration developed more quickly, while the speed of build-up land expansion slowed down for large cities adjacent to core cities. Therefore, it exhibited a trend of spatial convergence. Lorenz curve indicated that city-size distribution in YRD moved towards imbalance before 2000 and balance after 2000. Zipf's law and Gibrat's law verified the existence of convergence for city-size distribution in rapid urbanization period.

There are many other methods to measure spatial linkage among cities except location and status in road network. More suitable methods to measure spatial linkage still need further study and spatial linkage among cities includes both physical network and virtual network. For example, physical network based on road network and virtual network like information flow and economic flow. Relations among different networks in the urban agglomeration as well as the spatial and temporal relationship between spatial linkage based on various networks and urban expansion is yet to be studied. Results show that spatial linkage among different cities within the urban agglomeration plays an important role in the process of urban growth. But with urbanization accelerating, this role changes both magnitude and direction. Besides YRD, the correlation between spatial linkage and urban expansion is yet to be studied for other urban agglomerations at different urbanization level.

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