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Analysis of China's Urban Innovation Connection Network Evolution: A Case Study of Henan Province

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Abstract: The research on urban innovation links is of great significance for revealing the structural characteristics of innovation space. At the same time, it is of great significance for formulating regional innovation development strategies. Based on statistics from 2008, 2013 and 2018, the time and spatial characteristics of the urban innovation contact network evolution in Henan Province were investigated using the entropy weight and gravity-model method. The results show that the overall pattern of the regional innovation network in Henan Province is radial, with the characteristics of a "core edge". It shows that it radiates to the surrounding cities with Zhengzhou as the core. From the perspective of time evolution, the radiation range and intensity of the innovation center city have changed to varying degrees and the overall radiation pattern has not significantly changed. From the perspective of spatial evolution, the evolution of Henan Province's innovation network presents the following development trends. The central and southern regions developed rapidly, and the western, northern and eastern regions developed slowly.

Keywords: gravity model; innovation connection network; urban innovation

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1. Introduction

The scientific and technological innovation links formed between cities through knowledge flow and technical cooperation have gradually formed an innovation network between cities. The development of the innovation network has effectively promoted the improvement of the overall scientific and technological innovation level of the region and the economic growth of cities in such regions [1]. The pattern of urban innovation space is currently forming an evolution trend "from point to face, from face to network". Inter-city collaborative innovation has become a new trend in urban development and the network perspective is gradually being introduced into urban innovation research [2,3]. Current studies show that the structure of an innovation network is an important factor that affects the integration and utilization of regional innovation resources [4]. This is directly related to the efficiency of the innovation system in the whole region, and the economic development performance of each city depends not only on their respective innovation ability but also on the linkage of regional innovation as a whole [5–8]. Therefore, scholars are paying increasing attention to urban innovation network connections.

The research on urban innovation link networks, both at home and abroad, shows the following trends. From the perspective of the research scope, researchers pay more attention to the analysis of large-scale difference characteristics. From the perspective of the research area, the current research focus is on urban circles, urban belts and urban agglomerations [9,10]. From a research content perspective, importance is being attached to the relationship between urban innovation functions and innovative urban spatial systems [11–13]. Further, increasing attention is being paid to analysis of the innovation-ability measurement in specific regions, such as the Yangtze River Delta Megalopolis

(YDM) and the Yangtze River Economic Belt (YEB) [14–16]. Innovation ability is the internal driving force for the formation of urban innovation connection networks. One must pay attention to the space-time evolution of the city's innovation ability and the city's innovation connection network, use long-term spatial analysis to study the space-time evolution, and use quantitative analysis to show qualitative results [17–19]. Focusing on the factors that influence urban innovation network construction and identifying the factors that drive urban innovation would help to enhance urban-innovation capability and promote regional collaborative development [20,21]. Additionally, paying careful attention to a comparative analysis of innovation capability across different urban economic zones would also serve to enhance understandings in this area [22–24]. Currently, some focus is on the agglomeration and spillover effects of innovation space, as well as on the analysis of the innovation-network structure and its proximity mechanism—the agglomeration and spillover effects [25,26]. Accordingly, focusing on spatial analysis requires paying attention to study in this direction [27,28]. It is important to pay attention to the temporal and spatial evolution of urban innovation capabilities and urban innovation connection networks and use quantitative analysis to show qualitative results. Many researchers have improved the gravity model in the research process to reflect the radiation range, intensity and spatial pattern of the city's innovative connections more accurately [29,30]. However, in such research, there is also the use of social-network- and cluster-analysis methods to study urban innovation links [31–33]. In studies investigating driving factors, the regression analysis method has been used [34]. In studies on urban innovation capability, the networked-spatial analysis method has been used, and there has been infrequent use of the chart-analysis method [35]. Research on the characteristics and development mechanisms of agglomerated subgroups in urban innovation networks mostly uses agglomerated subgroup analysis methods and multi-valued ERGM [36].

The research theme of this study is the innovative connection between cities. Taking Henan Province as an example, the gravity model is used as a network tool to evaluate innovative connections between cities. We aim to study the innovation network connection between 18 cities and reveal the evolution process of the urban innovation network. The gravity model is often used to analyze the spatial connection between two regions [16]. This research is based on the comprehensive index system constructed, combined with the gravitational model method, to analyze the innovation network connection of Henan Province from the two dimensions of space and time. After that, the study distinguished the total innovation intensity of 18 cities. Finally, the article provides suggestions for the innovation and development of Henan Province. The novelty of this paper is the addition of two dimensions of the innovation foundation and innovation connection in the construction of a comprehensive index system to carry out quantitative analysis on the innovation scale, innovation attraction and innovation connection network among cities in Henan Province.

2. Description of the Study Area

Henan is a province in central China and the capital city of Henan Province is Zhengzhou. It is an important comprehensive transportation hub, and is the people flow and logistics information flow center in China. Henan Province is bounded by Anhui and Shandong in the east, Hebei and Shanxi in the north, Shaanxi in the west and Hubei in the south, and has a total area of 167,000 square kilometers (see Figure 1).

Henan is China's largest economic province, with the fifth largest gross domestic product (GDP) in the country and the first in the Midwest. Further, the Central Plains Economic Zone (with Henan as the main body) is the fourth largest economic zone in China. In 2019, the province's GDP was 542.5920 billion yuan, an increase of 7.0% over the previous year in terms of comparable prices and 0.9 percent higher than the national average. The added value of the tertiary industry was 260.801 billion yuan, an increase of 7.4%, with the GDP of the tertiary industry in seventh place. At the end of 2019, there were 37,311 valid invention patents and 3.88 invention patents per 10,000 population. Moreover, 9310 technical contracts were signed throughout the year, with a turnover of 23.407 billion yuan.

In 2018, Henan Province's public budget revenue reached 376.602 billion yuan, and public budget expenditure reached 921.773 billion yuan, respectively, where they were ranked third and fifth in the country. Henan Province has a total of 53,400 schools (institutions) at all levels and an educational population of 28.5355 million, of which 26.771 million are students and 1.7645 million are faculty and staff. Henan Province's educated population is ranked first in the country, with a resident population that is ranked third after Guangdong and Shandong. By the end of 2019, there were 16.206 million civilian vehicles, an increase of 11.1% above the end of the previous year, of which 14.808 million were private cars, which represents an increase of 11.5%. The number of civilian cars increased by 12.3% to 8.777 million, of which 8.3339 million were private cars, which represents an increase of 12.5%. Accordingly, in terms of economy, population, education, science and technology, Henan ranks among the top in the country.

Figure 1. Location analysis of Henan Province.

According to the statistics of Henan Province in 2008, 2013 and 2018, as shown in Table 1, it can be seen that the comprehensive strength of Henan Province has increased significantly in recent years.

The Central Plains urban agglomeration consists of the Central Plains region while considering Henan Province as the main body. With the implementation of Henan Province's comprehensive integration into the Central Plains urban agglomeration strategy, Henan cities and Central Plains urban agglomeration can gradually move towards deep integration. Further, the innovation ability of Henan cities will improve and explore the direction and path for the integrated development of the Central Plains urban agglomeration. This will further improve the regional innovation ability and innovation performance in the future.

Table 1. Comprehensive strength evaluation form of Henan Province.

Index	2018	2013	2008
Per capita regional GDP (yuan)	946,101	669,451	398,704
General public budget revenue (100 million yuan)	3557.75	2281.591	929.3512
Total investment in fixed assets of the whole society (100 million yuan)	47,556.15	26,087.77	10,468.84
Actual utilization of funds outside the province (US $10,000)	96,471,000	61,975,000	18,492,000
Total volume of public library (10,000 volumes)	2762.85	1881	1618.3
Number of Internet users (10,000)	11,199.63	5656.29	493.8573
Number of students in adult higher education	338,626	336,395	268,811
Number of education practitioners (10,000)	124.59	119.72	108.56
National financial expenditure on education (100 million yuan)	1655.05	1030.08	400.69
National financial expenditure on science (100 million yuan)	133.31	67.83	25.38
Number of legal entities in the scientific research and technology service industry	45,096	6616	1727
Research and experimental development (R&D) personnel	101,471	216,269	68,750
Research and experimental development (R&D) external expenditure (10,000 yuan)	171,763	109,470	55,065.7
Proportion of science and technology expenditure in financial expenditure	0.29	0.24	0.24
Number of patent applications	44,586	18,095	6480
Number of patents granted	9743	2104	1815
Output value of new products (10,000 yuan)	74,973,868	49,481,046	13,632,739
Published scientific papers	63,350	57,312	48,616
Proportion of tertiary industry in GDP	7.43	5.08	4.80
Number of R&D projects	53,480	33,015	27,349
Private vehicle ownership by city	13,273,579	6,282,190	2,487,712
Total freight volume (10,000 tons)	235,183	282,970	118,198
Total business volume of postal industry (100 million yuan)	436.72	51.00	46.11

3. Data Sources

The paper constructs an index system of the urban innovation network of Henan Province, with statistical data for 2008, 2013 and 2018 from statistical yearbooks about both Henan Province and Chinese cities. In 2008, several major events occurred: The snow disaster, the Wenchuan earthquake, Beijing Olympic Games and the global financial crisis (GFC). Therefore, 2008 was chosen as the starting year, with five years serving as the time interval, in line with the country's five-year planning period. Accordingly, in 2013, there were major events such as the establishment of the Shanghai Free Trade Zone and the Ya'an earthquake. For the first time in 2018, the country formulated a strategic plan for rural vitalization, an intensive national introduction of major initiatives to support the private economy and held China's first International Import Expo. The driving distance between 18 cities was the shortest driving distance of the Baidu Map in 2019. The coordinates of each city and municipal government are also provided by the Baidu Map.

4. Methods

4.1. Entropy Weight Method

The index entropy value can reflect the amount of information provided by the index to the decision maker. The entropy value can objectively determine the importance of the index and is widely used to determine the weight of the evaluation index. The calculation steps of the entropy method are as follows:

The critical value method is used to normalize the data in Table 1, and then the entropy weight method (4) is used to determine the weight w_j of the index.

Standardization treatment:

$$a_{ij} = x_{ij} / \sum_{i=1}^{m} x_{ij}, \quad (1)$$

Information entropy:

$$E_j = -k\sum_{i=1}^{m} a_{ij} ln(a_{ij}) \qquad k = \frac{1}{ln(m)}, \tag{2}$$

Value:

$$D_j = 1 - E_j, \tag{3}$$

Weight:

$$w_j = D_j / \sum D_j \ , \tag{4}$$

The Formula a_{ij} includes the proportion of the indicator, x_{ij} is the original data of the market i under the j indicator in the study year, D_j is the entropy value of the indicator and w_j is the weight of the index.

4.2. Gravity-Model Method

The gravity model is the most commonly used method to measure the interconnectedness of a regional economy. Reilly first introduced the gravity model of physics into the field of geography research in 1929 [37]. With the rise of metrological geography and regional science, the gravity model has been widely used in the research of "spatial interaction" [38]. Since then, the gravity model has become an important tool for measuring the flow of elements and innovative connections between regions.

The current study used the gravity-model method to determine the innovation link between 18 cities in Henan Province. It aimed to quantify the innovation scale and innovation gravity between Henan province, dividing the innovation scale into four levels (i.e., innovation basis, innovation input, innovation output and innovation link). On the basis of determining the weight of the entropy law, the innovation scale of each city is calculated, and the innovation link between cities is comprehensively captured.

Scale of urban outward innovation:

$$M = w_j a_{ij} \ , \tag{5}$$

Innovation space connection:

$$R_{ij} = \frac{KM_iM_j}{D_{ij}^2} \qquad K = 1000 \ , \tag{6}$$

Total number of urban external innovation linkages:

$$R_i = \sum_{j=1}^{n} R_{ij}, \tag{7}$$

Maximum gravitational line:

$$R_i^{max} = max\{R_{i1}, R_{i2}, R_{i3}, \ldots, R_{in}\}, \tag{8}$$

In the model, a_{ij} represents the proportion of the indicator and w_j is the weight of the indicator. Further, R_{ij} is the innovation space link between city i and j, M_i and M_j are the scales of outward innovation in cities i and j and D_{ij} is the shortest mileage of a city's i and j government seats.

5. Results

5.1. Construction of an Index System of Urban Innovation Network

Innovation output and investment were used to measure the scale of innovation, where the spatial connection of innovation, the spatial diffusion of innovation and the extroversion of spatial agglomeration were taken into account. Then, an innovation foundation and innovation links were added to the scale of innovation, and finally, a multi-criteria-level

indicator system was built to reflect the scale of the city's outward innovation. The weight of each index was calculated using Formulas (1)–(4); (see Table 2).

Table 2. Weight table of urban innovation link network indicators in Henan Province in 2018.

First-Level Indicators	Weight	Secondary Indicators	Title 4
Innovation Foundation (A)	0.222	Per capita regional GDP (yuan)	0.010
		General public budget revenue (100 million yuan)	0.042
		Total investment in fixed assets of the whole society (100 million yuan)	0.026
		Actual utilization of funds outside the province (US $10,000)	0.021
		Total volume of public library (10,000 volumes)	0.014
		Number of Internet users (10,000)	0.042
		Number of students in adult higher education	0.052
		Number of education practitioners (10,000)	0.014
Innovation investment (B)	0.250	National financial expenditure on education (100 million yuan)	0.023
		National financial expenditure on science (100 million yuan)	0.043
		Number of legal entities in the scientific research and technology service industry	0.075
		Research and experimental development (R&D) personnel	0.044
		Research and experimental development (R&D) external expenditure (10,000 yuan)	0.059
		Proportion of science and technology expenditure in financial expenditure	0.006
Innovation output (C)	0.398	Number of patent applications	0.075
		Number of patents granted	0.100
		Output value of new products (10,000 yuan)	0.089
		Published scientific papers	0.071
		Proportion of tertiary industry in GDP	0.003
		Number of R&D projects	0.060
Innovation links (D)	0.130	Private vehicle ownership by city	0.035
		Total freight volume (10,000 tons)	0.016
		Total business volume of postal industry (100 million yuan)	0.078

Specifically, Table 1 shows that when the weight proportion is higher, the contribution of the indicators to the urban innovation network is higher.

1. For the foundation of innovation, the number of students in adult higher education, the number of Internet users (10,000 households) and the general public budget revenue (100 million yuan) account for a higher proportion compared with other secondary indicators.
2. Second, for innovation input, the number of legal entities in the scientific research and technology service industry, the external expenditure of research and experimental development (10,000 yuan) and the national financial expenditure on science (100 million yuan) have a higher weight compared with the others.
3. Finally, for the innovation output, the number of authorized patents, the output value of new products and the total business volume of the postal industry in the innovation link account for a higher proportion.

5.2. Analysis of the Evolution of the Spatial Structure of Regional Innovation Linkages

5.2.1. Characteristics of the Spatial Pattern of Regional Innovation Linkages

Different criteria were used to divide the gravity of innovation linkages between the cities under study, with reference to the classification criteria of the innovation contact networks of other cities [17,18]. Combined with the actual situation in Henan Province, 0 to 0.8 was defined as weak gravity, 0.8 to 1.6 as gravity in general, 1.6 to 2.4 as strong gravity and >2.4 as very strong (see Figure 2). The results revealed the following:

1. The overall pattern of regional innovation network in Henan Province is radial with Zhengzhou as the center, which is similar to the pattern of the high-speed rail transportation network in Henan Province (see Figure 2).
2. The spatial structure of the innovation connection in Henan Province presents the characteristics of the "core-periphery" innovation network structure. We can take Zhengzhou as the first-level node city, Luoyang as the second-level node city and Nanyang, Xuchang, Xinxiang, Jiaozuo and Kaifeng as the third-level node cities (see Figure 3, Table 2).
3. The innovation link of the city was found to be strong in the core development area of the Central Plains city group. The core is Zhengzhou with Xinxiang in the north, Xuchang in the south, Luoyang in the west, Jiaozuo in the northwest and Kaifeng in the east. There are six cities in the core development zone. Further, the innovation connection of marginal cities is weak, and they are on the radiation edge of central cities (see Figure 3).

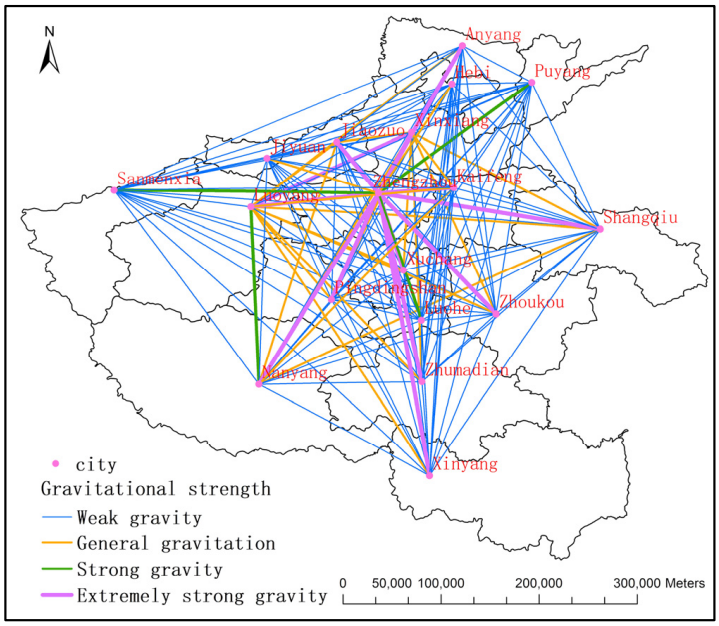

Figure 2. General situation of the urban innovation and contact network in Henan Province.

Taking into account the total number of urban innovation links and the intensity of innovation links between the cities, the urban innovation links in Henan Province can be divided into four levels, as shown in Table 3. From the above analysis, the following can be observed:

1. In this region of Henan Province, the innovation link conformed to the law of scale grade, where the larger the city scale and the higher the city level, the stronger the innovation link between the cities.
2. The innovation links also followed the law of the quantity of scale, where the larger the size of the city and the smaller the number of cities, the more a "pyramid" shape was revealed.
3. There are strong innovative connections between neighboring cities and cities in the main corridor of regional development, and weaker connections between marginal cities.

Table 3. Intensity classification of the innovation link in Henan Province.

Classification	Connection Strength	Reference	Indicator Meaning
First level	>2.4	Zhengzhou, Luoyang	Extremely strong gravity
Second level	1.6~2.4	Nanyang	Strong gravity
Third level	0.8~1.6	Xuchang, Xinxiang, Jiaozuo, Kaifeng, Anyang, Shangqiu, Zhoukou	General gravity
Fourth level	0~0.8	Pingdinshan, Hebi, Puyang, Luohe, Sanmenxia, Xinyang, Zhumadian, Jiyuan	Weak gravity

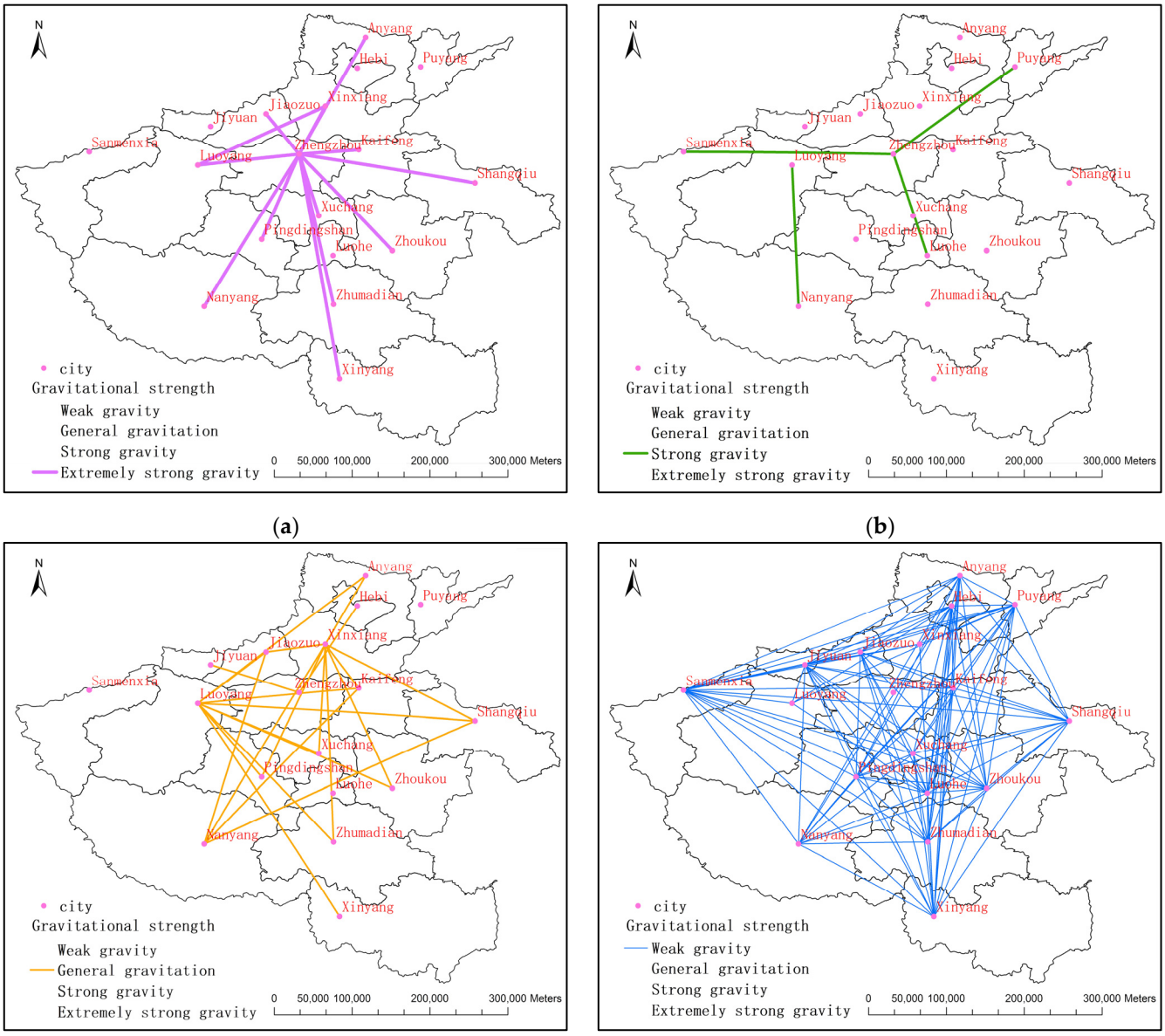

Figure 3. (**a**) First level; (**b**) second level; (**c**) third level; (**d**) fourth level.

5.2.2. Evolution of the Spatial Pattern of Regional Innovation Linkages

(1) Evolution of innovation linkage gravity in Henan Province

Figure 4 provides a visualization of the urban innovation contact data as a gravity intensity map of the innovation contact network.

1. First, from 2008 to 2018, the urban innovation link in Henan Province presented the structural characteristics of the "Zhengzhou-Loyang" dual core, where the trend of networking was obviously enhanced. The innovation connection development of Nanyang, Xinxiang, Xuchang and Jiaozuo caused the collection of innovation links to appear on the basis of a certain degree of difference. Simultaneously, the trend for the network characteristics of the urban innovation links was more significant, and the links between the cities were more complex.
2. Second, the lowest value of the innovation gravity in Henan Province in 2008 was 0.0064, and this was between the Three Gate Gorges and the crane wall; the maximum was 0.537, and this was between Zhengzhou and Luoyang.
3. Third, the maximum value of the innovation gravity in Henan Province in 2012 was 2.534, and this was between Zhengzhou and Luoyang; the minimum value was 0.015, and this was between Luohe and Hebi.
4. Next, the maximum innovation gravity in Henan Province in 2018 was 10.93, and this was between Zhengzhou and Luoyang—this was up from 0.537 in 2008 and 2.534 in 2013.

To better display the innovation relationship between the cities where the gravity was greater than or equal to the performance of 0.5 innovation link gravity on the drawing, the following were depicted (see Figure 5):

1. In 2008, the innovation link gravity reached more than 0.5 cities, and only Zhengzhou and Luoyang, and Zhengzhou and Xinxiang were the cities between the innovation links.
2. In 2013, Zhengzhou and Kaifeng, Pingdingshan, Anyang, Jiaozuo, Puyang, Xuchang, Sanmenxia, Nanyang City, Shangqiu City, Xinyang City, Zhoukou City, Zhumadian City, Luoyang and Xinxiang were added.
3. In 2018, the growth rate of new cities rose to meet the standards. This can be observed in Figure 5, where the weak link was Jiyuan, Hebi, Luohe and Sanmenxia, and other cities experienced more significant development.
4. Overall, the 5-year development rate from 2013 to 2018 was found to be quicker than that in the period of 2008–2013. Further, it can be observed that Zhengzhou's gravity became increasingly stronger, and the central clustering effect was more obvious. However, Luoyang City, Nanyang City, Xinxiang and Jiaozuo have witnessed a larger increase in innovation-linked gravity in recent years.

(2) Evolution of innovation-linkage gravity of central cities.

The evolution of innovation links in the 18 cities in Henan Province showed an increasing trend and the gravity of Zhengzhou showed an increasing trend of innovation with the evolution of gravity over time. The following can be observed from Figure 6.

1. In 2008, Zhengzhou's attraction to all cities was relatively weak. In 2013, the gravity between Luoyang and Zhengzhou reached a very strong level, and the gravity between Zhengzhou and Xinxiang reached a relatively strong level. By 2018, Zhengzhou's gravity to all surrounding cities will reach an average level or above.
2. Overall, Zhengzhou's radiation capacity and attraction capacity were strengthened, and the aggregation effect was obvious.

(3) Evolution of innovation linkage gravity of sub-central cities.

As can be observed from Figure 7, in 2008, 2013 and 2018, Luoyang's innovation attraction showed rapid growth. The urban innovation attraction between Luoyang and Nanyang, Zhengzhou, Xinxiang and other cities reached a relatively strong level.

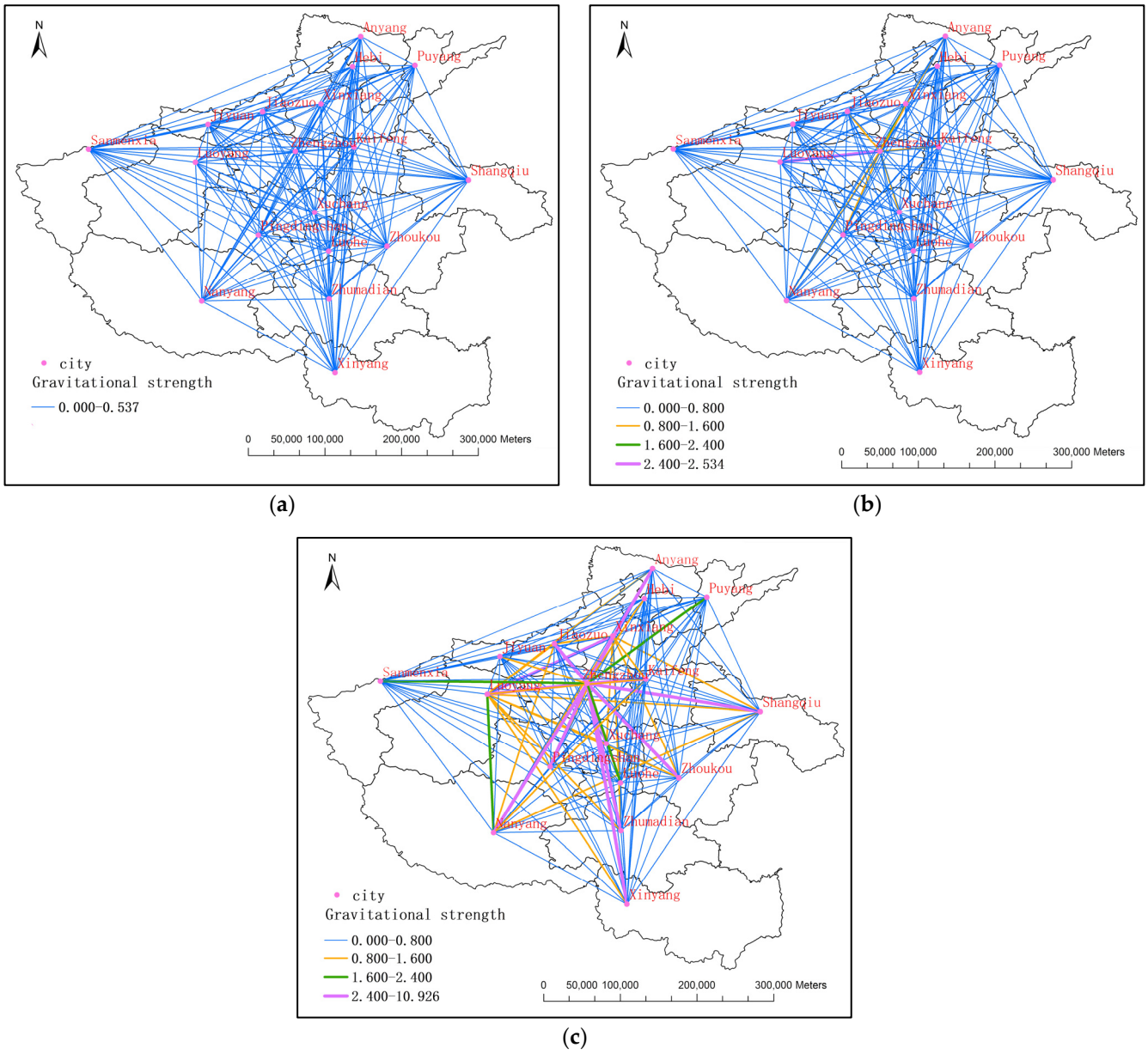

Figure 4. Gravitational strength of innovation networks in Henan Province in (**a**) 2008; (**b**) 2013; (**c**) 2018.

5.3. Evolution Pattern of the Regional-Innovation Time Linkage

The pattern of innovation contact time in Henan Province was found to have evolved. This finding was based on the different weights calculated by the 23 abovementioned indicators using Formulas (5)–(7). On the basis of calculating the weight of each index, the scale of outward innovation and the total number of innovation links of the city were calculated by year. The following can be observed from Table 4.

1. On the whole, the scale of outward innovation and the total number of innovation links were positively related. The scale of outward innovation and the total number of innovation links increased with the growth of the central cities and sub-central cities over time.
2. Second, the scale of outward innovation and the total number of innovation links in the various cities increased significantly. The maximum amount of outward innovation links in the cities increased from 4.117 in 2008 to 16.934 in 2013, and then to 72.2 in 2018. The minimum number of innovation links in the city, 699, increased from

0.412 in 2008 to 1.088 in 2013, and then to 3.861 in 2018. Further, the total number of innovation links increased significantly. The average scale of outward innovation increased from 0.008 in 2008 to 0.016 in 2013, and then to 0.032 in 2018.

3. Third, in terms of the growth rate of the total number of innovation contacts, the total number of innovation contacts in Zhengzhou and Luoyang in 2018 increased by 55.76 and 21.61, respectively, compared with 2013. The total number of innovation connections between Zhengzhou and Luoyang in 2013 increased by 12.82 and 5.74, respectively, compared with 2008. The growth rates of the two belonged to the top two, which shows that Zhengzhou and Luoyang have obvious agglomeration and radiation capabilities. Simultaneously, Zhengzhou and Luoyang increased much more in the period 2013–2018 than in the previous period of 2008–2013. The total number of external innovation links between Jiyuan, Hebi and Luohe did not change significantly. Here, the smallest growth rate was observed, and this lagged behind the other cities substantially.

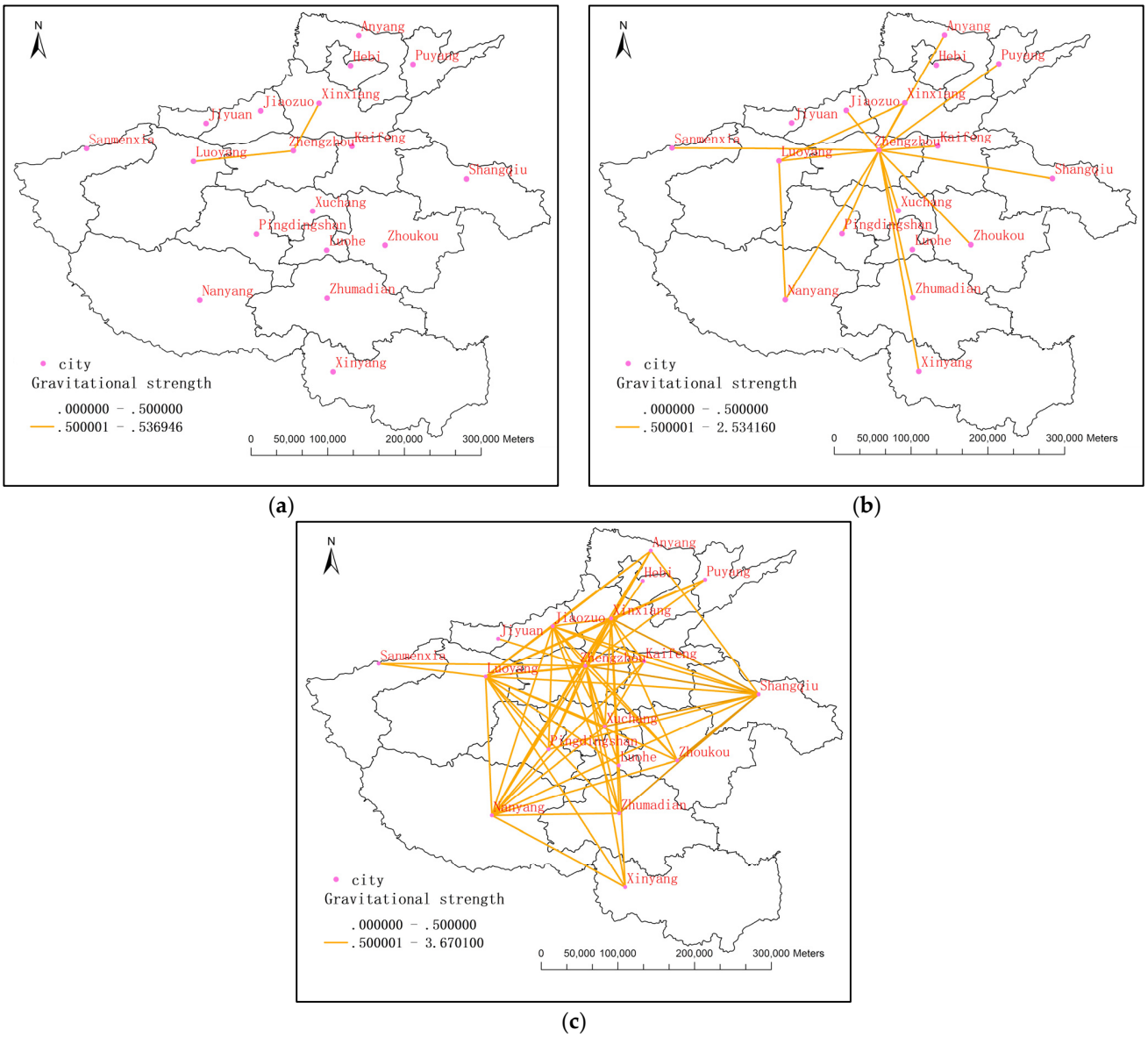

Figure 5. The attraction of innovation connection network in Henan Province in (**a**) 2008; (**b**) 2013; (**c**) 2018.

Table 4. Evolution of the time pattern of urban innovation linkage in Henan Province.

City	Extroverted Innovation Scale			Total Innovation Linkages		
	2008	2013	2018	2008	2013	2018
Zhengzhou	0.038	0.085	0.192	4.117	16.934	72.699
Kaifeng	0.007	0.011	0.024	0.950	2.889	13.129
Luoyang	0.014	0.030	0.057	1.834	7.578	29.191
Pingdingshan	0.007	0.013	0.019	0.972	3.629	10.555
Anyang	0.008	0.014	0.019	1.053	3.728	10.526
Hebi	0.002	0.003	0.007	0.325	0.953	4.177
Xinxiang	0.013	0.023	0.046	1.767	6.059	23.956
Jiaozuo	0.009	0.016	0.026	1.271	4.330	14.412
Puyang	0.004	0.006	0.012	0.498	1.769	6.545
Xuchang	0.006	0.015	0.023	0.846	3.977	12.748
Luohe	0.003	0.004	0.011	0.432	1.235	6.345
Sanmenxia	0.003	0.006	0.010	0.404	1.760	5.468
Nanyang	0.010	0.018	0.034	1.315	4.714	18.241
Shangqiu	0.005	0.009	0.026	0.674	2.417	14.391
Xinyang	0.004	0.009	0.017	0.518	2.372	9.251
Zhoukou	0.005	0.009	0.020	0.663	2.530	10.796
Zhumadian	0.005	0.009	0.020	0.743	2.404	10.890
Jiyuan	0.003	0.004	0.007	0.412	1.088	3.861

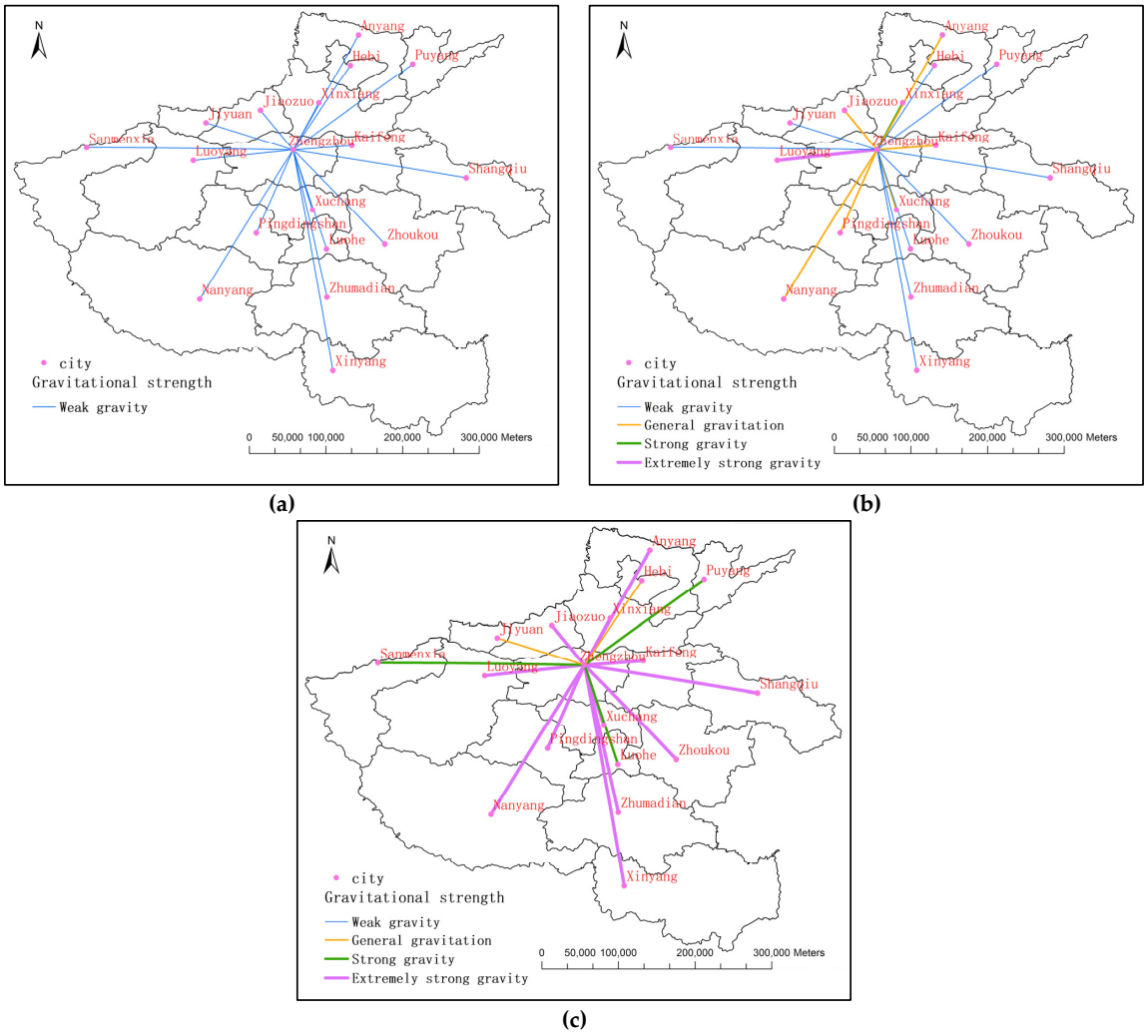

Figure 6. Gravitational strength of Zhengzhou City innovation networks in (**a**) 2008; (**b**) 2013; (**c**) 2018.

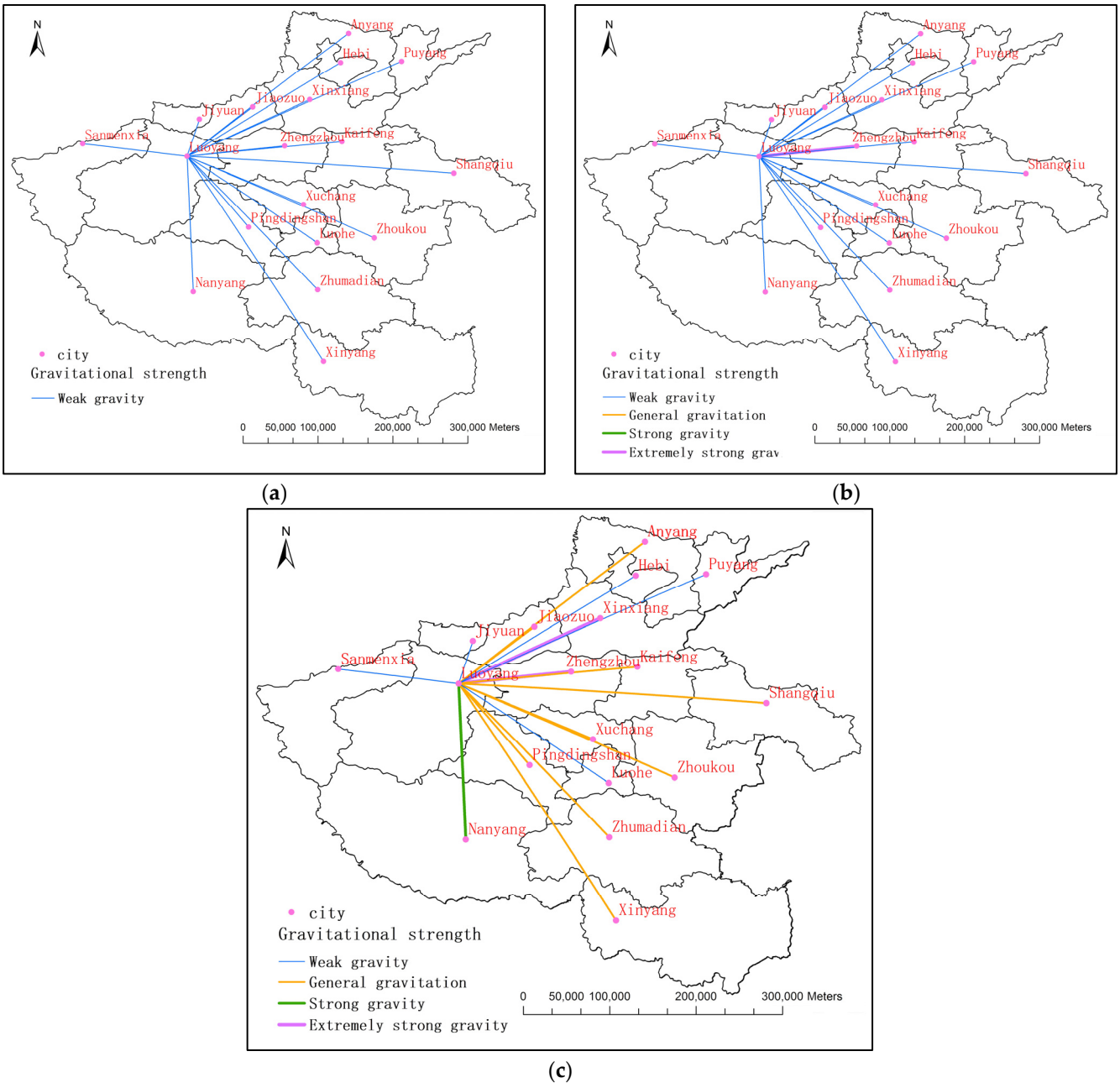

Figure 7. Gravitational strength of Luoyang City innovation networks in (**a**) 2008; (**b**) 2013; (**c**) 2018.

5.4. Evolution of the Total Innovation Linkages in Henan Province

According to the actual situation in Henan Province and referring to the dividing criteria of the total number of innovation links in other cities [17,18], the innovation links in Henan Province were divided into five levels: 0 to 5, representing weak innovation links; 5 to 10, representing general innovation links; 10 to 15, representing strong innovation links; 15 to 20, representing relatively strong innovation links; and >20, representing extremely strong innovation links.

The following can be observed from Figure 8.

1. The total number of innovation links in Henan Province was high in the middle, second highest in the south, higher in the east and low in the north and west. Overall, the development of Henan Province was quicker in the south when compared with the north, and quicker in the east when compared with the west.

2. In 2007, the maximum number of innovation links in Henan Province was 4.117 (in Zhengzhou) and most of the innovation links in various cities in Henan Province were at weak levels.
3. In 2012, the maximum number of innovation links in Henan Province was 16.934 in Zhengzhou, followed by Luoyang City. Further, the innovation links in various cities in Henan Province were ranked weak, weak and strong.
4. The maximum number of innovation links in Henan Province in 2017 was 72.699 in Zhengzhou, followed by Luoyang City, Xinxiang City, Nanyang City, Jiaozuo City and Shangqiu City, while the lowest innovation links in various cities in Henan Province were located in Jiyuan City and Hebi City.

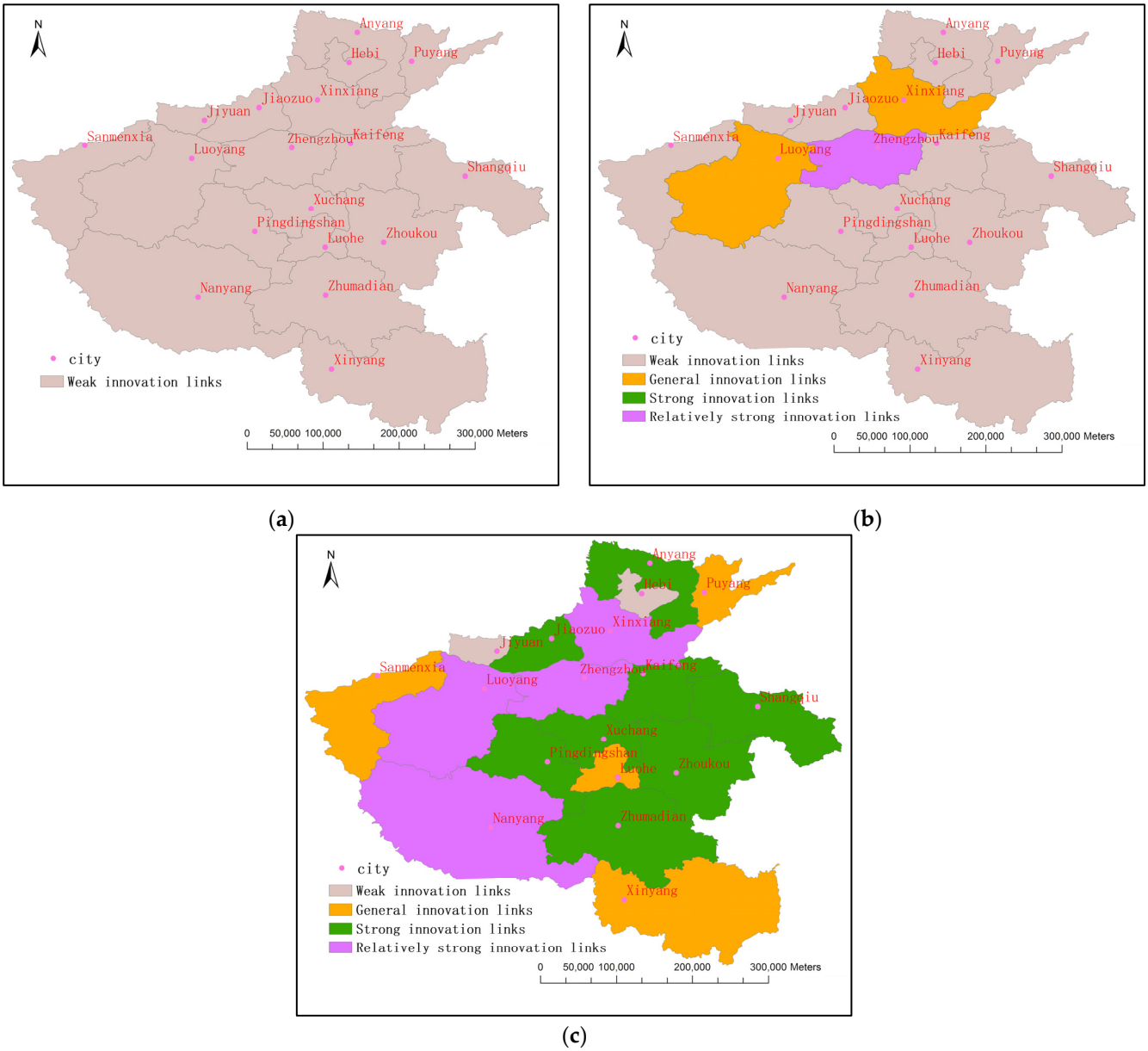

Figure 8. Total number of innovation links in Henan Province in (**a**) 2008; (**b**) 2013; (**c**) 2018.

The following can be observed from Figure 9.

1. The total evolution of urban innovation links in Henan Province showed an increasing trend.

2. The evolution and development trend of the total number of innovation contacts in Henan Province shows a certain law. The law is manifested in the rapid development of the central region, the rapid development of the south and the slow development of the north and east in the west.
3. Zhengzhou's growth rate ranked first among all of the cities and Luoyang's total innovation link growth rate was the second highest in Henan Province.
4. When compared with the development limitations of the ancient capitals, the total number of innovation links and the growth rate of Luoyang, Kaifeng City and Anyang City lagged.
5. In 18 cities, the growth rate of the total innovation links in Hebi, Jiyuan, Luohe, Sanmenxia, Puyang and other cities was found to be slow.

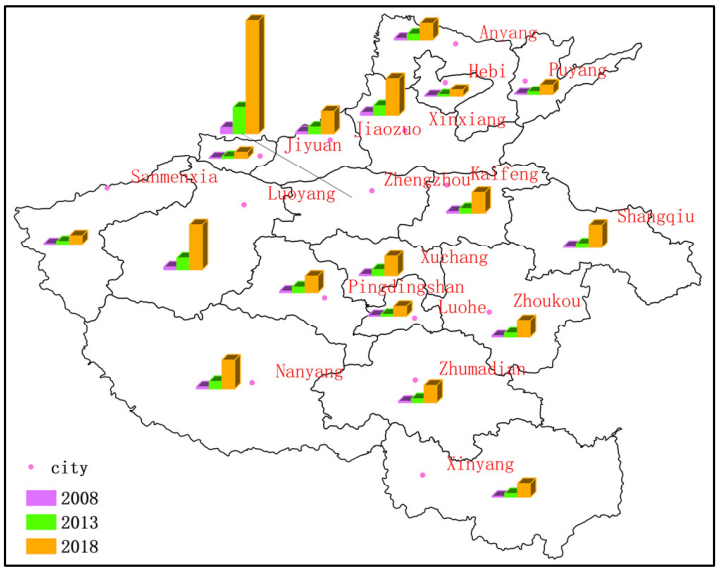

Figure 9. Evolution of the total number of urban innovation connections in Henan Province.

6. Discussion

The current study created a multi-criteria index system on an urban innovation contact network from the perspective of innovation connection. Using the gravity model, we indirectly measured the basic spatial pattern of innovation connections between the cities. It was revealed that the evolution law and characteristics of the urban innovation network are realistically and intuitively increasing. However, the strength of the innovation connection calculated by the gravity model is latent and does not have a connection value, which may deviate from the actual strength of the innovation connection between cities.

With the development and progress of society, the impact of the level of science and technology and the introduction of high-end talents on innovation links and intensity will continue to increase. The innovative connections between cities will also be more complex and diverse, and the influencing factors will also be more diverse. However, how to use multi-source data to measure and characterize innovative connections at the urban scale in more detail is the focus of future research. At the same time, future research should also focus on clarifying the influencing factors of the structural characteristics of the innovation connection network.

In addition, to further enhance the innovation connection of Henan Province, plan the new structure of the urban innovation network and narrow the development gap between cities, the following have been suggested:

(1) Realize the integration and complementarity of innovation resources.

It is important to encourage central cities to play a leading role, and guide cities to complement each other's advantages. The concentration level of innovation resources in key cities in Henan Province is different. Zhengzhou is the National Central City and

the core city of the Central Plains urban agglomeration; Luoyang is a national historical and cultural city and a sub-central city in Henan Province; and Kaifeng is a cultural tourism city and one of the central cities in the core area of China's Central Plains urban agglomeration. Henan Province needs to use Zhengzhou, Luoyang and Kaifeng as the core to break the barriers between cities and realize the innovative and integrated development of Henan Province. Cities need to promote the flow and diffusion of knowledge, talent and information, advocate the integration of resources and complement each other and realize the optimization of resource allocation.

(2) Strengthen the spillover effect of urban innovation.

There is a spillover effect in the innovation relationship, such as those in Zhengzhou, Luoyang and Kaifeng, which can significantly promote the overall tightness of the innovation network. All cities should challenge themselves, break through the stable connection of solidification, stimulate the positive spillover effect and expand the scope of the innovation radiation. Through the construction of a smooth and convenient logistics system between cities, the orderly and efficient flow of transportation factors can be realized. All governments should break through administrative boundary constraints to facilitate the flow of innovation resources. The state should promote the efficient allocation and open sharing of innovation resources in core cities and improve the level of innovation cooperation in Henan Province.

(3) Implement key innovation-driven measures.

Refining the key tasks of innovation-driven strategy and implementing various measures are the footholds of innovation network optimization. Therefore, it is necessary to speed up the upgrading of the overall industrial structure of Henan Province. Taking Zhengzhou as an example, it is important to consider relocating some industries in Zhengzhou City and carry out the "big adjustment of industrial structure" from point to point. Other cities should identify the right position, strengthen soft power and practice positive policies to accept the industrial transfer of central cities. Therefore, cities should be encouraged to attract innovative talents through talent introduction policies and entrepreneurial support policies, enhance the flow of talent resources between cities and achieve the vigorous development of innovation networks.

7. Conclusions

This paper calculates the urban innovation linkage of Henan Province from 2008 to 2018 using the entropy weight method and gravity-model method. The main conclusions are as follows:

1. We used the innovation output, innovation input, innovation foundation and innovation connection to measure the scale of innovation. Taking into account the spatial connection of innovation and the spatial diffusion of innovation and the extroversion of spatial agglomeration, a multi-criteria-level indicator system was finally constructed.
2. The regional innovation network of Henan Province presents an overall radial pattern with Zhengzhou as the center, which is similar to the pattern of the high-speed rail transportation network in Henan Province. The spatial structure of the innovation connection in Henan Province presents the characteristics of the "core-periphery" innovation network structure. Zhengzhou is the first-level node city, Luoyang is the second-level node city, and Nanyang, Xuchang, Xinxiang, Jiaozuo and Kaifeng are the third-level node cities.
3. The total amount of innovation contact in Henan Province showed a pattern of high in the middle, high in the south, higher in the east and low in the north and west. From the perspective of time, the radiation range and intensity of the innovation center city were found to have evolved to varying degrees, but the overall pattern did not show a significant change.
4. Except for the central cities in Henan Province, the fastest-growing area belongs to the southern Henan region, while the northern Henan region, which has been developing

strongly before, has shown a downward trend. With the exception of Luoyang City, the western Henan area has relatively slow development. In addition, the total amount of innovation connections in western Henan and the innovation attraction between cities are relatively weak, and the differences in innovation capabilities between cities are very obvious.

5. In 2008, the internal structure of the urban innovation network in Henan Province showed obvious unbalanced development. The first and second levels are the main contributors to the development of the urban innovation network in Henan Province, driving the growth of the whole network innovation performance. The innovative connection between cities in marginal areas and other urban nodes in the network has made slow progress. This imbalance of growth has become an obstacle to the innovation and development of Henan Province.
6. From 2008 to 2018, the scale of outward innovation, the total amount of innovation links and the gravitational strength of innovation link networks increased significantly. Zhengzhou, a city in the core region, plays a bridging role in innovation cooperation in the innovation contact network and promotes the collaborative innovation ability of the non-core regions by sharing innovation cooperation opportunities. On the whole, the leader of the evolution of the innovation network in the past decade is still the city in the core region. The leader has actively played the role of an intermediary, driving the improvement of the urban collaborative innovation ability and level among cities in Henan Province.

The scale of innovation and the attraction of the innovation network in Henan Province have gradually improved over the past decade, and the trend of coordinated development has become more and more obvious. With the continuous improvement of the country's national economy, the economic and ecological exchanges in Henan Province have become increasingly close, and the coupling and interaction effects between cities have increased year by year. Especially at the end of 2012, the State Council formally approved the programmatic document of the Central Plains Economic Zone Plan. The coordinated development of the Central Plains urban agglomeration is conducive to economic cooperation and ecological protection in various regions and provides a boost for the better and healthier development of Henan Province.

As one of the five development concepts, innovation has become the main driving force leading the sustainable development of the economy and also provides an important guarantee for the high-quality development of the economy and society. Although rapid transportation and communication technologies play an important role in weakening the influence of geographic distance, they have not completely eliminated the spatial effect of geographic proximity. Communication between innovation subjects plays an important role in innovation output and development. The clustering effect between cities will be more prominent, and its role in the spatial organization of Henan Province will also be more significant.

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References

1. Wang, C.; Wang, Y.; Shen, Z. Research on the evolution of innovation and cooperation network space of urban agglomerations in the Yangtze River Delta. *J. Shanghai Norm. Univ. (Philos. Soc. Sci.)* **2021**, *50*, 117–126.
2. Xu, C.; Wang, J.; Wang, H. Demand-oriented innovation of firms in China: An empirical study. *Front. Econ. China* **2008**, *3*, 548–559. [CrossRef]
3. Federica, C.; Gianni, G.; Stefano, P. Institutional fragmentation and urbanization in European Union cities. *Reg. Stud.* **2021**, *55*, 269–281. [CrossRef]
4. Tang, J.; Li, N.; Pan, P. Research on innovation network structure and driving factors of the Yangtze River Delta Urban Agglomeration. *Shanghai Econ. Res.* **2018**, *11*, 63–76.
5. Chen, X.; Lv, P.; Xue, S.; Li, M. What does the character of urban technology reveal about convergence versus divergence of innovation in China? *Growth Chang.* **2020**, *51*, 1631–1656. [CrossRef]
6. Xian, G.; Zeng, G.; Cao, X. Structural feature and proximity mechanism of Chinese intercity innovation network. *World Reg. Stud.* **2018**, *27*, 136–146.
7. Yuan, Y. Exploring inter-country connection in mass media: A case study of China. *Environ. Urban Syst.* **2017**, *62*, 86–96. [CrossRef]
8. Gehrke, S.R.; Clifton, K.J. An Activity-related Land Use Mix Construct and Its Connection to Pedestrian. *Travel Environ. Plan. B Urban Anal. City Sci.* **2019**, *46*, 9–26. [CrossRef]
9. Wang, X.; Feng, M.; Gu, H. Analysis on the scale difference characteristics of inter-city innovation links: A case study of the Yangtze River Delta Core Area. *J. Southeast Univ.* **2015**, *17*, 108–116.
10. Zhou, C.; Zeng, G.; Cao, X. Chinese inter-city innovation networks structure and city innovation capability. *Geogr. Res.* **2017**, *36*, 1297–1308.
11. Fang, C.; Yu, D. Urban agglomeration: An evolving concept of an emerging phenomenon. *Landsc. Urban Plan.* **2017**, *162*, 126–136. [CrossRef]
12. Hu, H.; Lv, L.; Huang, R. Urban innovation system and Function in Guangdong Province in the perspective of flow of urban innovation. *Res. Urban Dev.* **2015**, *22*, 71–76.
13. Lv, L.; Li, L. A research on Chinese renovation urban system based on urban renovation function. *Acta Geogr. Sin.* **2010**, *65*, 177–190.
14. Zhao, J.; Zeng, G. Spatial measurement of innovation: Data and indicator. *Econ. Geogr.* **2009**, *29*, 1250–1255.
15. Burger, M.J.; Ronald, S. Polycentricity and the Multiplexity of Urban Networks. *Eur. Plan. Stud.* **2014**, *22*, 816–840. [CrossRef]
16. Ma, S.; Zeng, Z. Analysis on the innovation and spatial structure of the Yangtze River Economic Belt. *World Reg. Stud.* **2018**, *27*, 57–65.
17. Yin, Y.; Zhang, X. Analysis on spatiotemporal evolution of Innovation linkage among the cities in Shandong province. *J. Nat. Sci. Hunan Norm. Univ.* **2018**, *41*, 1–10.
18. Zhang, H.; Liu, Q.; Li, G. Spatial structure change and optimization strategies of innovation linkage among the cities in Guangdong Province. *Prog. Geogr.* **2016**, *35*, 952–962.
19. Li, P. Metropolitan economic growth and spatial dependence. *Evid. A Panel China* **2008**, *3*, 277–295. [CrossRef]
20. Yan, Z. Research on the Evolution and Influencing Factors of China's Urban Innovation Link-Ages Network. Master's Thesis, East China Normal University, Shanghai, China, 2018.
21. Batisse, C. Dynamic externalities and local growth a panel data analysis applied to Chinese provinces. *China Econ. Rev.* **2002**, *13*, 231–251. [CrossRef]
22. Xie, Y. The Comparison of Innovation Ability of Three Megalopolises in China. Master Thesis, Guangzhou University, Guangzhou, China, 2011.
23. Lu, T.; Wu, Z.; Huang, L. International comparison of creative cities cluster—An analysis of social network and spatial organization on innovative collaboration: International comparison of creative cities cluster between the Bosnywash Megalopolis and the Yangtze River Delta Region. *Urban Plan. Forum* **2016**, *2*, 35–44.
24. Aghion, P.; Bloom, N.; Blundell, R.; Griffth, R.; Howitt, P. Competition and innovation: An inverted U relationship. *Q. J. Econ.* **2005**, *120*, 701–728.
25. Herstad, S.J.; Ebersberger, B. Urban agglomerations, knowledge-intensive services and innovation: Establishing the core connections. *Entrep. Reg. Dev.* **2014**, *26*, 211–233. [CrossRef]
26. Tong, H.; Shi, P.; Luo, J.; Liu, X. The Structure and pattern of urban network in the Lanzhou-Xining. *Urban Agglom.* **2020**, *30*, 59–74. [CrossRef]
27. Wang, W.; Sun, F. Spatial agglomeration and spillover effects of urban innovation in Yangtze River Delta. *Geogr. Res.* **2017**, *36*, 1042–1052.
28. Babones, S.J.; Alvarez, R.M.J. Standardized income inequality data for use in cross-national research. *Sociol. Inq.* **2007**, *77*, 3–22. [CrossRef]

29. Jiang, T.; Xie, M.; Liu, G. Spatial of regional innovation output based on gravity model: A case study in Zhejiang Province. *Sci. Geogr. Sin.* **2014**, *34*, 1320–1326.
30. Qian, C.; Ye, J.; Lu, C. Gravity zoning in Wuhan Metropolitan Area based on an improved urban gravity model. *Prog. Geogr.* **2015**, *34*, 237–245.
31. Hu, Y.; Shi, H. Analysis of the urban innovation spatial correlation in Yangtze River Delta urban agglomeration: Based on the method of social network analysis. *Shanghai Econ. Res.* **2017**, *4*, 87–97.
32. Ye, X.; Liu, X. Integrating social networks and spatial analyses of the built environment. *Environ. Plan. Anal. City Sci.* **2018**, *45*, 395–399. [CrossRef]
33. Bi, L.; Shi, L. Evaluation of city innovation capability and the construction of "regional Innovation circle" in Yangtze River Delta—Based on the factor and cluster analysis method. *Econ. Geogr.* **2008**, *28*, 946–951.
34. Qian, H.; Du, X.; Liang, Y. Urbanization response to the industrial structure evolvement in Henan Province. *Areal Res. Dev.* **2017**, *36*, 23–28.
35. Zheng, Y.; Zhao, H.; Lu, L. Evolution of spatial pattern of urban innovation links in Anhui Province. *Yunnan Geogr. Environ. Res.* **2017**, *29*, 28–35.
36. Sun, Y.; Peng, S. Development Mechanism of Cohesive Subgroups' Urban Innovation Networks in the Yangtze River Delta: Based on the Valued ERGM. *Sci. Geogr. Sin.* **2020**, *40*, 874–881. [CrossRef]
37. Reilly, W.J. *Methods for the Study of Retail Relationships*; University of Texas: Austin, TX, USA, 1929.
38. Haggett, P. *Locational Analysis in Human Geography*; Edward Arnold Ltd.: London, UK, 1965.