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Spatio-Temporal Evolution of Urban Innovation Networks: A Case Study of the Urban Agglomeration in the Middle Reaches of the Yangtze River, China

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Abstract: Understanding the evolutionary characteristics of innovation network structure can improve urban innovation and regional construction. Urban innovative development is affected by various factors, which can be analyzed via models of innovation networks. We establish a multi-criteria evaluation system of innovation capability and use an improved gravity model to construct an innovation network for 2015–2018, employing social network methods to analyze structural characteristics and spatial patterns. Results show that: (1) The innovation of cities in the urban agglomeration in the middle reaches of the Yangtze River has gradually increased, with an accompanying increase in the complexity of innovation networks. The cities of Wuhan, Changsha, and Nanchang are located at the absolute core of this network, which exhibits a Matthew effect, and has a triangle integration mode of growth. (2) The attraction of innovative resources and the promotion of individual innovation are increasing every year within the cities. The aggregation pattern of innovation shows a multi-core state in the urban agglomeration in the middle reaches of the Yangtze River, but the innovation radiation pattern has changed from a single center to a double center. (3) Multiple spatial innovation axes are seen in the network, with a location and direction consistent with the urban agglomeration's development axis in the Yangtze River's middle reaches and a triangle integration growth mode. Policy implications are proposed for regional innovation and development, and our results can provide future policy guidance and direction for governmental entities and other stakeholders.

Keywords: innovation network; network structure; spatiotemporal evolution; urban agglomeration

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1. Introduction

Innovation is a necessity for city competition in a fast-changing world and is a driving force for city development [1,2]. Cities that possess world-class innovation can attract global talents and allow strategic initiatives for international competition [3]. The current driving force of urban development in China has shifted from factor-driven to innovation-driven [4].

Spatial dependence or autocorrelation is a common feature of spatial data [5]. Innovation also has spatial correlation because of its spatial diffusion and knowledge spillover characteristics [6]. Freeman [7] put forward the concept of an innovation network and defined innovation networks as a new form of cooperation formed by innovation subjects to adapt to systematic innovation. The construction of innovation connection networks can help the flow and integration of innovation resources among network nodes to promote the development of regional innovation [8]. The social network method was first applied to innovation system research in 1996 [9]. Since then, research on the structural characteristics of innovative networks based on social network analysis has been extensive.

Innovation networks are mainly considered from two perspectives. In the first approach, the construction of innovation networks is based on data generated by cooperative innovation [10–15]. For example, Li et al. analyzed published papers and applied patents to construct an innovation network in China [13]. Yu et al. considered corporations and used the data of collaborative patents to reveal the temporal and spatial evolution of the Zhongguancun IUR cooperative innovation network [14]. Kong et al. used 53 high-end equipment manufacturing enterprises in Shanghai to explore knowledge cooperation's influence on enterprise innovation performance in innovation networks [15]. However, A few factors cannot fully reflect the innovation link between cities, which is affected by multiple factors [16]. The second approach considers the role of multiple factors when constructing innovation networks [17–20]. For example, Zhu et al. constructed the index system from the foundation of innovation, innovation input, and innovation output. They used the gravity model method to measure the basic spatial pattern of innovation connections between the cities [19]. Sun considered the influence of innovation input, innovation output, and innovation environment when constructing an innovation network in the Yangtze River Delta region [20]. The formation of innovation networks is affected by multifaceted factors. However, a few studies consider the impact of economy, culture, education, and technology in the construction of an innovation network.

The gravity model has been widely used in urban studies, but some critiques remain due to the linear distance fuzziness [21]. In the traditional gravity model, the innovative connections between two regions increase with innovation capacity and decrease with distance [22]. Communication technology and transportation facilities have progressed greatly, narrowing the distances between cities in both space and time [23], and diversifying linkages. The constraint of geospatial space on innovation networks is obviously reduced with ongoing improvements to high-speed rail and other fast transportation networks [24]. Therefore, the traditional gravity model cannot accurately represent the actual innovative connection strength. In order to calculate the innovation connection strength between cities more reasonably, we apply three significant improvements to the gravity model.

The research perspectives of innovation networks are diversified. In the network structure analysis perspective, network density, centrality, openness, cohesion, average path, hub, and other characteristics of innovation connection networks and employed [25–27]. The spatial analysis perspective considers the characteristics and situation of cyberspace innovation at different regional levels [10,28,29] to explain its dynamic mechanisms of evolution [30]. However, there is a lack of analysis of the spatiotemporal characteristics of innovation networks.

The scope of innovation network research typically focuses on the country [31], urban belts [24], and urban agglomerations [32]. An urban agglomeration is a vital innovation space and carrier in the new knowledge economy. In China, most research on the innovation networks of urban agglomerations is mainly concentrated on the Yangtze River Delta, the Pearl River Delta, the Yangtze River economic belt, and the Beijing Tianjin Hebei Urban Agglomeration [33–35]. The urban agglomeration in the middle reaches of the Yangtze River is a core of new urbanization in China and a new growth center of the national economy. However, regional development strategies of gradual reform have marginalized and weakened regional economic ties. According to the Development Report on Changjiang Middle Reaches Megalopolis (2018) [36], the overall innovation level of urban agglomeration in the middle reaches of the Yangtze River lags behind eastern China. The optimization of its structure has a critical influence on the sustainable development of regional innovation [29]. Therefore, it is necessary to closely analyze the innovation networks of the urban agglomeration in the middle reaches of the Yangtze River.

We here construct an innovation network of the urban agglomeration in the middle reaches of the Yangtze River by calculating the urban innovation capability indicators using an integration of multiple indicators, and determining the innovation connection between cities by improving the gravity model. The innovation network is then centrally analyzed and divided into cohesive subgroups to discuss the characteristics and evolution of the innovation network and provide suggestions for the development of regional innovation in the middle reaches of the Yangtze River. Our objectives herein are:

(1) Compare the innovation capability of various cities in the urban agglomeration in the middle reaches of the Yangtze River.
(2) Evaluate the radiation ability, attraction ability, and intermediary role of urban innovation in the urban agglomeration in the middle reaches of the Yangtze River and analyze the small regional groups of innovation.
(3) Identify the evolution of innovation patterns in the urban agglomeration in the middle reaches of the Yangtze River and put forward policy suggestions for cultivating innovation growth poles and expanding innovation axes.

2. Materials and Methods

2.1. Study Area

The urban agglomeration in the middle reaches of the Yangtze River (UAMRYR) is located in the center of China, within a latitude range of 26°07′–32°10′ N and a longitude range of 110°15′–118°29′ E (Figure 1). The UAMRYR is one of seven national-level urban agglomerations approved by the State Council, which has a vast economic reach and a solid foundation for exchanges. The UAMRYR is composed of the Wuhan Metropolitan Area (WMA), the Ring of Changsha-Zhuzhou-Xiangtan Urban Agglomeration (RCZXUA), and the Urban Agglomeration around Poyang Lake (UAAPL). In 2019, a research report on promoting innovation cooperation of urban agglomerations in the middle reaches of the Yangtze River detailed multiple issues impacting the development of innovation cooperation in the UAMRYR [37], such as insufficient coordination of innovation policies, low quality of innovation input and output, weak linkage of industrial innovation, and insufficient exchanges and cooperation among innovation subjects. In this context, studying the innovation network of the UAMRYR is necessary to provide new development insight for the innovative construction of this urban agglomeration.

2.2. Materials

We consider the years 2015–2018 as our study period, with relevant data were collected from the China Urban Statistical Yearbook (2015–2018), the Hubei statistical yearbook (2015–2018), the Hunan statistical yearbook (2015–2018), and the Jiangxi statistical yearbook (2015–2018) (https://data.cnki.net/yearbook, accessed on 1 April 2022). The map resources are taken from National Catalogue Service for Geographic Information(www.webmap.cn, accessed on 1 April 2022). The railway traffic data (2015–2018) comes from the SMSKB app, and road network data (2015–2018) comes from OpenStreetMap (www.openstreetmap.org, accessed on 1 April 2022). The data on the highway and railway passenger volume are from the statistical bulletin on the development of the transportation industry.

2.3. Methods

2.3.1. Research Framework

In order to measure the spatial pattern and reveal the structural characteristics of the innovation network, we design a research framework, as shown in Figure 2. First, we use the entropy, a commonly used weighting method, to evaluate the innovation capability of each city. The gravity model was used to investigate the correlations between two cities. However, the traditional gravity model cannot well measure the innovative connection of cities. Second, we improve three aspects of the traditional spatial gravity model—city quality, the gravitation coefficient, and city distance. This improved gravity model is then applied to calculate the intensity of innovation linkages between cities, and the innovation network of urban agglomeration is constructed. Third, we analyze the influence of cities, divide them into subgroups, and investigate the density matrix of different subgroups.

Finally, we identify urban agglomerations' innovative spatial structure patterns in different periods and put forward relevant suggestions for regional innovation and development.

2.3.2. Entropy Method

The innovation level of a city is affected by many factors [17–19,38]. Selecting an appropriate indicator is the fundamental requirement for assessing urban innovation capability. We establish an evaluation index system of urban innovation capability (Table 1).

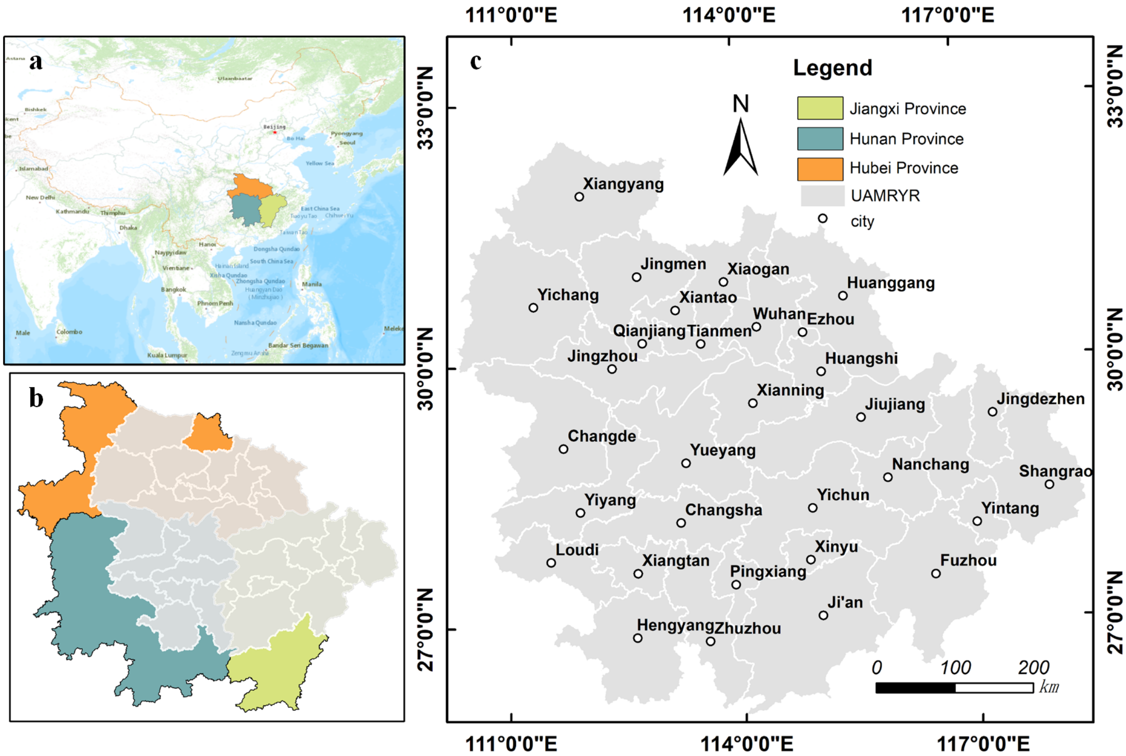

Figure 1. Study area: (**a**) Location of Jiangxi Province, Hunan Province, and Hubei Province in China. (**b**) Location of UAMRYR in three provinces. (**c**) Cities included in UAMRYR.

Table 1. Innovation ability evaluation index.

Index	Weight	The Description of the Index
Number of persons engaged in education	0.048	Which is the investment intensity of talent training in a city [39–41].
Number of college students	0.132	
Internal R&D expenditure of industrial enterprises above the designated size	0.080	Which is the financial support capacity of enterprises and government for innovation activities within a city [39,41–43].
Proportion of government science and technology appropriation in fiscal expenditure	0.026	
Number of domestic patents granted	0.095	Which is the ability of innovation output within a city [44–46].
Number of domestic patents applications	0.103	
Total profits of industrial enterprises above the designated size	0.042	Which are the economic benefits of innovation [47,48].
Per capita regional GDP	0.038	Which shows a city's economic growth and indirectly indicates the potential for improving innovation capability [42,49].
Actual utilization of foreign capital	0.113	Which is the support of external finance for urban innovation [46,50].
Passenger transport volume	0.036	Which represents the support of traffic environment for urban innovation [51–53].
Cargo transportation volume	0.048	
Number of Internet broadband users	0.059	Which is the level of communication facilities and indicates the diffusion speed of innovation factors [42,54–56].
Number of fixed telephone subscribers	0.050	
Number of mobile phone users	0.054	
Library collection (C_{15})	0.076	Which shows the support of cultural investment for urban innovation [43,56].

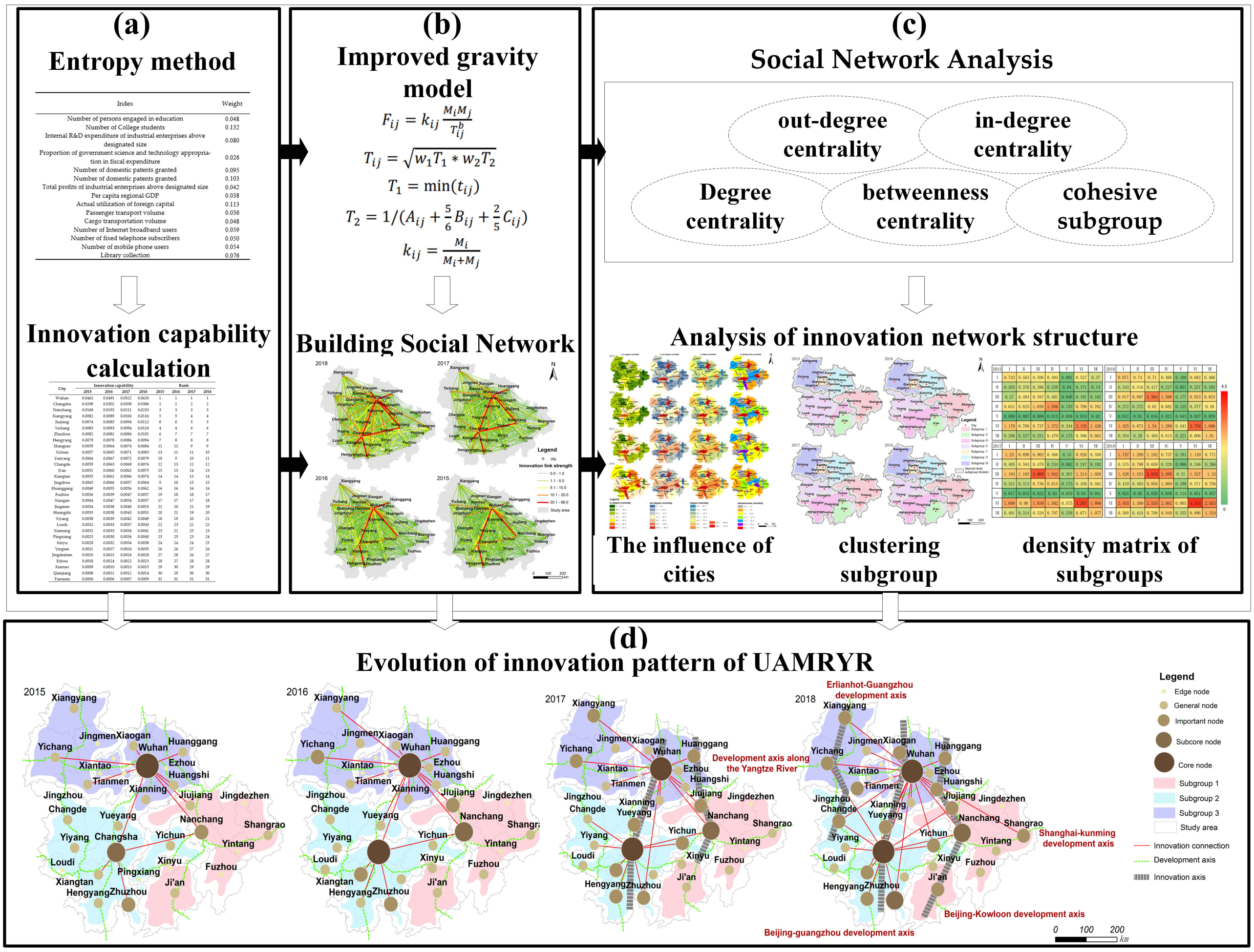

Figure 2. Research framework: (**a**) Calculating the innovation capability (results see Section 3.1). (**b**) Building the innovation network (results see Section 3.2). (**c**) Analyzing the structure of the innovation network (results see Sections 3.3 and 3.4). (**d**) Discussing the innovative pattern (results see Section 4).

The entropy method is a commonly used weighting method that measures value dispersion in decision-making [41,57,58], which is more objective than the analytic hierarchy process [59]. In order to solve the problem of information overlap between multiple variables and the assumption of the subjective weight assignment method [60], we use the entropy method to calculate the weight of each innovation indicator. The derivation of city innovation capability is detailed below:

(1) Data matrix construction. The original indicator matrix can be expressed as:

$$X = \left(x_{\lambda ij}\right)_{t\times n\times p} \quad (1 \le \lambda \le t, 1 \le i \le n, 1 \le j \le p) \tag{1}$$

where $x_{\lambda ij}$ represents the value of indicator j of city i in year λ. Here, t is 4, n is 31, and p is 15.

(2) Data standardization. A range standard method is used for the dimensionless treatment of various indicators in this research, according to:

$$Z_{\lambda ij} = \left(x_{\lambda ij} - x_{min}\right) / \left(x_{max} - x_{min}\right) \tag{2}$$

where x_{max} is the maximum value of innovation indicator j, x_{min} is the minimum value of innovation indicator j, $x_{\lambda ij}$ is the value of indicator j before nondimensionalization, and $Z_{\lambda ij}$ is the value of indicator j after nondimensionalization.

(3) Indicator normalization. The proportion of indicator j for city i in the year of λ is calculated according to:

$$R_{\lambda ij} = Z_{\lambda ij} / \sum_{\lambda=1}^{t} \sum_{i=1}^{n} Z_{\lambda ij} \quad (3)$$

where $R_{\lambda ij}$ is the normalized matrix, and $Z_{\lambda ij}$ is the value of indicator j after nondimensionalization. Other parameters are the same as (2).

(4) Indicator entropy value calculation:

$$E_j = -k \times \sum_{\lambda=1}^{t} \sum_{i=1}^{n} R_{\lambda ij} \ln R_{\lambda ij} \quad (4)$$

$$k = 1/ \ln(t \times p) \quad (5)$$

where E_j is the entropy value of indicator j, and $R_{\lambda ij}$ is the normalized matrix.

(5) Indicator redundancy calculation:

$$D_j = 1 - E_j \quad (6)$$

where D_j is the redundancy of indicator j, and E_j is the entropy value of indicator j.

(6) Indicator weight calculation:

$$W_j = D_j / \sum_{j}^{p} D_j \quad (7)$$

where W_j is the weight of indicator j, D_j is the redundancy of indicator j, and p is the number of indicators. The weight of each indicator is shown in Table 1.

(7) City innovation capability calculation:

$$C_{\lambda i} = \sum_{j=1}^{p} R_{\lambda ij} \times W_j \quad (8)$$

where $C_{\lambda j}$ is the innovation capability of city i in year λ, $R_{\lambda ij}$ is the normalized matrix, and W_j is the weight of indicator j.

2.3.3. Improved Gravity Model

In 1946, a gravity model based on Newton's universal law of gravitation was applied to study urban spatial interaction [61]. The calculation of the gravity model is given by:

$$F_{ij} = k \frac{M_i M_j}{D_{ij}^{\beta}} \quad (9)$$

where F_{ij} is the connection degree between city i and city j, k is the gravitational coefficient, M_i and M_j are the quality of city i and city j, D_{ij}^{β} is the distance between city i and city j, and β is the distance friction coefficient, with a value of 1.5 [21]. We apply three significant improvements to the gravity model.

First, the city quality parameters are improved, using city innovation capability to replace urban quality (Equation (8)).

Second, the city distance parameter is improved. Path distance cannot accurately describe the cost of connection and exchange between the two places. The level of inter-city traffic also affects the strength of inter-city links. Thus, we use traffic convenience to characterize the distance between cities. Since road and railway are the main modes of transportation in China, only these two modes of transportation are considered in the calculation of the distance parameters, according to:

$$T_{ij} = \sqrt{w_1 T_1 \times w_2 T_2} \quad (10)$$

$$T_1 = \sum_{j=1,i=1,i\neq j}^{n} min\left(l_{ij}\right)/V_{ij} \quad (11)$$

$$T_2 = 1/\left(A_{ij} + \frac{5}{6}B_{ij} + \frac{2}{5}C_{ij} + 0.05\right) \quad (12)$$

Here, T_{ij} represents the traffic convenience between city i and city j; the larger the value, the lower the traffic convenience between cities. T_1 represents the convenience of the highway, T_2 represents the convenience of the railway, w_1 represents the convenience coefficient of the highway, and w_2 represents the convenience coefficient of the highway. Values are determined by the proportion of national highway and railway passenger traffic each year. $min\left(l_{ij}\right)$ represents the shortest path distance from city i to city j, V_{ij} represents the highway travel speed from city i to city j, A_{ij} represents the daily number of high-speed rail trains from city i to city j, B_{ij} represents the daily number of bullet trains from city i to city j, and C_{ij} represents the daily number of express trains from city i to city j. Indirect connections (e.g., transfers) have little impact on the final measurement result of railway convenience, so accessibility values add a value of 0.05 to account for this.

Third, the gravitational coefficient is improved. The innovation acting intensity of city i to city j is different from that of city j to city i. Hence, the proportion of urban innovation capability to the sum of innovation capability of the two associated cities is used to amend the empirical constant k as:

$$k_{ij} = \frac{M_i}{M_i + M_j} \quad (13)$$

where M_i and M_j are the innovation capability of city i and city j.

2.3.4. Social Network Analysis

We use social network analysis on the innovation network structure to describe the interactive structural relationship and its development between individuals. This approach can reveal the overall structural characteristics of the network and reflect the importance of individuals in the network structure [62]. We analyze the node relationship and overall structural characteristics of the innovation network of the UAMRYR from the aspects of centrality analysis and cohesive subgroups.

Centrality analysis of the innovation network structure utilizes four relevant metrics: in-degree centrality, out-degree centrality, degree centrality, and betweenness centrality. The calculation formula of each index is shown in Table 2.

Table 2. Calculation formulae of centrality analysis.

Name	Formula	Description
Out-degree centrality	$C_{out\ i} = \sum_{j=1}^{n} V_{ij}$	$C_{out\ i}$ denotes the out-degree centrality of city i, and V_{ij} is the innovation link strength between city i and city j. When the value of $C_{out\ i}$ increases, it indicates that the innovation radiation capacity of the city i becomes stronger.
In-degree centrality	$C_{in\ i} = \sum_{j=1}^{n} V_{ji}$	$C_{in\ i}$ denotes the in-degree centrality of city i, and V_{ji} is the innovation link strength between city j and city i. When the value of $C_{in\ i}$ increases, it indicates that city i's ability to absorb innovative resources has become stronger
Degree centrality	$C_i = C_{out\ i} + C_{in\ i}$	$C_{\ i}$ denotes the degree centrality of city i, and $C_{out\ i}$ is the out-degree centrality of city i, $C_{in\ i}$ is the in-degree centrality of city i. When the value of $C_{\ i}$ increases, it indicates that the status of city i in the innovation network is higher.
Betweenness centrality	$C_{RBi} = \frac{2\sum_j^n \sum_k^n b_{jk}(i)}{3n^2-3n+2}$	C_{RBi} denotes the betweenness centrality of city i, and $b_{jk}(i)$ indicates the ability of the city i to control the communication between city j and city k. When the value of C_{RBi} increases, it indicates that the status of city i plays a greater role as a bridge between other cities.

The cohesive subgroup is a clustering method, which can be measured from the reciprocity, proximity or accessibility, frequency, and closeness of the relationship among the members of the subgroup [63]. The CONCOR (Convergent Correlations) iteration was adopted when implementing the innovation subgroup analysis. CONCOR is an iterative correlation convergence method that can directly analyze multivalued matrix and multivariate relationship matrix and use Pearson's product distance coefficient to measure the number of small groups in the matrix [64].

3. Results

3.1. Innovation Capacity of the Urban Agglomeration in the Middle Reaches of the Yangtze River

The ranking of the innovation capability index of different cities from 2015 to 2018 has volatility, with the top three cities being Wuhan, Changsha, and Nanchang (Table 3). This shows that these three cities are leading the innovative development of the UAMRYR. By comparing the cities with the strongest and weakest innovation ability in 2015–2018, we find that the innovation index gap is still significant, and the "Matthew effect" [65] has appeared. For example, the innovation index of Wuhan was 68 times that of Tianmen in 2018. This demonstrates that the development of regional innovation is unbalanced. For overall innovation development, the regional innovation capacity of UAMRYR increased year by year from 2015 to 2018 (Figure 3). The innovation index increased from 0.218 to 0.292, the average innovation index increased from 0.0050 to 0.0066, and the growth rates of the innovation index were 0.08, 0.09, and 0.14, respectively. Although the innovation growth rate of UAMRYR is low, it is also developing continuously to become a core growth pole of China.

Table 3. Innovation capability and ranking of cities in the UAMRYR from 2015 to 2018.

City	Innovation Capability				Rank			
	2015	2016	2017	2018	2015	2016	2017	2018
Wuhan	0.0462	0.0491	0.0522	0.0620	1	1	1	1
Changsha	0.0298	0.0302	0.0358	0.0386	2	2	2	2
Nanchang	0.0168	0.0193	0.0211	0.0233	3	3	3	3
Xiangyang	0.0082	0.0089	0.0106	0.0116	5	5	4	4
Jiujiang	0.0074	0.0083	0.0094	0.0112	8	6	5	5
Yichang	0.0085	0.0093	0.0094	0.0110	4	4	6	6
Zhuzhou	0.0082	0.0082	0.0086	0.0101	6	7	7	7
Hengyang	0.0079	0.0078	0.0086	0.0094	7	8	8	8
Shangrao	0.0059	0.0064	0.0074	0.0084	11	12	9	9
Yichun	0.0057	0.0065	0.0071	0.0083	13	11	11	10
Yueyang	0.0064	0.0067	0.0072	0.0079	10	9	10	11
Changde	0.0059	0.0063	0.0069	0.0076	12	13	12	12
Ji'an	0.0051	0.0060	0.0062	0.0075	15	15	14	13
Xiangtan	0.0055	0.0061	0.0066	0.0074	14	14	13	14
Jingzhou	0.0065	0.0066	0.0057	0.0064	9	10	15	15
Huanggang	0.0049	0.0055	0.0056	0.0062	16	16	16	16
Fuzhou	0.0036	0.0039	0.0047	0.0057	19	18	18	17
Xiaogan	0.0044	0.0047	0.0054	0.0057	17	17	17	18
Jingmen	0.0034	0.0038	0.0040	0.0053	21	20	21	19
Huangshi	0.0035	0.0038	0.0043	0.0051	20	21	19	20
Yiyang	0.0038	0.0039	0.0042	0.0049	18	19	20	21
Loudi	0.0032	0.0033	0.0037	0.0043	22	23	22	22
Xianning	0.0032	0.0033	0.0034	0.0041	23	22	25	23
Pingxiang	0.0025	0.0030	0.0036	0.0040	25	25	23	24
Xinyu	0.0028	0.0032	0.0034	0.0038	24	24	24	25
Yingtan	0.0021	0.0027	0.0026	0.0035	26	26	27	26
Jingdezhen	0.0020	0.0023	0.0026	0.0028	27	28	26	27
Ezhou	0.0018	0.0024	0.0022	0.0023	28	27	28	28
Xiantao	0.0009	0.0010	0.0013	0.0015	29	30	29	29
Qianjiang	0.0008	0.0011	0.0012	0.0014	30	29	30	30
Tianmen	0.0006	0.0006	0.0007	0.0009	31	31	31	31

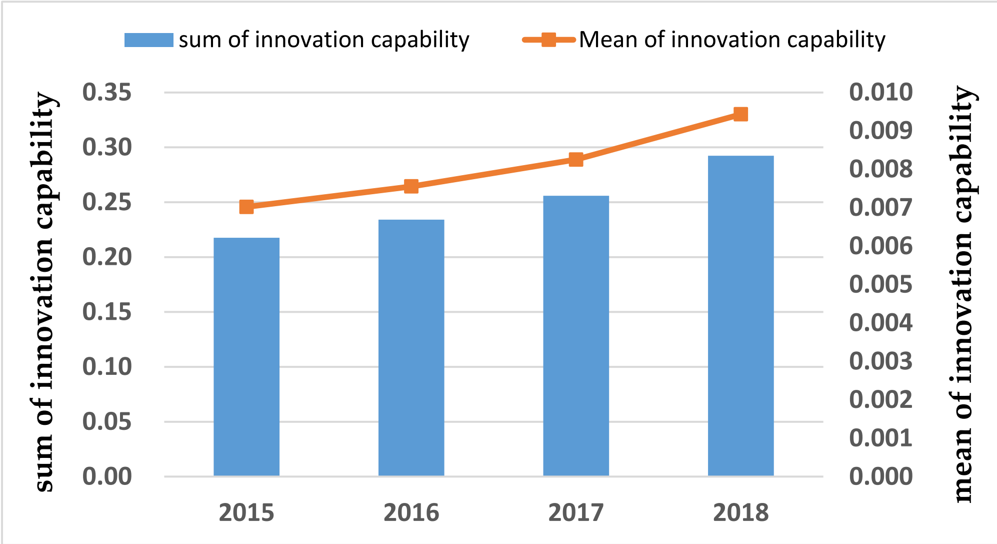

Figure 3. Evolution of the innovation capability in UAMRYR.

3.2. Spatial Network Structure of the Urban Agglomeration in the Middle Reaches of the Yangtze River

The innovation network of UAMRYR shows a "stratification" (Figure 4). Overall, the innovation network density and connection strength of the UAMRYR have increased. The innovation link network formed between Wuhan, Changsha, and Nanchang constitutes a stable "triangle," and the urban innovation links are highly concentrated on the links among the three. The innovation links at the fifth level have decreased year by year, while the links at other levels have increased. The urban innovation network structure is thus becoming more stable. The innovation links within UAMRYR were relatively sparse, and the intensity of innovation links between cities varied greatly in 2015. Wuhan, Changsha, and Nanchang have become leading cities of innovation within the urban agglomeration. The innovation connection intensity between most cities located on the edge of the region is less than 1, and the "core periphery" feature is significant. In 2017, the intensity of innovation links among the three provincial capitals became closer, and the first "triangle" appeared in the urban agglomeration. While strengthening the innovation links with other cities in their respective provinces, Wuhan and Changsha broke the inter-provincial barriers in the cluster. They strengthened the links with cities outside the province. Meanwhile, the innovation linkage level in Nanchang mainly occurs in Jiangxi Province. The network formed by pairs of cities with innovation connection strength greater than 10 shows that many small "triangles" have expanded outward with Wuhan, Changsha, and Nanchang as a core during 2018. This reveals that the development of surrounding urban clusters driven by the development of core urban clusters is important to developing the innovation network structure of urban clusters in the middle reaches of the Yangtze River.

3.3. Centrality Analysis of Innovation Networks in the Urban Agglomeration in the Middle Reaches of the Yangtze River

Centrality analysis can effectively measure the status and influence of cities in the innovation network(Figure 5). The in-degree value of a city in UAMRYR increases year by year (Figure 5a), meaning that cities are becoming more attractive to innovative resources. Although there have been small dynamic changes in rank, the top five cities of the UAMRYR, according to their in-degree centrality, always include Changsha, Zhuzhou, Wuhan, Zhuzhou, and Xiangtan. This shows that the innovative development of the provincial capital cities is affected by the surrounding cities. Meanwhile, Changsha, Zhuzhou, and Xiangtan have seen better conditions for innovative development.

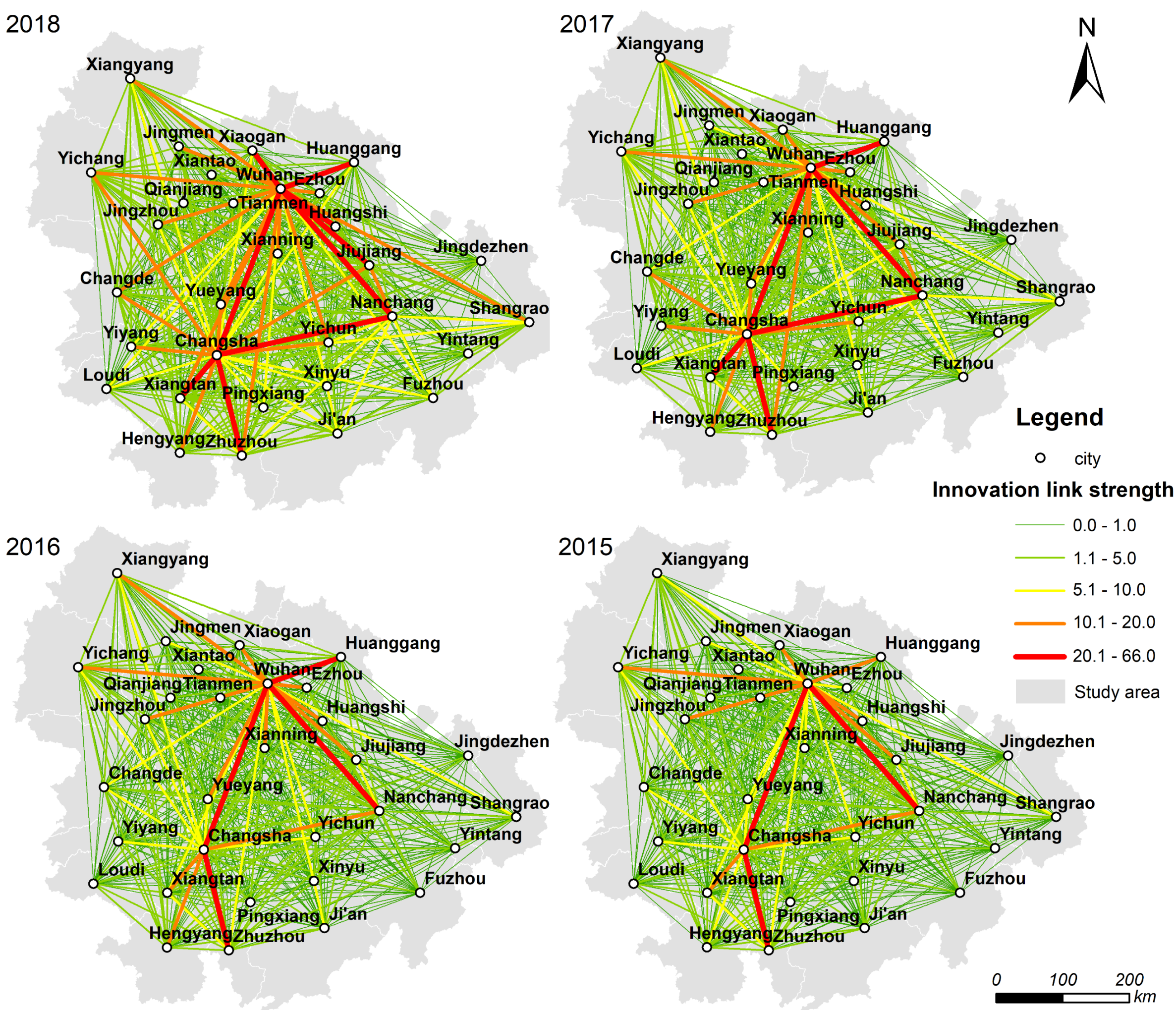

Figure 4. Evolution of the hierarchical structure of innovation networks in the UAMRYR.

The out-degree value of cities in the UAMRYR increased from 2015 to 2018 (Figure 5b), which illustrates that the innovation radiation ability of these cities is enhanced. There is a large gap in the innovation radiation capacity between different cities, particularly in the Wuhan urban circle. In 2018, the out-degree value of Wuhan, Changsha, and Nanchang was greater than 100, while the value of Xiantao, Qianjiang, Tianmen, and Jingdezhen was less than 5. Wuhan and Changsha have strong innovation radiation ability and occupy a core position in the process of innovation spillover. Although the innovation power of Nanchang is weaker than that of Wuhan and Changsha, it has played an important role in driving the surrounding cities. Comparisons of the inflow and outflow of each city show that the innovation inflow of most cities is greater than the outflow, showing that each city is improving its attraction of innovation resources and promoting individual innovation development.

The degree centrality is calculated by combining in-degree centrality and out-degree centrality to measure the city's position in the innovation network (Figure 5c). From 2015 to 2018, the number of edge nodes and general nodes in the innovation network gradually decreased, and each node city played an important role in the innovation network. In 2018, Wuhan and Changsha were core nodes in the innovation network, Nanchang was a sub-core node, and most cities were only important nodes. The distribution location of network nodes at each level shows that important nodes, sub-core nodes, and core nodes form a clear spatial axis, which is roughly consistent with the development axis of urban agglomeration in the middle reaches of the Yangtze River.

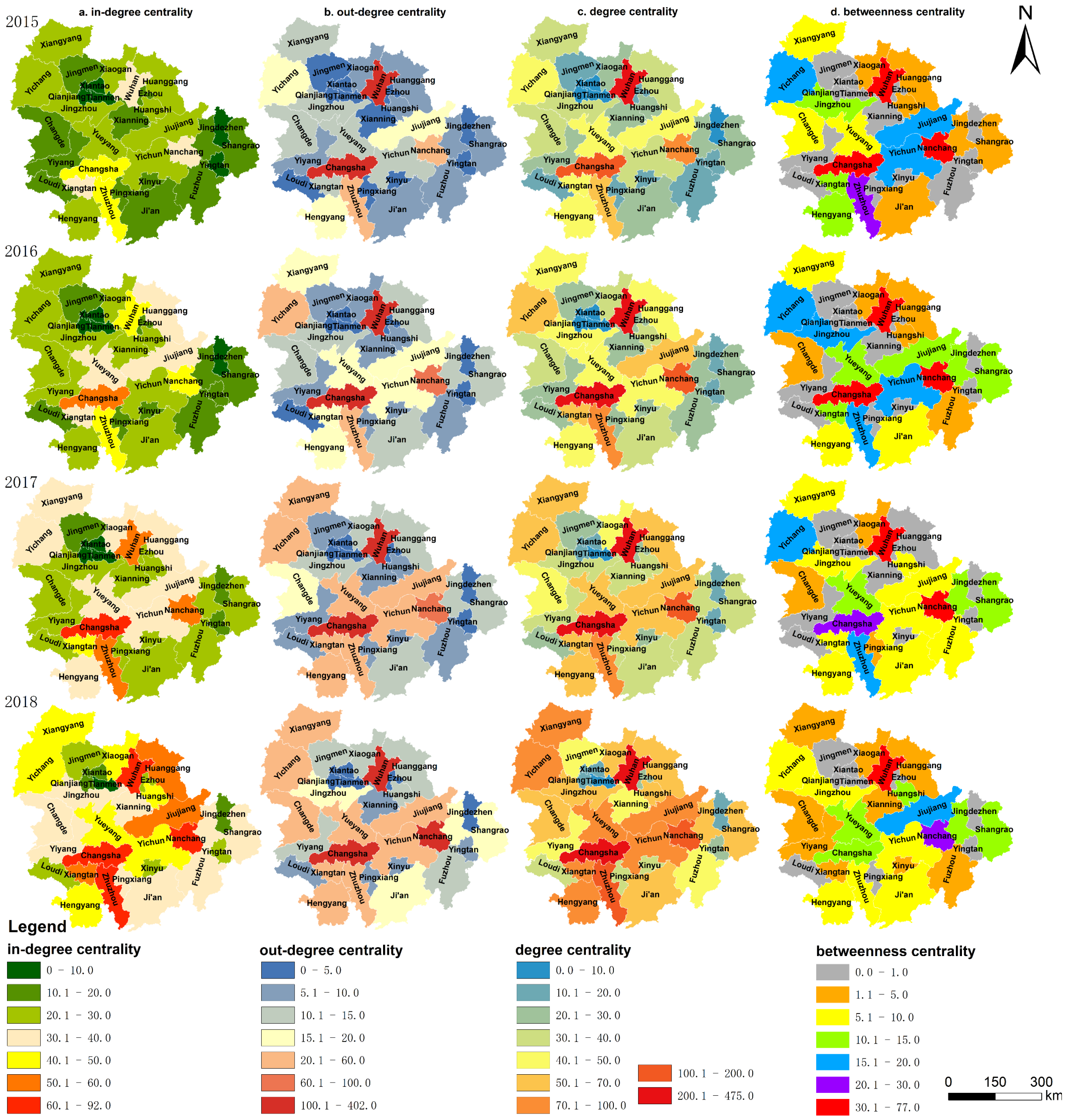

Figure 5. Centrality analysis results of innovation network in UAMRYR: (**a**) in-degree centrality; (**b**) out-degree centrality; (**c**) degree centrality; (**d**) betweenness centrality.

The betweenness centrality of cities is shown in Figure 5d. From 2015 to 2018, the betweenness centrality of the innovation network decreased from 333 to 188, indicating that the degree of resource control of cities in the urban agglomeration is weakening, and the innovation connection is gradually becoming more balanced. Wuhan, Changsha, and Nanchang have high betweenness centrality, which plays an important intermediary role in the connection of other cities. Although the total external innovation of Shangrao and Huangshi is not significant, their intermediary role in the innovation network has increased, which has helped promote the innovation connection of surrounding cities. Tianmen, Xiantao, Qianjiang, Ezhou, and Jingdezhen are on the edge of the innovation grid.

3.4. Analysis of Cohesive-Subgroups in the Urban Agglomeration in the Middle Reaches of the Yangtze River

The emergence of clustering subgroups is an important manifestation of the maturity of urban agglomeration innovation systems. An accurate analysis of subgroups is helpful to understand the overall structure and organization of urban networks. The clustering subgroup division results of the innovation network of the UAMRYR are shown in Figure 6. From 2015 to 2018, the innovation connection network of the UAMRYR can be divided into four sub-cluster systems at the secondary level, and the innovation sub-community structure is relatively stable as a whole. Yichun and Pingxiang are divided into subgroups dominated by cities under the jurisdiction of Hunan Province. Changsha has a strong innovation radiation ability, but the overall innovation radiation ability in Jiangxi Province is weak, and the innovation attraction among cities in Jiangxi Province is weak. On the basis of the division at the second level, the subgroups are further divided at a third level, yielding seven total subgroups from 2015 to 2018.

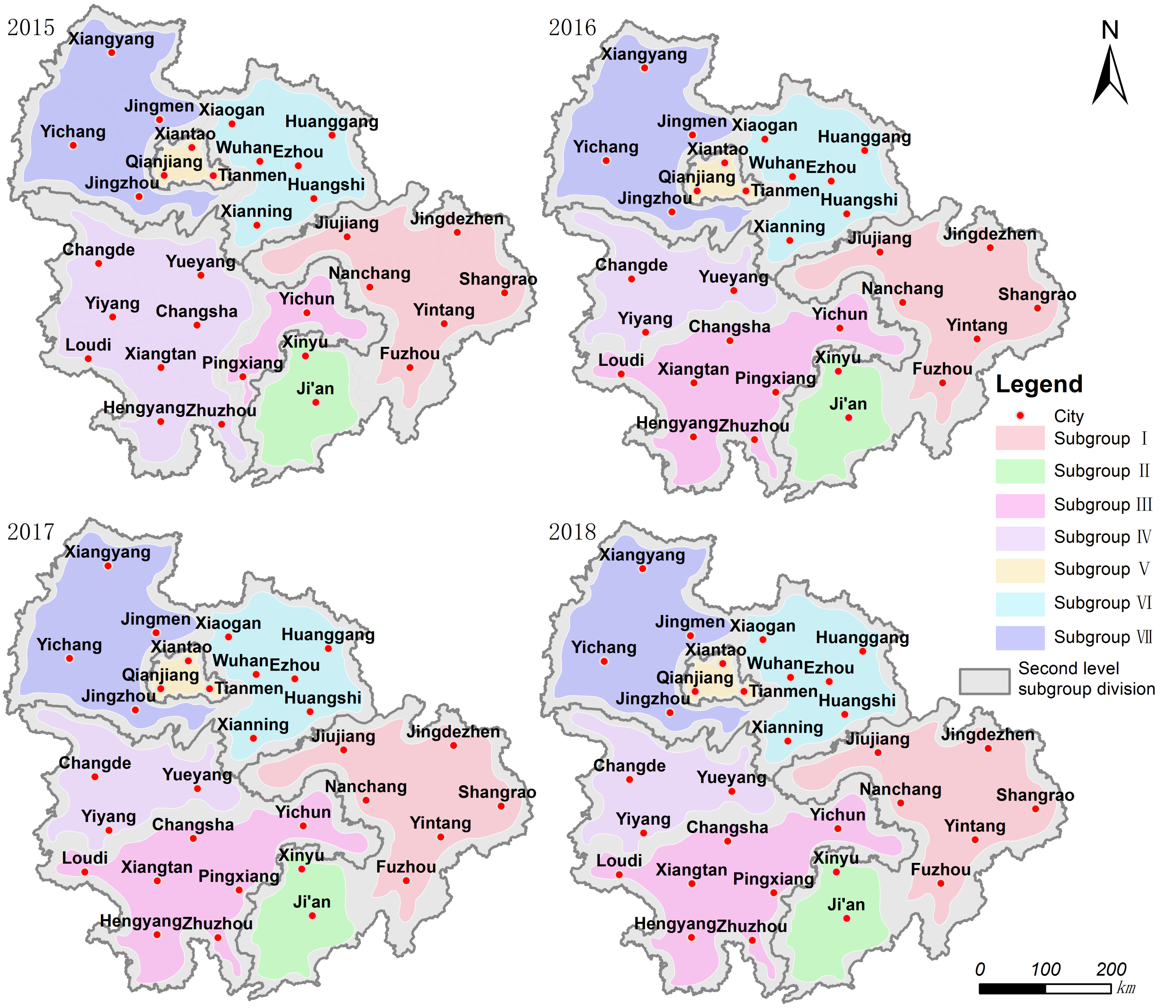

Figure 6. Evolution of cohesive subgroups in the innovation network of the UAMRYR.

These seven subgroups' internal and external correlation density is then counted (Figure 7). The network density of subgroup VI was largest from 2015 to 2018. However, the subgroup with the second largest network density has changed from subgroup IV to subgroup III. This is because the position of the subgroup of the small group with Changsha as its core has changed. The inflow and outflow directions of each subgroup in 2015 show that the largest inflow direction of most subgroups is subgroup VI, with Wuhan as its core. The maximum inflow direction of subgroup III and subgroup VI comes from subgroup IV, which means that subgroup VI has become an innovation radiation center subgroup.

Subgroup IV has become a sub-central subgroup of innovation radiation in the UAMRYR. Meanwhile, the maximum outflow direction of subgroup I and subgroup III are subgroup II, the maximum outflow direction of subgroup II and subgroup IV are subgroup III, and the maximum outflow direction of subgroup V and subgroup VII are subgroup VI. This suggests that there are multiple innovation aggregation center subgroups in UAMRYR. The connection density between subgroups also changed from 2016 to 2018, along with the change of cities included in subgroup III and subgroup IV. However, the internal density of subgroups and the density between subgroups increased year by year. During this period, the maximum inflow directions of subgroup II, subgroup IV, subgroup VI, and subgroup III came from subgroup III. The maximum inflow directions of subgroup I, subgroup III, subgroup V, and subgroup VII came from subgroup VI. This shows that the innovation radiation ability of subgroup III with Changsha as its core is enhanced, and the innovation radiation pattern in the middle reaches of the UAMRYR has changed from a single center to a double center. The members of the subgroup of innovation aggregation center have changed from subgroup II, subgroup III, and subgroup VII to subgroup III, subgroup IV, and subgroup VII. The overall innovation aggregation pattern in the UAMRYR still maintains a multi-core state.

2015	I	II	III	IV	V	VI	VII
I	0.743	0.563	0.506	0.494	0.082	0.527	0.37
II	0.263	0.376	0.396	0.239	0.04	0.171	0.14
III	0.27	0.484	0.587	0.401	0.046	0.191	0.162
IV	0.631	0.625	1.038	1.936	0.153	0.798	0.762
V	0.009	0.007	0.008	0.013	0.039	0.019	0.02
VI	1.179	0.709	0.737	1.372	0.344	2.135	1.426
VII	0.296	0.227	0.251	0.479	0.175	0.506	0.863

2016	I	II	III	IV	V	VI	VII
I	0.971	0.74	0.71	0.468	0.109	0.682	0.466
II	0.343	0.516	0.417	0.217	0.051	0.227	0.182
III	0.817	0.897	2.364	1.506	0.177	0.923	0.824
IV	0.272	0.272	0.62	0.682	0.122	0.377	0.49
V	0.012	0.01	0.016	0.021	0.043	0.027	0.029
VI	1.425	0.873	1.54	1.288	0.441	2.758	1.686
VII	0.354	0.28	0.468	0.615	0.221	0.606	1.01

2017	I	II	III	IV	V	VI	VII
I	1.23	0.898	0.902	0.566	0.15	0.826	0.558
II	0.405	0.584	0.479	0.244	0.063	0.247	0.192
III	1.104	1.103	3.009	1.942	0.267	1.214	1.028
IV	0.321	0.313	0.736	0.815	0.173	0.436	0.582
V	0.017	0.015	0.022	0.03	0.079	0.04	0.041
VI	1.689	0.98	1.839	1.502	0.575	3.207	1.886
VII	0.401	0.314	0.529	0.707	0.258	0.671	1.077

2018	I	II	III	IV	V	VI	VII
I	1.747	1.209	1.192	0.737	0.191	1.149	0.771
II	0.575	0.798	0.659	0.329	0.088	0.346	0.266
III	1.428	1.423	3.916	2.495	0.31	1.527	1.33
IV	0.419	0.403	0.958	1.069	0.199	0.571	0.756
V	0.024	0.02	0.028	0.036	0.114	0.051	0.057
VI	2.453	1.389	2.535	2.062	0.803	4.314	2.653
VII	0.568	0.424	0.708	0.949	0.355	0.896	1.524

4.5

0

Figure 7. Correlation density matrix of different subgroups from 2015 to 2018: I, II, III, IV, V, VI, and VII in the figure indicate subgroup numbers. Subgroup locations are displayed in Figure 6.

4. Discussion

4.1. Overview of Findings

The positive impact of innovation networks on the optimal allocation of innovation resources has been previously demonstrated [66,67]. Understanding the evolution characteristics of innovation network structures can help improve urban innovation ability and promote regional collaborative innovation development [68]. Our study established the innovation connection network of the urban agglomeration in the middle reaches of the Yangtze River. It analyzed the structural system of the innovation network combined with a complex network analysis method.

The innovation ability of cities in the UAMRYR strengthened from 2015 to 2018. Wuhan, Changsha, and Nanchang have strong innovation ability and have played a leading role in the innovation and development of the greater urban agglomeration, which is the main driver for robust economic growth [69]. The innovation gap between cities in the urban agglomeration is significant, and the polarization of innovation ability between provincial capital cities and ordinary cities is significant. The provincial capital cities have accumulated innovation ability and experience over a long period. In response to motives of profit, the talents and resources of the surrounding cities are constantly transferred to the provincial capital cities, which further exacerbates the innovation gap between cities [70]. Therefore, to improve the region's overall innovation level, the government must accelerate the innovative development of ordinary cities.

The biggest effect of network innovation lies in integrating innovation resources [71]. A reasonable innovation network structure can significantly improve the quality of regional innovation development [72]. However, the innovation network of the UAMRYR is still developing, and there are differences in innovation links among cities with significant core edge characteristics. In addition to the relatively stable innovation network formed between Wuhan, Changsha, and Nanchang, the links between other cities are weak, and there is still much room for improvement (Figure 8). This indicates the positive relationship between the innovation agglomeration and the position of a city in the urban hierarchy [73]. In order to improve the efficiency of innovation and the integration of the region, the government should establish long-term cooperation mechanisms driven by the core cities to promote the development of peripheral cities, rationally distribute innovative resources, and maintain stable cooperative relations [33]. Wuhan and Changsha have broken inter-provincial barriers in the urban agglomeration. They have gradually established strong ties with other cities in the urban agglomeration, while Nanchang has improved innovative ties with other cities in Jiangxi Province. Breaking down the barriers among provinces facilitates information transfer, and the creation of an external environment conducive to the flow of innovative elements will improve overall regional innovation performance [74,75]. In the future, Nanchang should break administrative barriers, increase the sharing and absorption of innovation resources, strive to keep up with the development process of Wuhan and Changsha, and become a core city of the innovation network.

The status and influence of different cities in the innovation network are different. Although the ranking of innovation resource attractiveness of cities fluctuates, Changsha, Zhuzhou, Wuhan, Zhuzhou, and Xiangtan have always ranked in the top five. This result is closely related to the support of national policies. For example, to promote innovation-driven development, China established the Wuhan East Lake National Independent Innovation Demonstration Zone in 2009 and the Chang Zhu Tan National Independent Innovation Demonstration Zone in 2015 [76]. Wuhan, Changsha, and Nanchang all have strong innovation radiation ability. Similarly, Wuhan, Changsha, and Nanchang also have strong communication connectivity in the information flow network of the UAMRYR [77]. These results verify the ability of information exchange has a tangible influence on urban innovation [78]. Tianmen, Xiantao, Qianjiang, Ezhou, and Jingdezhen have always been located at the edge of the innovation network. The lack of innovative resources and traffic [79] restrictions may be the reason for this observation. The innovation aggregation pattern within the urban agglomeration has maintained a multi-core state, but the innovation radiation pattern has changed from a single-center to a double-center. This development model can be more conducive to regionally coordinated development and is also reflected in the economic development network of the Yangtze River Delta [80].

The connection of important nodes, sub-core nodes, and core nodes leads to the spatial formation of multiple innovation axes (Figure 8). The location and direction of the axis are consistent with the development axis and plan of the urban agglomeration in the middle reaches of the Yangtze River. A previous study also found that improving transport efficiency can bring a more significant positive spillover effect to the surrounding areas of innovation [81]. Therefore, there is a clear link between innovation and transportation. The Beijing-Guangzhou development axis, the Beijing-Kowloon development axis, and the Erlianhot-Guangzhou development axis in the north-south direction have been extensively developed, but the east-west direction has not been fully formed. Further strengthening the innovation and development of cities on these two axes should be an important future focus of the urban agglomeration in the middle reaches of the Yangtze River.

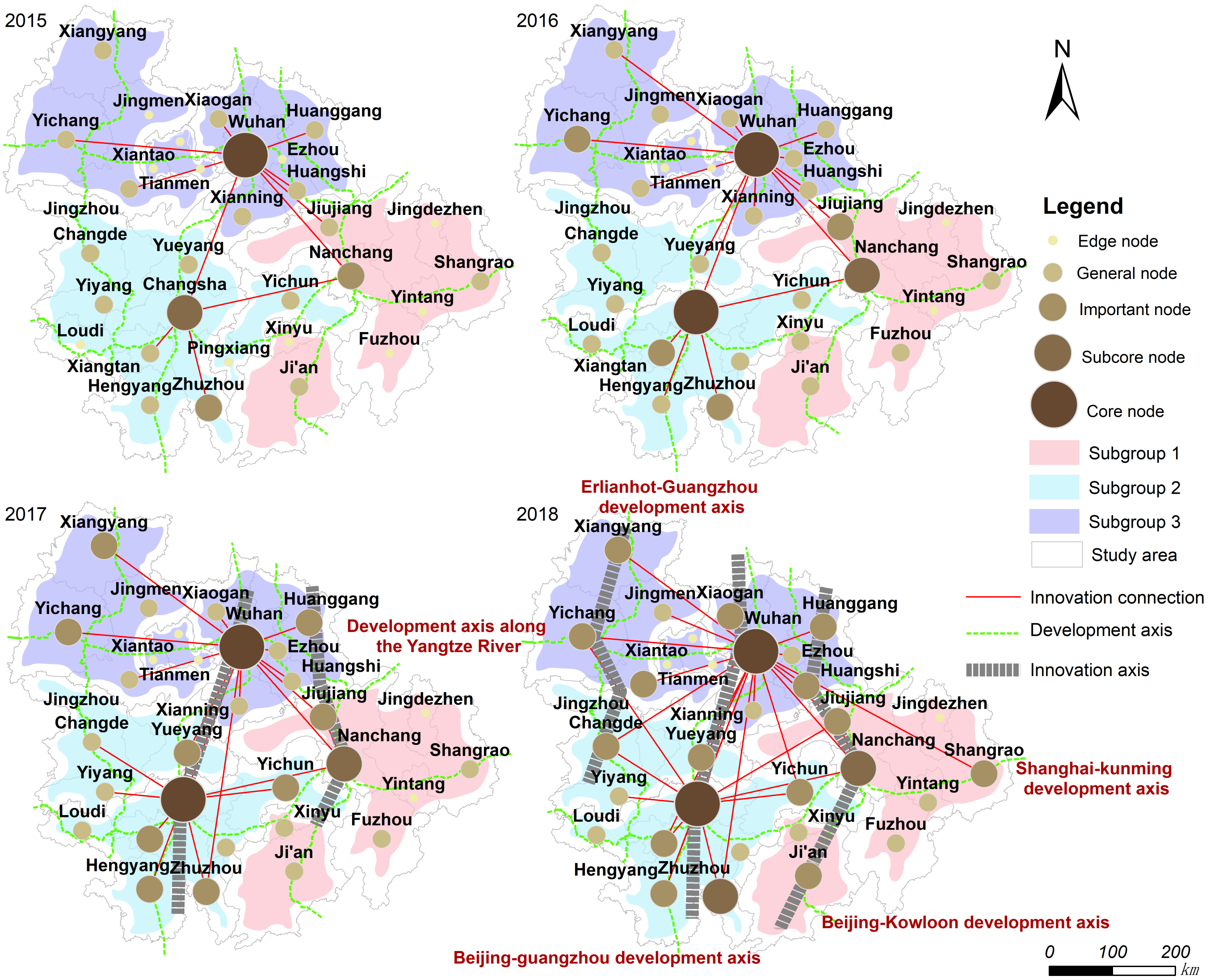

Figure 8. Evolution of innovation patterns in the UAMRYR from 2015 to 2018 is based on the centrality of cities, the intensity of innovation links between cities, and the division results of cohesive subgroups. The status of cities in the innovation network is divided according to the centrality of cities.

The formation of growth triangles links three areas with different factor endowments and different comparative advantages to form a larger region with greater potential for economic growth [82]. This theory is also a useful model in the innovative development of the UAMRYR. The growth triangle integration mode is clear in our chosen study period. The innovation connection axis among Wuhan, Changsha, and Nanchang constituted a stable "triangle" in 2015 (Figure 8). Since 2015, the "growth triangle" integration model has received more response in the urban agglomeration, and the outward expansion area centered in the middle of the urban agglomeration began to develop. By 2018, there were 10 "triangles" in the central, southwest, and western regions of the urban agglomeration in the middle reaches of the Yangtze River. The existence of this development model urges the core node cities to drive the important node cities and form a high-level industrial structure [83,84]. Therefore, this development model efficiently promotes the overall innovative development of the urban agglomeration in the middle reaches of the Yangtze River.

4.2. Policy Implications

The innovative development of cities and the cultivation of new innovative growth poles should be a primary future policy focus. Improving the innovation ability of individual cities is the key to the innovative development of urban agglomerations. The development process of the innovation network in the UAMRYR shows a clear "Matthew Effect." In order to narrow the innovation gap, cities with weak innovation capability should improve their innovation ability. This can be accomplished by improving regional economics, optimizing industrial structure, and strengthening cultural construction [33]. In addition, the government should formulate regional innovation policies, increase innovation investment, and strengthen the optimal allocation of innovation resources. Wuhan, Changsha, and Nanchang should create more spillover effects and radiation effects, advantageous for the spatial integration and coordinated development of innovation in the UAMRYR. However, Nanchang's innovation ability and radiation ability are weaker than Wuhan and Changsha's. Therefore, more innovative resources should be directed to Nanchang, which should also strengthen all construction aspects to promote its innovation development and adjust its innovation structure.

A secondary policy focus should be on expanding the innovation axis and optimizing the innovation network structure of the urban agglomeration. The urban agglomeration's innovation network in the Yangtze River's middle reaches is fragile, and the connection between cities is limited by provincial administrative divisions. The area should break the limits of administrative barriers, improve the layout of transportation facilities and strengthen inter-city "industry-university-research" cooperation, thereby promoting the stability of the spatial network structure of innovation and attaining holistic innovation development of the urban agglomeration. In particular, Wuhan, Changsha, and Nanchang, as the core node of the innovation network, should prevent and overcome regional protectionism, increase the open sharing of information resources of scientific research institutions in colleges, hasten the flow of innovation technologies, leading to the common development of surrounding cities. Moreover, to promote the coordinated development of regional innovation, the government should further strengthen the construction of the innovation axis along the Yangtze River and the axis of Shanghai-Kunming in the east-west direction.

4.3. Limitations and Future Research Directions

An improved evaluation index system of regional innovation ability could be developed in the future to further expand the concepts presented here. Urban innovation connection is a complex connection between the collection of materials and information flow. Here, we were limited by the difficulty of collecting dynamic relationship data. Thus, future research should consider more factors which include co-authored papers [13], tourism [85], social media [86], and other factors. To get more reasonable weights of indicators, we will combine the subjective weighting method and the objective weighting method to calculate the weights of indicators in future research. A longer study period may also give more insights, as we here only employed a four-year period, which may not fully reflect the temporal and spatial evolution characteristics of the innovation network of the UAMRYR. The resilience of the innovation network structure was also not assessed in the present work. A detailed analysis of the resilience of urban network structure could likely lead to an improved understanding of the resilience of cities to different impact factors [87]; this is another promising direction for future research.

5. Conclusions

This paper proposed a research framework for measuring the spatial pattern and revealing structural characteristics of the innovation network. We created a multi-criteria indicator system for the UAMRYR innovation network based on innovation connectivity.

We indirectly measured the basic spatial pattern of innovation connections between cities using an improved gravity model. We also employed methods of social networks to reveal structural characteristics and spatial patterns of the innovation network in the UAMRYR. Our main conclusions are as follows:

First, the innovation ability of cities in UAMRYR increased from 2015 to 2018, and the innovation gap between cities gradually decreased. The deficiency and imbalance in the allocation of innovation resources are one of the reasons for the large gap in innovation development between cities. At present, UAMRYR is in the state of core city-driven development; the innovation resources of core cities are better than marginal cities, which leads to a large innovation gap between cities. However, the gap will gradually decrease with the development of urban agglomeration and the rational allocation of innovation resources.

Second, the structure of the innovation network in the UAMRYR is significantly hierarchical and increasingly complex. The complexity of the network structure shows that the connection between cities has been strengthened, and the region is in the integrated development stage of coordinated innovation. Wuhan, Changsha, and Nanchang comprise the absolute core of the network and have a strong influence on the innovation development of the surrounding cities. The stable "triangle," composed of Wuhan, Changsha, and Nanchang, is important for supporting the innovative network of the UAMRYR. However, the innovation connection between most cities on the edge of the UAMRYR is weak. A strengthening of the innovative connection between cities has enabled many small "triangles" to expand outward from Wuhan, Changsha, and Nanchang. The growth triangle integration mode is thus an adequate representation of the period from 2015 to 2018.

Third, the status and influence of cities in the innovation network are different. The ability of cities to attract innovative resources and radiate innovation has continuously increased from 2015 to 2018. The innovation inflow of most cities is greater than the outflow, which suggests that these cities are strongly attracting innovation resources and promoting individual innovation development. Wuhan and Changsha are core nodes in the innovation network, and Nanchang is a sub-core node, with most cities being important nodes. There are multiple spatial innovation axes composed of important nodes, sub-core nodes, and core nodes. In addition, the location and direction of the axis are consistent with the development axis and plan of the urban agglomeration in the middle reaches of the Yangtze River. The innovation links between regional cities are more direct and close. In addition to the important intermediary roles of Wuhan, Changsha, and Nanchang in urban innovation linkages, the intermediary roles of Shangrao and Huangshi also increased from 2015 to 2018. The innovation aggregation pattern maintains a multi-core state in the UAMRYR, but the innovation radiation pattern has changed from a single-center to a double-center.

Finally, our study suggests policy guidelines to cultivate innovation growth poles and expand innovation axes by the structural characteristics and development status of the innovation network of UAMRYR. This study applied the proposed research framework to a case study, UAMRYR, to explore the spatial patterns of innovation networks from 2015 to 2018. As the main form of new urbanization development, the urban agglomeration has become an important growth point for future regional spatial development [88]. The formation of an innovation network helps the flow of innovation resources and promotes the complementarity of innovation advantages in urban agglomerations. In summary, the framework is highly feasible, and the case study can be used as a reference for other urban agglomerations.

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References

1. Miao, C.; Fang, D.; Sun, L.; Luo, Q. Natural resources utilization efficiency under the influence of green technological innovation. *Resour. Conserv. Recycl.* **2017**, *126*, 153–161. [CrossRef]
2. Angelidou, M.; Psaltoglou, A. An empirical investigation of social innovation initiatives for sustainable urban development. *Sustain. Cities Soc.* **2017**, *33*, 113–125. [CrossRef]
3. Duan, D.; Du, D.; Liu, C.; Grimes, S. Spatio-temporal evolution of urban innovation structure based on zip code geodatabase: An empirical study from Shanghai and Beijing. *J. Geogr. Sci.* **2016**, *26*, 1707–1724. [CrossRef]
4. Xiao, W.; Pan, J.-D.; Liu, L.-Y. China's industrial structure upgrade in the "New Normal": Empirical test and determinants. *Singap. Econ. Rev.* **2018**, *63*, 1037–1058. [CrossRef]
5. Anselin, L. *Spatial Econometrics: Methods and Models*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 1988; Volume 4.
6. Maggioni, M.A.; Nosvelli, M.; Uberti, T.E. Space versus networks in the geography of innovation: A European analysis. *Pap. Reg. Sci.* **2007**, *86*, 471–493. [CrossRef]
7. Freeman, C.J.R.p. Networks of innovators: A synthesis of research issues. *Res. Policy* **1991**, *20*, 499–514. [CrossRef]
8. Huggins, R.; Prokop, D. Network structure and regional innovation: A study of university–industry ties. *Urban Stud.* **2017**, *54*, 931–952. [CrossRef]
9. Leoncini, R.; Maggioni, M.A.; Montresor, S. Intersectoral innovation flows and national technological systems: Network analysis for comparing Italy and Germany. *Res. Policy* **1996**, *25*, 415–430. [CrossRef]
10. Hu, S.S.; Kim, H.-H. Spatial structure and dynamic evolution of urban cooperative innovation network in Guangdong-Hong Kong-Macao greater bay area, China: An analysis based on cooperative invention patents. *J. Asian Financ. Econ. Bus.* **2021**, *8*, 113–119.
11. Pan, X.; Pan, X.; Ai, B.; Guo, S. Structural heterogeneity and proximity mechanism of China's inter-regional innovation cooperation network. *Technol. Anal. Strateg. Manag.* **2020**, *32*, 1066–1081. [CrossRef]
12. Capone, F.; Lazzeretti, L.; Innocenti, N. Innovation and diversity: The role of knowledge networks in the inventive capacity of cities. *Small Bus. Econ.* **2021**, *56*, 773–788. [CrossRef]
13. Li, D.; Wei, Y.D.; Wang, T. Spatial and temporal evolution of urban innovation network in China. *Habitat Int.* **2015**, *49*, 484–496. [CrossRef]
14. Lyu, L.; Wu, W.; Hu, H.; Huang, R. An evolving regional innovation network: Collaboration among industry, university, and research institution in China's first technology hub. *J. Technol. Transf.* **2019**, *44*, 659–680. [CrossRef]
15. Kong, X.-d.; Zhang, D. The Influence of knowledge cooperation on enterprise innovation performance in innovation network—The moderating effect of network characteristics. In Proceedings of the 2018 International Conference on Management Science and Engineering (ICMSE), Frankfurt, Germany, 17–20 August 2018; pp. 31–39.
16. Han, M.; Sun, B.; Su, X. Can a region's network location characteristics affect its innovation capability? Empirical evidence from China. *Chin. Manag. Stud.* **2020**, *15*, 328–349. [CrossRef]
17. Pan, X.; Chu, J.; Pan, X.; Wang, M. A comparative analysis of changes in urban innovation spatial correlation effect in China and its driving factors. *Asian J. Technol. Innov.* **2021**, *29*, 1–15. [CrossRef]
18. Kunze, K. Empirical analysis of innovation and trade in Europe: A gravity model approach. *Int. J. Trade Glob. Mark.* **2016**, *9*, 197–211. [CrossRef]
19. Zhu, W.; Yue, Z.; He, N.; Luan, K.; Ye, L.; Qian, C. Analysis of China's Urban Innovation Connection Network Evolution: A Case Study of Henan Province. *Sustainability* **2022**, *14*, 1089. [CrossRef]
20. Sun, X. Research on the innovation radiation of Shanghai science and technology innovation center to the Yangtze River delta. *J. Phys. Conf. Ser.* **2021**, *1802*, 042046. [CrossRef]
21. Ewing, G. Gravity and linear regression models of spatial interaction: A cautionary note. *Econ. Geogr.* **1974**, *50*, 83–88. [CrossRef]
22. Picci, L. The internationalization of inventive activity: A gravity model using patent data. *Res. Policy* **2010**, *39*, 1070–1081. [CrossRef]
23. Wang, F.; Wei, X.; Liu, J.; He, L.; Gao, M. Impact of high-speed rail on population mobility and urbanisation: A case study on Yangtze River Delta urban agglomeration, China. *Transp. Res. Part A Policy Pract.* **2019**, *127*, 99–114. [CrossRef]

24. Zhang, R.; Tai, H.; Cheng, K.-T.; Cao, Z.; Dong, H.; Hou, J. Analysis on evolution characteristics and dynamic mechanism of urban green innovation network: A case study of Yangtze River economic belt. *Sustainability* **2022**, *14*, 297. [CrossRef]
25. Krätke, S. Regional knowledge networks: A network analysis approach to the interlinking of knowledge resources. *Eur. Urban Reg. Stud.* **2010**, *17*, 83–97. [CrossRef]
26. Fu, N.J.C. Innovation Efficiency and the Spatial Correlation Network Characteristics of Intelligent-Manufacturing Enterprises. *Complexity* **2021**, *2021*, 4299045. [CrossRef]
27. Tseng, C.-Y.; Lin, S.-C.; Pai, D.-C.; Tung, C.-W. The relationship between innovation network and innovation capability: A social network perspective. *Technol. Anal. Strateg. Manag.* **2016**, *28*, 1029–1040. [CrossRef]
28. Li, M.; Zhang, M.; Agyeman, F.O.; Ud Din Khan, H.S. Research on the influence of industry-university-research cooperation innovation network characteristics on subject innovation performance. *Math. Probl. Eng.* **2021**, *2021*, 477113. [CrossRef]
29. Peng, F.; Zhang, Q.; Han, Z.; Ding, Y.; Fu, N. Evolution characteristics of government-industry-university cooperative innovation network of electronic information industry in Liaoning Province, China. *Chin. Geogr. Sci.* **2019**, *29*, 528–540. [CrossRef]
30. Kong, X.; Xu, Q.; Zhu, T.J.S. Dynamic evolution of knowledge sharing behavior among enterprises in the cluster innovation network based on evolutionary game theory. *Sustainability* **2020**, *12*, 75. [CrossRef]
31. Can, Z.; Gang, Z.; Xianzhong, C. Chinese inter-city innovation networks structure and city innovation capability. *Geogr. Res.* **2017**, *36*, 1297–1308.
32. Zhou, F.; Zhang, B. Detecting and Visualizing the Communities of Innovation in Beijing-Tianjin-Hebei Urban Agglomeration Based on the Patent Cooperation Network. *Complexity* **2021**, *2021*, 5354170. [CrossRef]
33. Li, Y.; Luo, W. Influencing Factors of Knowledge Cooperation in Urban Agglomeration on Yangtze River Delta from the Perspective of Innovation Network. *J. Phys. Conf. Ser.* **2020**, *1852*, 042041. [CrossRef]
34. Peipei, X.; Ladi, W. Research on the Structural Evolution and Driving Mechanism of Regional Collaborative Innovation Network: Evidence from the Beijing-Tianjin-Hebei Urban Agglomeration. In Proceedings of the 6th International Conference on Humanities and Social Science Research (ICHSSR 2020), Hangzhou, China, 10–12 April 2020; pp. 502–506.
35. Liu, C.; Niu, C.; Han, J.J.S. Spatial dynamics of intercity technology transfer networks in China's three urban agglomerations: A patent transaction perspective. *Sustainability* **2019**, *11*, 1647. [CrossRef]
36. Qin, Z.; Peng, Z.; Zhang, J. *Development Report on Changjiang Middle Reaches Megalopoli (2018)*; Social Science Academic Press: Beijing, China, 2018; pp. 120–141.
37. Zhang, J. Research on Promoting Innovative Cooperation of Urban Agglomeration in the Middle Reaches of the Yangtze River. Available online: https://zys.hubei.gov.cn/bmdt/yjcg/zlcg/201910/t20191025_11219.shtml (accessed on 1 April 2022).
38. Wang, H.; Yang, G.; Qin, J. City Centrality, Migrants and Green Inovation Efficiency: Evidence from 106 Cities in the Yangtze River Economic Belt of China. *Int. J. Environ. Res. Public Health* **2020**, *17*, 652. [CrossRef]
39. Lu, L.; Huang, R. Urban hierarchy of innovation capability and inter-city linkages of knowledge in post-reform China. *Chin. Geogr. Sci.* **2012**, *22*, 602–616. [CrossRef]
40. Lo, M.F.; Tian, F. Enhancing competitive advantage in Hong Kong higher education: Linking knowledge sharing, absorptive capacity and innovation capability. *High. Educ. Q.* **2020**, *74*, 426–441. [CrossRef]
41. Xue-dong, L.; Jin-guang, Z.; Zhi, X. Evaluation of regional technology innovation capability based on R clustering and entropy methods. In Proceedings of the 2013 International Conference on Management Science and Engineering 20th Annual Conference Proceedings, Harbin, China, 17–19 July 2013; pp. 1937–1943.
42. Shan, D. Research of the construction of regional innovation capability evaluation system: Based on indicator analysis of hangzhou and ningbo. *Procedia Eng.* **2017**, *174*, 1244–1251. [CrossRef]
43. Fu, Y.; Supriyadi, A.; Wang, T.; Wang, L.; Cirella, G.T. Effects of regional innovation capability on the green technology efficiency of China's manufacturing industry: Evidence from listed companies. *Energies* **2020**, *13*, 5467. [CrossRef]
44. He, S.; Du, D.; Jiao, M.; Lin, Y. Spatial-temporal characteristics of urban innovation capability and impact factors analysis in China. *Sci. Geogr. Sin* **2017**, *37*, 1014–1022.
45. Pei, J.; Zhong, K.; Li, J.; Xu, J.; Wang, X. ECNN: Evaluating a cluster-neural network model for city innovation capability. *Neural Comput. Appl.* **2021**, *2021*, 1–13. [CrossRef]
46. Zhang, D.; Gao, Y.; Peng, Z. Independent innovation capability evaluation and analysis on wanjiang city-zone. In Proceedings of the 2011 International Conference on Computer Science and Service System (CSSS), Nanjing, China, 27–29 June 2011; pp. 2286–2289.
47. Sheng, K.; Liu, S. On evaluation system for regional scientific and technical innovation ability and a positive study of 5 cities in south of Jiangsu. *J. Grey Syst.* **2015**, *27*, 92–104.
48. Tianying, J.; Minghao, H. Research on regional innovation spatial linkage of Yangtze River Delta. *Forum Sci. Technol. China* **2014**, *10*, 126–131. [CrossRef]
49. Chen, Y.; Li, W.; Yi, P. Evaluation of city innovation capability using the TOPSIS-based order relation method: The case of Liaoning province, China. *Technol. Soc.* **2020**, *63*, 101330. [CrossRef]
50. Zhaoyang, W. Analysis of actual value of foreign investment and Wuhan Regional Technical Innovation Ability. In Proceedings of the 2011 International Conference on Product Innovation Management (ICPIM 2011), Wuhan, China, 16–17 July 2011; pp. 293–296.
51. Ming, M.; Guo-Hao, Z. The Impact of Transportation Infrastructure on Regional Innovation Capability: A Dynamic Durbin Panel Data Approach. *DEStech Trans. Econ. Bus. Manag.* **2017**. [CrossRef]

52. Niu, X.; Chen, X.-D. Innovation connection between cities and spatial structure of innovation network. *Chin. J. Manag.* **2013**, *10*, 575–582.
53. Zhang, B.; Qi, R. Transportation infrastructure, innovation capability, and urban economic development. *Transform. Bus. Econ.* **2021**, *20*, 526–545.
54. Garcia-Ochoa Mayor, M.; Blázquez de la Hera, M.L.; de Diego Ruiz, E. Empirical study of national technological innovation capability in Africa. *South Afr. J. Econ. Manag. Sci.* **2012**, *15*, 440–463. [CrossRef]
55. Penglin, L.; Dong, J.; Chen, C. Research on the evaluation of urban science and technology innovation ability in Shaanxi province based on bp neural network. In Proceedings of the 2017 2nd International Conference on Modern Management, Education Technology, and Social Science (MMETSS 2017), Singapore, 28–30 July 2017; pp. 222–232.
56. Heng, T. Analysis of evaluation about regional capacity of science and technology. In *International Conference on Advances in Education and Management*; Springer: Berlin/Heidelberg, Germany, 2011; pp. 307–315.
57. He, L.; Liu, Y. Based on entropy method regional innovation capability evaluation in gansu province. In *Proceedings of the Ninth International Conference on Management Science and Engineering Management*; Springer: Midtown Manhattan, NY, USA, 2015; pp. 893–901.
58. Zhu, Y.; Tian, D.; Yan, F. Effectiveness of entropy weight method in decision-making. *Math. Probl. Eng.* **2020**, *2020*, 3564835. [CrossRef]
59. Li, L.; Liu, F.; Li, C. Customer satisfaction evaluation method for customized product development using Entropy weight and Analytic Hierarchy Process. *Comput. Ind. Eng.* **2014**, *77*, 80–87. [CrossRef]
60. Ma, J.; Fan, Z.P.; Huang, L.H. A subjective and objective integrated approach to determine attribute weights. *Eur. J. Oper. Res.* **1999**, *112*, 397–404. [CrossRef]
61. Zipf, G.K. *Human Behavior and the Principle of Least Effort: An Introduction to Human Ecology*; Ravenio Books, 2016.
62. Knoke, D.; Yang, S. *Social Network Analysis*; SAGE Publications: Thousand Oaks, CA, USA, 2019.
63. Jialing, Z.; Weidong, L. Trade network of China and countries along 'Belt and Road Initiative'areas from 2001 to 2013. *Sci. Geogr. Sin.* **2016**, *36*, 1629–1636.
64. Duan, X.; Meng, Q.; Fei, X.; Lin, M.; Xiao, R. The impacts of farmland loss on regional food self-sufficiency in Yangtze river delta urban agglomeration over last two decades. *Remote Sens.* **2021**, *13*, 3514. [CrossRef]
65. Sun, F.; Wang, D.; Yu, N. Competition patterns of high-speed rail versus highways and aviation. *Geogr. Res.* **2017**, *36*, 171–187.
66. Yuan, Y.; Han, Z.; Yang, W. A co-innovation network in Northeast China oriented to high-quality development. *Technol. Anal. Strateg. Manag.* **2021**, 1–18. [CrossRef]
67. 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.
68. Li, Y.; Ye, M. Evolution and development strategy of collaborative innovation network among cities in the Yangtze River delta-based on urban innovation index data. *Afr. Asian Stud.* **2021**, *20*, 291–323. [CrossRef]
69. Law, S.H.; Sarmidi, T.; Goh, L.T. Impact of innovation on economic growth: Evidence from Malaysia. *Malays. Econ. Assoc.* **2020**, *57*, 113–132. [CrossRef]
70. Wang, X.; Wan, T.; Yang, Q.; Zhang, M.; Sun, Y. Research on innovation non-equilibrium of Chinese urban agglomeration based on SOM neural network. *Sustainability* **2021**, *13*, 9506. [CrossRef]
71. Doz, Y.L. Technology partnerships between larger and smaller firms: Some critical issues. *Int. Stud. Manag. Organ.* **1987**, *17*, 31–57. [CrossRef]
72. Braczyk, H.-J.; Heidenreich, M. Regional governance structures in a globalized world. *Reg. Innov. Syst.* **1998**, *414*, 440.
73. Fan, F.; Dai, S.; Zhang, K.; Ke, H. Innovation agglomeration and urban hierarchy: Evidence from Chinese cities. *Appl. Econ.* **2021**, *53*, 6300–6318. [CrossRef]
74. Wang, X.; Fang, H.; Zhang, F.; Fang, S. The spatial analysis of regional innovation performance and industry-university-research institution collaborative innovation—An empirical study of Chinese provincial data. *Sustainability* **2018**, *10*, 1243. [CrossRef]
75. Zhang, L. The knowledge spillover effects of FDI on the productivity and efficiency of research activities in China. *China Econ. Rev.* **2017**, *42*, 1–14. [CrossRef]
76. Shuai, Z.; Kefan, X. Radiation effect of independent innovation demonstration area: A case study of east lake demonstration area. In Proceedings of the 13th International Conference on Innovation & Management, Wuhan, China, 28–30 November 2016; pp. 242–246.
77. Zheng, W.; Du, N.; Zhang, Q.; Wang, X. Using Geodetector to explore the factors affecting evolution of the spatial structure of information flow in the middle reaches of the Yangtze River urban agglomeration. *GeoJournal* **2021**, 1–19. [CrossRef]
78. Zhou, R.; Zhang, Y.; Gao, X. The spatial interaction effect of environmental regulation on urban innovation capacity: Empirical evidence from China. *Int. J. Environ. Res. Public Health* **2021**, *18*, 4470. [CrossRef]
79. Wang, J.; Cai, S. The construction of high-speed railway and urban innovation capacity: Based on the perspective of knowledge Spillover. *China Econ. Rev.* **2020**, *63*, 101539. [CrossRef]
80. Zhang, Y.; Wang, T.; Supriyadi, A.; Zhang, K.; Tang, Z. Evolution and Optimization of Urban Network Spatial Structure: A Case Study of Financial Enterprise Network in Yangtze River Delta, China. *ISPRS Int. J. Geo-Inf.* **2020**, *9*, 611. [CrossRef]
81. Zou, S.; Li, M.; Chen, J.; Chen, Y. Does the construction of an integrated transport network promote urban innovation? A perspective based on the theory of flow space. *PLoS ONE* **2021**, *16*, e0259974. [CrossRef]

82. Wang, S.; Gao, Q.; Wang, D. A New Urban Integration Pattern—Adjacent Urban Integration. *Sci. Geogr. Sinica.* **2001**, *06*, 558–563.
83. Liu, T.; Li, Y. Green development of China's Pan-Pearl river delta mega-urban agglomeration. *Sci. Rep.* **2021**, *11*, 15717. [CrossRef]
84. Fang, C. The basic law of the formation and expansion in urban agglomerations. *J. Geogr. Sci.* **2019**, *29*, 1699–1712. [CrossRef]
85. Xiao, X.; Fang, C.; Lin, H. Characterizing Tourism Destination Image Using Photos' Visual Content. *ISPRS Int. J. Geo-Inf.* **2020**, *9*, 730. [CrossRef]
86. Xiao, X.; Fang, C.; Lin, H.; Liu, L.; Tian, Y.; He, Q. Exploring spatiotemporal changes in the multi-granularity emotions of people in the city: A case study of Nanchang, China. *Comput. Urban Sci.* **2022**, *2*, 1. [CrossRef]
87. Jabareen, Y. Planning the resilient city: Concepts and strategies for coping with climate change and environmental risk. *Cities* **2013**, *31*, 220–229. [CrossRef]
88. Fang, C.; Song, J.; Zhang, Q.e.a.; Li, M. The formation, development and spatial heterogeneity patterns for the structures system of urban agglomerations in China. *Acta Geogr. Sin.-Chin. Ed.* **2005**, *60*, 827.