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The Scientific Cooperation Network of Chinese Scientists and Its Proximity Mechanism

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Abstract: The collaboration of scientists is important for promoting the scientific development and technological progress of a country, and even of the world. Based on the cooperation data of academicians of the Chinese Academy of Sciences (CAS) in the China National Knowledge Infrastructure (CNKI), we portray the scientific cooperation network of Chinese scientists using Pajek, Gephi, ArcGIS, and other software, and the complexity of the scientific cooperation network of Chinese scientists and its proximity mechanism are explored by combining complex network analysis, spatial statistical analysis, and negative binomial regression models. Our main conclusions are as follows: (1) In terms of network structure, the scientific cooperation network of Chinese scientists has a multi-triangular skeleton, with Beijing as its apex. The network has an obvious hierarchical structure. Beijing and Shanghai are located in the core area, and 16 cities are located in the semi-periphery of the network, while other cities are located at the periphery of the network. (2) In terms of spatial distribution, the regional imbalance of the scientific cooperation of Chinese scientists is obvious. Beijing–Tianjin–Hebei, the Yangtze River Delta, and the central-south region of Liaoning are hot spots for the scientific research activities of Chinese scientists. (3) The negative binomial regression model accurately explains the proximity mechanism of the scientific cooperation network of Chinese scientists. The geographical proximity positively affects the scientific cooperation of Chinese scientists under certain conditions. The educational proximity is the primary consideration for scientists to cooperate in scientific research. The closer the educational level of the cities, the greater the cooperation. Economic and social proximity can promote scientific cooperation among scientists, whereas institutional proximity negatively and significantly affects scientific cooperation.

Keywords: Chinese scientists; academicians of Chinese Academy of Sciences; scientific cooperation; complex network; proximity mechanism

1. Introduction

In the era of the knowledge economy, talent, and especially scientific and technological talent, has become the core element of regional scientific and technological innovation and economic growth [1,2]. The rapid development of science and technology has expanded the breadth and depth of scientific research, and scientific and technological talents have become increasingly specialized. The complexity and refinement of disciplines under the background high-level sciences require scientists in different professional fields to participate in cooperative scientific activities [3–5] to offset their respective deficiencies in knowledge, funding, equipment, and other aspects [6]. Interdisciplinary, inter-agency, and cross-regional scientific cooperation has become a trend in the development of scientific research models [7]. Compared with traditional (independent) scientific research methods, scientific cooperation enables the rapid flow and exchange of knowledge among scientists between different disciplines. The new transformation of this research method produces more scientific output and promotes high-quality, innovative achievements and expands scientific boundaries [4,8,9]. Throughout the 75-year history of the Nobel Prize, two-thirds of the 286 Nobel Prize winners have made scientific achievements through cooperation [10]. Therefore, to explore the evolutionary laws and deep-seated mechanisms of the scientific cooperation of Chinese scientists is important for promoting knowledge innovation and for the scientific progress of China and the world.

Since the establishment of the Chinese Academy of Sciences in 1949, academicians have provided outstanding contributions to the development of modern Chinese science and technology, creating the foundation of Chinese scientific careers. At present, many scientists have played core roles in national scientific and technological tasks, actively working at the international science and technology forefront as the Chinese representatives in their fields. As academicians of the Chinese Academy of Sciences have been shown to be the top innovative talent in China [11,12], their cooperation is bound to profoundly impact the scientific development and technological progress of China and even the world [13,14].

The objective of this study was to use the complex network analysis method to study the scientific cooperation network of Chinese scientists and to analyze its internal mechanisms under the framework of multidimensional proximity. This article attempts to answer the following questions: (1) What is the structure of the scientific cooperation network of Chinese scientists? Which cities are at the core and periphery of the network? (2) Are there regional differences in scientific cooperation among Chinese scientists? Which cities are hot spots of scientific cooperation? (3) Which proximity influences the scientific cooperation of Chinese scientists? What is the role of geographical proximity, social proximity, economic proximity, institutional proximity, and educational proximity? This paper hopefully contributes to the cooperation network of senior talents in contemporary China to help improve the level of Chinese scientific research, promote the output of Chinese scientific research, accelerate the knowledge spillover among regions, and promote collaborative innovation.

This study of the scientific cooperation network of academicians of the Chinese Academy of Sciences can help people to understand the scientific activities of Chinese scientists and provides new insight into their scientific cooperation, which can help researchers to discover the laws of science and improve the efficiency of scientific research and their innovation ability. The findings depict the spatial distribution of Chinese scientific activity centers and provide a practical basis for the country to formulate scientific and technological strategies.

The structure of this paper is as follows: Section 2 provides a literature review. Section 3 describes the data and methods. Sections 4–6 present the analysis results of this study. The final section contains the conclusion and discussion.

2. Literature Review and Hypotheses

With the increasingly frequent circulation of knowledge, research on scientific cooperation continues emerging. From the perspective of scientific achievements, the most intuitive type of scientific cooperation is paper co-authorship [15,16]. Therefore, different types of scientific networks based on the relationship information of co-authored papers have received extensive attention from the academic community. From the perspective of literature knowledge co-occurrence, studies of co-occurrence have mainly focused on authors, institutions, disciplines, and locations. Therefore, scientific cooperation networks are generally studied from the perspectives of author cooperation networks, institution cooperation networks, discipline cooperation networks, and region cooperation networks.

In terms of author cooperation networks, studies have revealed that high-yielding scientists are the most active group in scientific cooperation [17]. From the perspective of individuals, the cooperation network of authors is characterized by clustering, small world, and hierarchy [18–20]. From the perspective of an institution cooperation network, scientific institutions of scientists can be divided into different types: universities, research institutes, governments, academic groups, enterprises, hospitals, etc. Many studies found that scientific research institutes and universities play an important role in the institution cooperation network, among which local and foreign first-class universities play a particularly prominent role in scientific cooperation [6,21,22]. Given discipline cooperation networks, interdisciplinary scientific cooperation can achieve breakthrough achievements. Studies have found that basic disciplines play a dominant role in the process of discipline cooperation [23,24].

Geographers have studied scientific cooperation networks from different spatial scales; discussed the situations of scientific cooperation among cities, regions, and countries; and revealed the topological structure, hierarchical structure, and spatial clustering characteristics of the paper cooperation network [25,26]. Ma et al. found that the hierarchical structure of the Chinese urban scientific cooperation network is prominent. Beijing is the core of the whole network, and most provincial cities are distributed through the second and third levels of the network. The network conforms to the scale-free rule and has obvious regional clustering characteristics. Differences exist in the connectivity among the western, eastern, and central regions in China [27]. In terms of transnational scientific exchange and cooperation, the international scientific cooperation network has always been dominated by a core group [28,29] with a clear core–peripheral structure [30]. Zitt reported that France, Germany, Japan, the United Kingdom, and the United States were the the top five countries of scientific cooperation from 1986 to 1996 [31]. Gui et al. studied the structure, dynamics, and determinants of the international scientific cooperation network from 2000 to 2015, and found that the United States, the United Kingdom, Germany, France, and Canada, and other traditional scientific powers, still occupied a central position in the network [32].

Since the concept of multidimensional proximity was proposed by the French School of Proximity Dynamics [33], proximity mechanisms have gradually been used to explore the mechanisms driving the scientific cooperation network. Studies have found that geographic proximity, cognitive proximity, organizational proximity, social proximity, and institutional proximity impact the exchange, sharing, and learning of explicit and implicit knowledge between subjects [34–37]. The influence of geographic proximity on scientific cooperation has been the focus of scholars. Hoekman used a gravity model to demonstrate that geographic and institutional proximity had significant positive effects on European regional scientific cooperation [38]. Wang et al. found that the interaction between geographic and institutional proximity jointly promotes the evolution of the spatial structure of biotechnology knowledge network [39]. With the development of modern technology, some scholars found that the influence of geographical distance on scientific cooperation has gradually weakened, while the social and institutional proximity have continually strengthened [40,41]. Others showed that the role of geographical distance between research subjects in scientific cooperation networks has not weakened but has instead strengthened [42,43]. In conclusion, the relative importance of proximity of different dimensions in the process of scientific cooperation changes depending on the type of knowledge produced [44,45]. It is worth emphasizing that there is a large gap in the resources of higher education between Chinese cities, which is an important factor affecting the scientific cooperation of Chinese scientists. Other studies have also found that the factors of scientific cooperation also include the number of scientific researchers, economic scale, innovation capacity, common language, and network status [46–49].

With the continuous development of science and technology, the number of scientific achievements have increased, where top scientists serve as the leaders of scientific activities. By reviewing the literature, we found that the research into the scientific cooperation of Chinese scientists has mainly been concentrated in the fields of management science and library and information science, whereas few studies have systematically explored the complexity of the scientific cooperation network of Chinese scientists from the perspective of geography. In view of this, we built a scientific cooperation database of Chinese scientists based on the scientific papers published by academicians of the Chinese Academy of Sciences in the China National Knowledge Infrastructure. The complex network analysis method was adopted to portray the scientific cooperation network of Chinese scientists and to analyze the internal mechanism under the framework of multidimensional proximity.

We applied the multidimensional proximity concept as reference and divided proximity into the five dimensions of geography, society, cognition, institution, and organization, combined with Boschma [33,50]. Given the characteristics of Chinese scientists, we aimed to explore the influence mechanisms of geographical proximity, social proximity, economic proximity, institutional proximity, and educational proximity on the scientific cooperation of Chinese scientists. Based on the above combing of the literature, we put forward the following hypotheses:

Hypothesis 1. *Geographical proximity has a positive impact on scientific cooperation of Chinese scientists.*

Hypothesis 2. *Social proximity has a positive impact on scientific cooperation of Chinese scientists.*

Hypothesis 3. *Economic proximity has a positive impact on scientific cooperation of Chinese scientists.*

Hypothesis 4. *Institutional proximity has a positive impact on scientific cooperation of Chinese scientists.*

Hypothesis 5. *Educational proximity has a positive impact on scientific cooperation of Chinese scientists.*

3. Data and Methods

3.1. Data Source

3.1.1. Research Object

Academician is one of the highest academic titles established by the State in the field of science and technology, representing the highest level of science and technology in China [12]. Therefore, we selected academicians of the Chinese Academy of Sciences as the typical representatives of scientists. The list of academicians of the Chinese Academy of Sciences was downloaded from the website of Chinese Academy of Sciences (http://www.cas.cn/). In 2017, a total of 1370 Chinese academicians were listed (including those deceased; excluding those foreign). During the study period, in November 2019, the Chinese Academy of Sciences elected 64 new members of the Chinese Academy of Sciences, all of whom were outside the scope of this study.

3.1.2. Data Collection and Processing

Data of cooperative papers of academicians of the Chinese Academy of Sciences were obtained from the China National Knowledge Infrastructure (CNKI, http://www.cnki.net/). The process of data collection and processing was as follows: First, the literature search was set as the "China Academic Journal Network Publishing Database" on the advanced search page to accurately search the publication paper status of each academician of the Chinese Academy of Sciences. To avoid data interference (such as duplicates), the author unit of the academician was specified. Then, Python data crawler technology was used to obtain the title, author, author unit, source, publication time, and other information about the paper. Then, the data were further screened through the research topics of each academician of the Chinese Academy of Sciences, and a total database of the papers of each academician of the Chinese Academy of Sciences was established, including 29,770 pieces of datum. Finally, the related information was extracted according to the database of academician's papers, and the related sub-database of academician paper cooperation was established. The cooperation data at different levels were as follows: (1) a co-author paper database of academicians of the Chinese Academy of Sciences, where the papers published independently by academicians were excluded, and the collaborators of the paper and the number of papers cooperated with each collaborator were sorted; (2) an organizational cooperative database of papers of Chinese Academy of Sciences academicians, where the organization of each author in the database was identified and the cooperation frequency of the corresponding organization was counted; and (3) a city cooperation database of papers of Chinese Academy of Sciences academicians. To obtain the geographic information and cooperative links of the institutions to which the academician and collaborator belong onto the urban space, we determined the urban cooperative relationship.

3.2. Measurement Model

The paper cooperation network of scientists is an undirected network based on the cooperative relationships of scientists working together to complete papers; that is, a relationship exists when two or more authors collaborated to publish a paper. We mainly discussed the geographical characteristics of the scientific cooperation network of Chinese scientists.

3.2.1. Social Network Analysis

Network density refers to the density of the connections among nodes in a network. In the analysis of social networks, network density is used to summarize the total distribution of each line to measure the difference between the distribution and the complete graph. The more connections that exist among the network nodes, the denser the network. An undirected network can be represented by the ratio of the actual number of connections in a network G to the maximum number of possible connections:

$$\mathrm{d(G)} = 2\mathrm{M}/[\mathrm{N}(\mathrm{N}-1)], \tag{1}$$

where d(G) represents the network density, M is the number of actual connections in the network, and N is the number of network nodes. The value range of network density is [0, 1]. When the network is completely connected, the network density is 1.

Degree centrality, or degree for short, refers to the number of other nodes directly connected to a certain node and represents the degree of connection. If a node is directly connected to many nodes, then the node has a high degree centrality. In the scientific cooperation network of Chinese scientists, the degree centrality of nodes indicates the number of cities that have paper cooperation relationships with the scientists in the city. The higher the degree centrality, the higher the number of cities that cooperated with the scientists in the city. The measurement model of degree centrality is calculated as follows:

$$C_d(i) = \sum\nolimits_{j=1}^{n} a_{ij}, \tag{2}$$

where $C_{\mathrm{d}}(i)$ represents the degree centrality of a city and a_{ij} represents the city matrix of the scientific cooperation network of scientists, with an assignment of 1 for cooperative relationship and 0 for no cooperative relationship.

Weighted degree centrality (weighted degree) refers to the weight of the edge directly connected to a node. In the scientific cooperation network of Chinese scientists, the weighted centrality of nodes represents the sum of the number of cooperative papers of scientists in two cities. The measurement model of weighted degree centrality is as follows:

$$C_S(i) = \sum\nolimits_{j \in v} w_{ij}, \tag{3}$$

where $C_S(i)$ refers to the weighted degree centrality of the author, v represents the set of nodes directly connected to node i, and w_{ij} represents the number of papers that scientists have collaborated on between cities i and j, which is the weight. The greater the weighted degree centrality of a city, the more important the city in terms of the scientific cooperation network of scientists.

Betweenness centrality, also known as intermediacy centrality, refers to the proportion between the number of shortest paths passing through the node and the total number of shortest paths of all nodes in the network. The betweenness centrality of a node measures the degree to which the node controls the ability of other nodes to interact. In the scientific cooperation network of Chinese scientists, this index indicates the accessibility of scientists in a certain city in the scientific cooperation network and also reflects the ability of an intermediary and a transit station in the scientific cooperation network of the city. The betweenness centrality measure model is calculated as follows:

$$C_b(i) = \sum_{j=1;k=1;j\neq k\neq 1}^{n} \frac{n_{jk}(i)}{n_{jk}}, \quad (4)$$

where $C_b(i)$ refers to the betweenness centrality of a city, n_{jk} refers to the number of shortest paths between node v_j and node v_k, and $n_{jk}(i)$ represents the number of shortest paths between node v_j and node v_k passing through node v_i.

3.2.2. Proximity and Negative Binomial Regression Model

Geographic proximity refers to the geographical distance between cities in the scientific cooperation network. We calculated the physical distance between cities according to the longitude and latitude. As the actual physical distance gap between cities may cause deviation in the estimated results, the actual distance is processed using the following formula [47]:

$$Geopro_{ij} = 1 - \ln\left(\frac{d_{ij}}{max\ d_{ij}}\right), \quad (5)$$

where $Geopro_{ij}$ is the geographic proximity, d_{ij} is the geographic distance between cities i and j, and $max\ d_{ij}$ is the maximum distance between cities in the study sample.

Social proximity originates from embeddedness theory, which refers to the distance between social embeddedness and affinity between behavior subjects [41]. Taking Scherngell and relevant studies on social proximity as references [34,47,51], we used the Jaccard coefficient to measure the social proximity in the scientific cooperation network of scientists. The Jaccard coefficient is also known as the Jaccard similarity coefficient, which is typically used to compare the similarity and difference between finite sample sets. The larger the Jaccard coefficient, the higher the sample similarity. It is the intersection of two samples divided by their union. When the two samples are exactly the same, the result is 1; when the two samples are completely different, the result is 0. The calculation formula is as follows:

$$Socpro_{ij} = \frac{I_{ij}}{I_i + I_j - I_{ij}}, \quad (6)$$

where $Socpro_{ij}$ refers to social proximity; I_i and I_j are the number of cities with which cities i and j cooperate, respectively; and I_{ij} represents the number of cities with which cities i and j jointly cooperate.

Institutional proximity is the dummy variable of city cooperation of scientists, which is expressed by $Inspro_{ij}$. Cities with the same provincial administrative units share the same policy background and similar cultural environment, and the standards, rules, and laws that affect scientific cooperation tend to be homogeneous. Referencing Boschma's [52] research method, if cities from both sides of the scientific cooperation belong to the same provincial administrative unit, the value is 1; otherwise, it is 0.

The difference between the gross domestic product (GDP) of cities i and j in 2018 was selected to measure their economic proximity. To eliminate the dimensional relationship between variables and to enable data comparison, the GDP of each city was first standardized. The smaller the difference, the closer the economic situation between cities. The calculation formula is as follows:

$$Ecopro_{ij} = \left|\frac{GDP_i - GDP_{min}}{GDP_{max} - GDP_{min}} - \frac{GDP_j - GDP_{min}}{GDP_{max} - GDP_{min}}\right|, \quad (7)$$

where $Ecopro_{ij}$ represents economic proximity; GDP_i and GDP_j are the GDPs of cities i and j, respectively; and GDP_{min} and GDP_{max} represent the minimum and maximum of GDP of all cities, respectively.

For educational proximity, the existing evaluation standards for urban higher education level are mainly measured using higher education resources, such as the number of universities, students, teachers, and education funds; however, no consensus exists about this measurement [53]. As we mainly considered the proximity of urban education levels in the process of scientific cooperation of scientists, only the quality of urban higher education was considered here. According to the List of Double First-Class Universities (published by the Ministry of Education), if a city has a first-class university, it is assigned a value of 3; if it has a first-class discipline, it is assigned a value of 2; if it has an ordinary university, it is assigned a value of 1; and if it has no university, it is assigned a value of 0. Then, $Edupro_{ij}$ was used to measure the educational proximity.

As the number of cooperative scientific papers is a non-negative integer and the explanatory variable is excessively dispersed, the variance is obviously larger than the expectation. Therefore, the negative binomial regression model was adopted to explore the proximity mechanism of scientific cooperation of Chinese scientists. The formula is as follows:

$$I_{ij} = \alpha + \beta_1 Mass_i + \beta_2 Mass_j + \beta_3 Scientists_i + \beta_4 Scientists_j + \beta_5 Geopro_{ij} + \beta_6 Socpro_{ij} + \beta_7 Ecopro_{ij} + \beta_8 Inspro_{ij} + \beta_9 Edupro_{ij} + \varepsilon_i, \quad (8)$$

where the dependent variable I_{ij} refers to the number of papers published cooperatively by scientists between cities i and j; α is a constant term; β_{1-8} are the coefficients to be estimated; ε_i is a random error term; $Mass_i$ and $Mass_j$ are the number of papers respectively published by scientists in cities i and j, respectively; $Scientist_i$ and $Scientist_j$ are the number of scientists in cities i and j, respectively; $Mass_i$, $Mass_j$, $Scientist_i$, and $Scientist_j$ are the attribute characteristics of urban subjects in the scientific cooperation network of scientists, which are taken as the control variables; and $Geopro_{ij}$, $Socpro_{ij}$, $Ecopro_{ij}$, $Inspro_{ij}$, and $Edupro_{ij}$ represent the geographical proximity, social proximity, economic proximity, institutional proximity, and educational proximity between cities i and j, respectively.

4. Topological Structure of Scientific Cooperation Network of Chinese Scientists

4.1. Network Characteristics

The main technical software in this paper were Gephi [54], Pajek [55], VOSviewer [56] and ArcGIS [57]. Gephi software and the city cooperation database of academicians of the Chinese Academy of Sciences were used to draw the scientific cooperation network of Chinese scientists (Figure 1).

The scientific cooperative network of Chinese scientists shows a multi-triangle structure, with Beijing as the apex and absolutely as the core of the network. In terms of network size, collaboration among Chinese scientists was relatively weak. The whole network had 173 nodes and 700 edges, but the density of the network was only 0.047 and the diameter was 4, indicating that the network scale was small with few connections between nodes. From the network attribute, the scientific cooperation network conforms to small world characteristics. The average clustering coefficient of the whole network was 0.782, far higher than the average clustering coefficient of the random graph generated by the same node set, which was 0.046. The average path length in the scientific cooperation network of Chinese scientists was 2.305, indicating that the scientific cooperation network of Chinese scientists was highly concentrated in some cities; the network had obvious small-world and scale-free characteristics. From the perspective of node centrality, a node with high centrality is highly concentrated in a few cities. Figure 1 shows that municipalities directly under the central government and provincial capitals were the main participants in the scientific cooperation network of Chinese scientists. In the top 20 cities in terms of degree centrality, except for Qingdao, Dalian, and Xiamen, most were municipalities directly under the central government or provincial cities occupying subordinate positions in the whole network (Table 1). Beijing was the most important node in the scientific cooperation network of Chinese scientists, where the number of cities and authors cooperating with scientists in Beijing was the largest. The network had 173 nodes, and Beijing's degree centrality was 125, indicating that more than 70% of the cities in the network had cooperated with Beijing in scientific research. The weighted centrality of Beijing was as high as 24,828, more than twice as high as that of Shanghai, which indicates that Beijing was the leading city for the scientific cooperation of Chinese scientists.

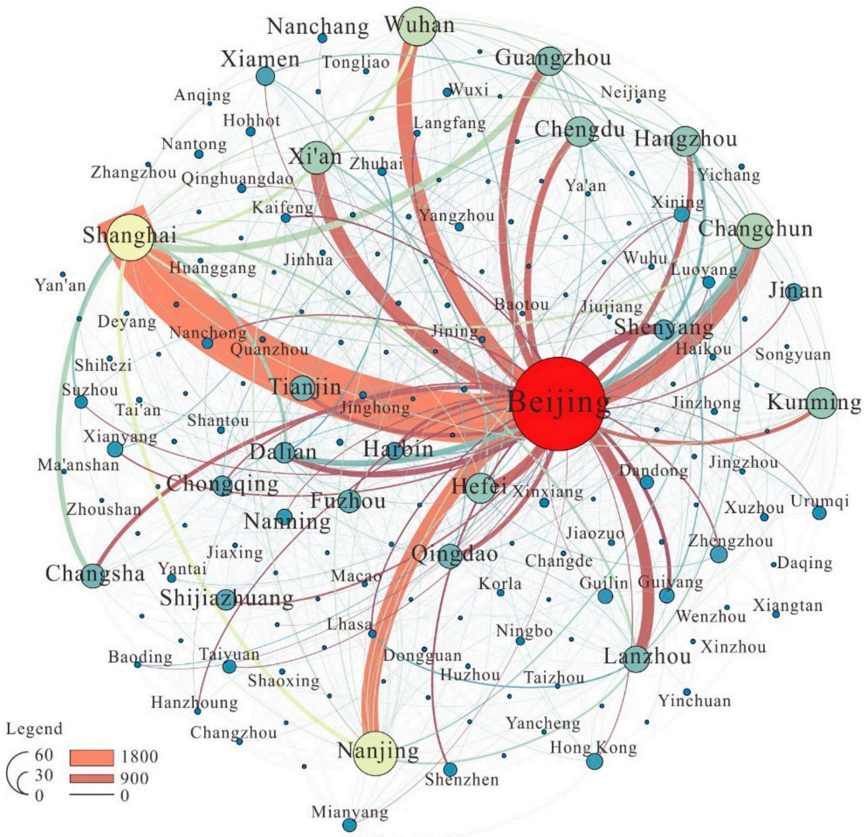

Figure 1. Scientific cooperation network of Chinese scientists. The size of nodes in the figure is proportional to the number of cooperating cities in scientific research, indicating the degree centrality of nodes, and the size of node connection is proportional to the frequency of paper cooperation between cities.

Table 1. The top 20 cities in terms of degree centrality in the scientific cooperation network of Chinese scientists.

Rank	City	Degree Centrality	Intensity Centrality	Rank	City	Degree Centrality	Intensity Centrality
1	Beijing	125	24,828	11	Guangzhou	35	2562
2	Shanghai	60	10,003	12	Lanzhou	32	2483
3	Nanjing	57	3769	13	Tianjin	30	810
4	Wuhan	49	2978	14	Changsha	29	1263
5	Changchun	44	4280	15	Qingdao	29	1239
6	Xi’an	41	2662	16	Fuzhou	27	561
7	Kunming	38	1073	17	Dalian	24	2196
8	Hefei	37	2158	18	Shijiazhuang	24	344
9	Chengdu	37	1690	19	Shenyang	23	1794
10	Hangzhou	37	1678	20	Chongqing	23	604

4.2. Hierarchical Structure

Hierarchical clustering in the Pajek block model analysis was adopted, where hierarchical files were obtained according to the weighted degree centrality, and the scientific cooperation network of Chinese scientists was divided into three levels, showing a pyramidal hierarchical structure (Table 2). Only two cities, Beijing and Shanghai, were included in the first level. The average degree centrality, average intensity centrality, average intimacy centrality, average betweenness centrality, density, and other network statistical coefficients for this level were far higher than the average values of the whole network. These two cities were thus located at the top of the pyramid structure. In the second level, 16 cities had statistical indicators higher than the average of the whole network. These 16 cities were located in the middle of the pyramid structure. The third level had the highest number of cities, with 155. All statistical coefficients in this level were lower than the average value of the whole network and these cities were located at the base of the pyramid structure.

Table 2. Chinese scientists research cooperation network at different levels of index statistics.

Level	No. Nodes	Average Degree Centrality	Average Intensity Centrality	Average Intimacy Centrality	Average Betweenness Centrality	Density
1	2	92.50	17,415.50	0.69	4707.46	0.0714
2	16	34.88	2084.19	0.55	478.27	0.0214
3	155	4.24	62.31	0.43	15.15	0.0033
Whole network	173	8.09	449.92	0.44	112.23	0.0058

By exporting the discriminant files generated by Pajek to VOS viewer in two-dimensional (2D) format, a core-periphery structure map of the scientific cooperation network of Chinese scientists was drawn (Figure 2). Figure 2 shows that the scientific cooperation network of Chinese scientists developed into an obvious progressive form of core-periphery, which can be divided into three major groups—core, semi-periphery, and periphery areas.

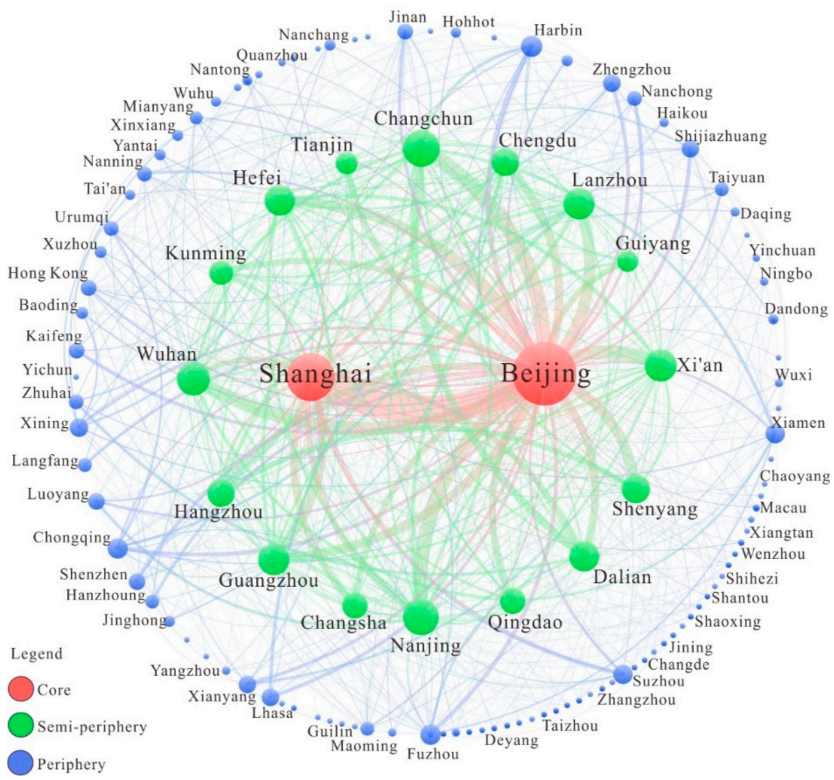

Figure 2. The core-periphery structure of the scientific cooperation network of Chinese scientists. The size of the nodes in the graph is proportional to the weighted degree centrality of the node and the size of the edges are positively correlated with the number of collaborated papers between the two cities.

The core area consists of cities in the first level, which is the hub node of the scientific cooperation network of Chinese scientists. Beijing and Shanghai are located in the core area, where these two nodes had many edges with an average degree centrality of 92.5 and weighted degree centrality of up to 17,415.50. These two cities are the rich nodes of the whole network, where the connection degree between them is the strongest in the whole network. Beijing and Shanghai had 5406 cases of cooperation in the scientific cooperation network of Chinese scientists, and their cooperation ranked first in all partnerships, with obvious rich club characteristics. Beijing and Shanghai are home to numerous research institutes and institutions of higher learning and are the main workplaces for academicians of the Chinese Academy of Sciences. Their output of papers ranked first and second among all cities in China. These two cities were closely linked with other cities in scientific cooperation, playing a crucial role in the scientific cooperation network of Chinese scientists.

The semi-periphery area consisted of 16 cities at the second level—Changchun, Nanjing, Wuhan, Xi'an, Guangzhou, Lanzhou, Dalian, Hefei, Shenyang, Chengdu, Hangzhou, Changsha, Qingdao, Kunming, Tianjin, and Guiyang. These cities played a secondary role in the scientific cooperation network of scientists, having a relatively strong paper cooperation relationship with the core cities, but with low connection strength among other semi-periphery cities or with the cities in the periphery area. The cities in the semi-periphery area were hot spots of scientific activities of scientists within the region and the cities with high paper output. As the hubs of scientific cooperation with the core cities in the region, the semi-periphery cities maintained a high-intensity cooperative relationship with Beijing and Shanghai. The semi-periphery area was the main workplace for academicians of the Chinese Academy of Sciences in this region. For example, Lanzhou and Chengdu were the main work places for academicians of the Chinese Academy of Sciences in the western region, where high-quality scientific resources of the region are gathered and produce the majority the scientific output of Chinese scientists in the region.

A total of 155 cities were located in the third level of the scientific cooperation network of Chinese scientists; this was called the periphery area. These cities were low value areas for scientific cooperation of Chinese scientists and their statistical indicators were lower than the average level of the whole network. The network density of this area was only 0.0033, the average degree centrality was 4.24, and the average weighted degree centrality was 62.31, indicating that the Chinese scientists were rarely connected with this area, and the frequency of scientific cooperation of scientists in the periphery area cities was very low. Fewer scientific institutions and universities were located in the cities in the periphery area, and their overall scientific level was lagging with a low research output, which led to weak scientific links between cities. In general, these cities did not actively seek cooperation in the whole scientific cooperation network of Chinese scientists, playing only an auxiliary role in the network.

5. Spatial Pattern of the Scientific Cooperation Network of Chinese Scientists

Using ArcGIS and Gephi software, the spatial distribution map of the scientific cooperation network of Chinese scientists was drawn (Figure 3). The sizes of the circles indicate the number of cities cooperating with the city and the width of a line indicates the number of cooperation papers between cities. We found that the scientific cooperation network of Chinese scientists had an obvious regional imbalance, among which the regions of Beijing–Tianjin–Hebei, the Yangtze River Delta, and the central-south region of Liaoning were the hot spots of Chinese scientific activities. Some regional key cities have also become hot spots for the scientific activities of Chinese scientists, such as Xi'an and Lanzhou in Northwest China; Chengdu and Kunming in Southwest China; Wuhan and Changsha in Hubei and Hunan provinces, respectively; and Guangzhou, Shenzhen, Xiamen, Fuzhou, and other cities in Southeast China. From the perspective of cooperation frequency, scientific cooperation was mainly concentrated in the regional central cities. Beijing is, the most important scientific center in China and its cooperative cities are distributed throughout the country, among which the most closely related cities were Shanghai and Nanjing in the Yangtze River Delta, Wuhan in the central region, Changchun in the northeast region, Xi'an and Lanzhou in the northwest region, and Guangzhou in the Pearl River Delta. The regions of Beijing–Tianjin–Hebei, the Yangtze River Delta, and the central-south region of Liaoning were closely connected with each other, while other cities did not demonstrate strong cooperation in scientific research.

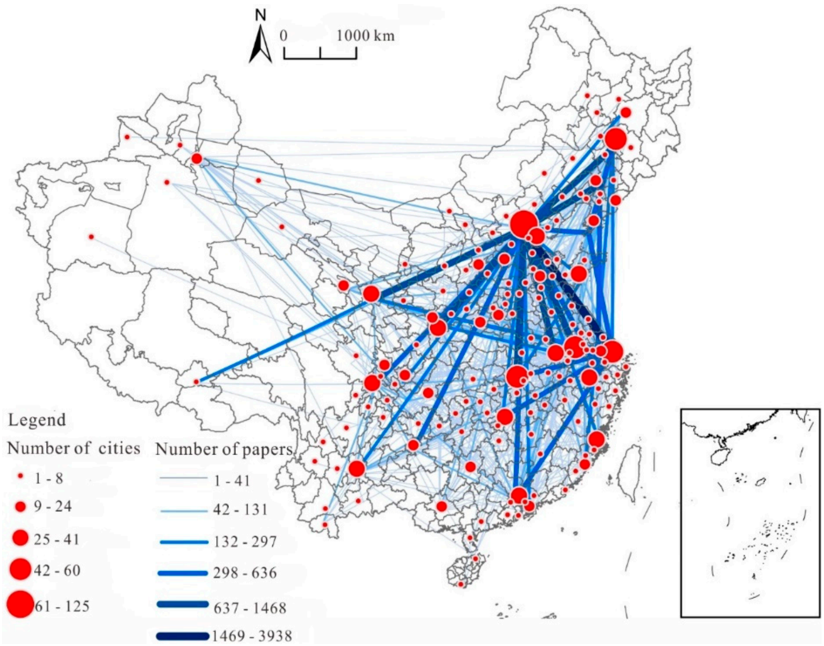

Figure 3. Spatial distribution of the scientific collaboration network of Chinese scientists.

Centrality reflects the relative importance of each node in the network. Here, the degree centrality, weighted degree centrality, and betweenness centrality of nodes in the scientific cooperation network of Chinese scientists were further examined (Figure 4). The node characteristics of the scientific cooperation network of Chinese scientists were unbalanced in space.

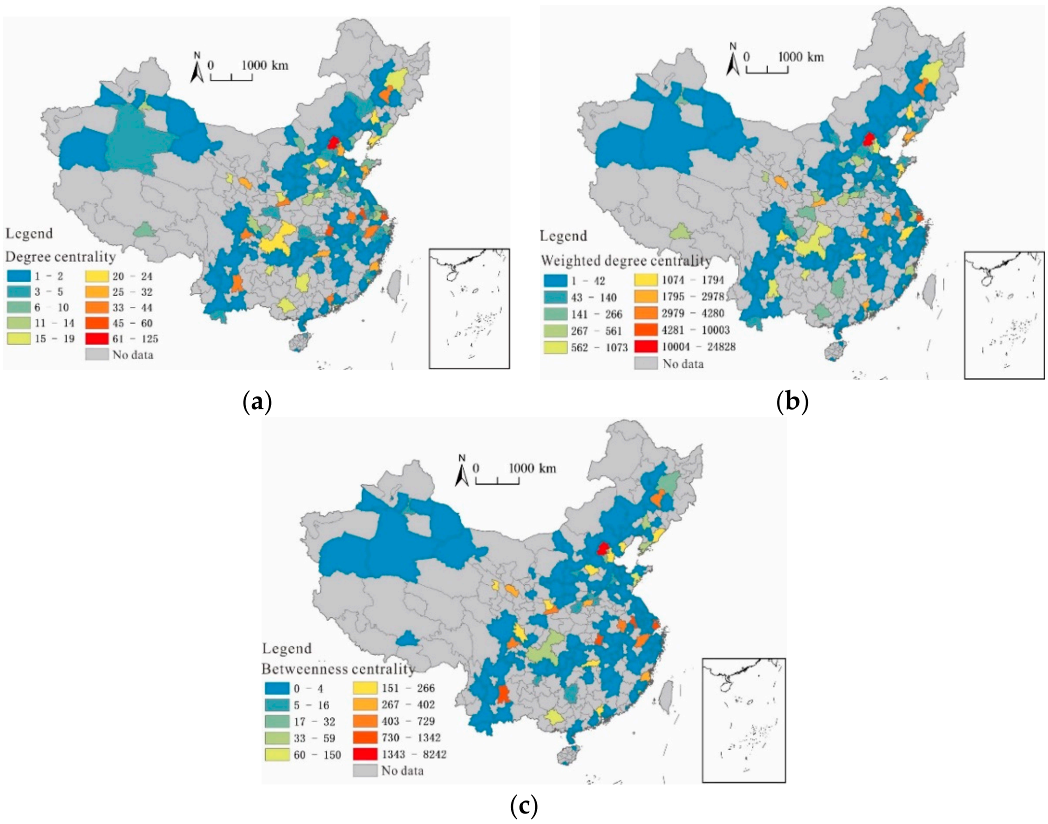

Figure 4. Spatial distribution of (**a**) degree centrality, (**b**) weighted degree centrality, and (**c**) betweenness centrality.

5.1. Degree Centrality

The areas with high degree centrality were mainly distributed in provincial capitals and municipalities in Central and Eastern China, such as Beijing, Shanghai, Nanjing, Wuhan, Changchun, Hefei, Hangzhou, and Guangzhou. Western cities, such as Xi'an, Chengdu, and Kunming, also had high degree centrality in the scientific cooperation network of Chinese scientists, indicating that more cities were connected with these cities in the scientific cooperation network of Chinese scientists. The common features of these cities were their high concentration of scientific research institutions and institutions of higher learning. They were the cities with the most high-quality scientific resources in China and the main cities of employment for Chinese scientists and other scientific workers.

5.2. Weighted Degree Centrality

Compared with degree centrality, the tendency of weighted degree centrality with high values concentrated in individual cities was more obvious, where the two poles pattern is prominent. The weighted degree centrality of Beijing was 24,828, which is 31.90% of the weighted degree centrality of all cities and was the most important pole. The weighted degree centrality of Shanghai was 10,003, which is 12.85% of the weighted degree centrality of all cities. In addition to these two major cities, the cities with weighted degree centrality of more than 1000 were Changchun, Nanjing, Wuhan, Xi'an, Guangzhou, Lanzhou, Dalian, Hefei, Shenyang, Chengdu, Hangzhou, Changsha, Qingdao, and Kunming. In the scientific cooperation network of Chinese scientists, the number of papers jointly written by scientists in these cities was relatively high, which also reflects many research institutions in these cities having strong scientific strength and numerous scientific achievements.

5.3. Betweenness Centrality

The spatial distribution of high-value betweenness centrality was scattered, presenting a spatial pattern of one super power and multiple great powers. As the city with the highest betweenness centrality of 8241.87, Beijing served as an important bridge for the scientific cooperation of Chinese scientists. Some other cities had higher betweenness centrality, including Shanghai, Nanjing, Hefei, and Hangzhou in the Yangtze River Delta region; Kunming and Chengdu in Southwest China; Zhengzhou, Wuhan, and Changsha in Central China; Changchun in Northeast China; Xi'an, Lanzhou, and Xining in Northwest China; Shijiazhuang and Tianjin in Northern China; Fuzhou in Eastern China; and Guangzhou in Southern China. As the central cities of the region (and even the whole country), these cities not only played the role of transit, but also acted as important hub cities for the scientific cooperation of Chinese scientists.

6. Proximity Mechanism of the Scientific Cooperation of Chinese Scientists

To ensure the accuracy and reliability of the calculated results, before using the negative binomial regression model to analyze the proximity mechanisms that affect the scientific cooperation of Chinese scientists, the model was first tested for multicollinearity, endogeneity, and heteroscedasticity. To judge multicollinearity, two criteria must be met simultaneously: the maximum VIF (Variance Inflation Factor) must be less than 10 and the average VIF must be greater than 1 [58]. The multicollinearity test result showed that the average VIF was 1.49 and the maximum value was 2.74, indicating that no multicollinearity in the data. The test result of endogeneity showed that p was 0.9413, indicating that no endogeneity problem in the data. In the test of heteroscedasticity, P was 0.0002, which is less than 0.05, such that the possibility of heteroscedasticity could not be ruled out. Therefore, robust standard error was adopted for estimation to eliminate the influence of heteroscedasticity. To increase the robustness of estimation results and enable comparison with the regression results, proximity variables (Models 1–5) were introduced hierarchically, with all proximity variables (Model 6) added. The final interpretation was based on Model 6. The negative binomial regression results are shown in

Table 3. In terms of the model fitting degree, the α parameter was not equal to 0, and the significance level of each dependent variable was high, indicating the good explanatory power of the model.

Table 3. Estimation results of negative binomial regression model.

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Variable	I_{ij}	I_{ij}	I_{ij}	I_{ij}	I_{ij}	I_{ij}
$Mass_i$	0.0020 *	0.0030 **	0.0020 *	0.0019 *	0.0018	0.0026 *
	(0.0012)	(0.0015)	(0.0012)	(0.0012)	(0.0012)	(0.0014)
$Mass_j$	0.0045 ***	0.0054 ***	0.0045 ***	0.0045 ***	0.0044 ***	0.0049 ***
	(0.0009)	(0.0007)	(0.0009)	(0.0009)	(0.0010)	(0.0007)
$Scientist_i$	0.0005 ***	0.0005 ***	0.0006 ***	0.0005 ***	0.0007 ***	0.0006 ***
	(0.0002)	(0.0001)	(0.0002)	(0.0002)	(0.0002)	(0.0002)
$Scientist_j$	−0.0001	−0.0000	−0.0001	−0.0002	−0.0001	−0.0001
	(0.0005)	(0.0005)	(0.0006)	(0.0005)	(0.0005)	(0.0004)
$Geopro_{ij}$	0.0023					0.0054 ***
	(0.0023)					(0.0016)
$Edupro_{ij}$		23.3207 ***				22.5827 ***
		(8.1427)				(7.5222)
$Ecopro_{ij}$			0.0001 ***			0.0002 ***
			(0.0000)			(0.0000)
$Inspro_{ij}$				−1.0500 ***		−1.2376 ***
				(0.3878)		(0.2425)
$Socpro_{ij}$					3.7408 ***	4.8300 ***
					(1.3624)	(1.1953)
Constant	3.5418 ***	−8.2114 **	3.5525 ***	3.6110 ***	3.2313 ***	−8.2887 **
	(0.1387)	(4.1652)	(0.1398)	(0.1397)	(0.1947)	(3.8211)
lnα	−0.2248 *	−0.3299 **	−0.2249 *	−0.2476 **	−0.2584 **	−0.4314 ***
	(0.1244)	(0.1457)	(0.1247)	(0.1240)	(0.1271)	(0.1522)
Wald χ^2	132.75	176.03	128.23	150.51	117.16	316.44
Prob > χ^2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Log pseudolikelihood	−966.63615	−955.48099	−966.6055	−964.13563	−962.94202	−944.71319
Observations	182	182	182	182	182	182

Note: Standard errors are shown in parentheses, *** $p < 0.01$, ** $p < 0.05$, and * $p < 0.1$. I_{ij} refers to the number of papers published cooperatively by scientists between cities *i* and *j*. $Mass_i$ and $Mass_j$ are the number of papers respectively published by scientists in cities *i* and *j*, respectively. $Scientist_i$ and $Scientist_j$ are the number of scientists in cities *i* and *j*, respectively. $Geopro_{ij}$, $Socpro_{ij}$, $Ecopro_{ij}$, $Inspro_{ij}$, and $Edupro_{ij}$ represent the geographical proximity, social proximity, economic proximity, institutional proximity, and educational proximity between cities *i* and *j*, respectively.

Our results confirm Hypothesis 1: geographical proximity had a positive effect on the scientific cooperation of Chinese scientists under the simultaneous influence of all proximities. The result estimated by Model 1 shows that the regression coefficient of geographic proximity was positive under the assumption that Chinese scientists' scientific cooperation had no other proximity effect, but it failed the significance test; indicating that geographic proximity had no effect on the cooperation of scientists under the assumption that no other proximity effect existed. Model 6 shows that geographical proximity had a significant positive impact on the scientific cooperation of Chinese scientists under the influence of all dependent variables. The regression results showed that distance was not the most important factor for Chinese scientists to consider in their scientific cooperation. Research on scientific cooperation showed that geographic distance has a significant negative relationship with paper cooperation [38,51,59]; our results further confirms those results. However, an addition is recommended: considering the influence based on other proximities (educational proximity, economic proximity, institutional proximity, and social proximity), the closer the geographical distance of Chinese scientists, the more frequent their scientific cooperation. The reason for this finding is that achieving the established scientific objectives is the most important reason for scientists to seek scientific partners, so scientists were more likely to look for partners in nearby geographical locations, under the condition that all scientific partners are similar in quality.

Modern science and technology are continuously advancing, so scientists tend to conduct cross-disciplinary and comprehensive studies. Many original achievements and breakthroughs require the collaboration of scientists of different disciplines, and scientists need to mobilize the most high-quality scientific resources of the country and even the world. Therefore, geographical proximity is not the primary factor for scientific collaboration. Geographical proximity is conducive to face-to-face communication among scientists; direct communication between scientists is conducive to the spread of knowledge and the flow of information, which improves the efficiency of knowledge output. It is easier for nearby scientists to establish academic connections and expand their network of academic relationships. In daily local academic seminars, conferences, and other formal or informal communication activities, scientists in geographical proximity are more likely to establish academic connections by virtue of reciprocity and transmission in interpersonal communication. With the development of information technology, people's online seminars and online communication tools are widely used, but this paper provides strong evidence to support the notion that informal, 'face-to-face' communication may be an essential ingredient in scientific cooperation [38,51,59].

Our results confirm Hypothesis 5: educational proximity had a significantly positive effect on scientific cooperation of Chinese scientists. Model 6 shows that the regression coefficient of educational proximity was the largest among all dependent variables of proximity ($p < 0.01$), indicating that closer educational levels between two cities leads to higher possibilities that their scientists will tend to cooperate. According to the regression coefficient and significance test of each dependent variable, educational proximity is the primary factor for to consider in scientific cooperation. The closer the educational levels between cities, the more frequent the scientists collaborate. Scientific cooperation between scientists is characterized by strong combination and complementing each other's advantages.

Our results confirm Hypothesis 3: economic proximity had a significantly positive effect on scientific cooperation of Chinese scientists. The proximity of economic levels between cities helps scientists to collaborate in scientific research. A city with many scientific achievements is also characterized by a high economic level. The reason why cities with a high economic level have more cooperation is that the basic conditions for scientific research in cities with high economic level are superior, funds are sufficient, and the salaries of scientists are better, which are conducive to promoting scientific cooperation between scientists in the two cities.

The influence coefficient of institutional proximity on the scientific cooperation of Chinese scientists was negative and significant, indicating that scientific cooperation tended to occur between cities with different institutional types. This empirical result was inconsistent with hypothesis. Therefore, Hypothesis 4 was rejected. As scientists cooperate with others with different cultures, customs, and conventions, different institutional backgrounds, knowledge, and theoretical backgrounds can stimulate their imagination, help break habitual thinking patterns, and lead to the production of original results. This indicates that scientists do not tend to collaborate with people of the same institutional background, which promotes complementarity of policies and integration of interdisciplinary knowledge. The scientific cooperation of Chinese scientists has broken the traditional scientific research model of local protectionism.

Our results confirm Hypothesis 2: the regression coefficient of social proximity for the scientific cooperation of Chinese scientists was significantly positive, indicating that social proximity promotes scientific collaboration among scientists. Social proximity helps to establish social trust relationships, further promoting the transmission of tacit knowledge, which is crucial in the process of knowledge creation and production, through which the friction of channels in the process of cooperation can be reduced, and close learning cooperation relationships can be finally established. Good social relationships are conducive to the development and deepening of knowledge cooperation. When seeking collaborative partners, scientists will evaluate and make decisions on scientific cooperation based on their own interpersonal relationships.

The number of scientists in cities and the number of papers published by scientists had an positive effect on scientific cooperation; that is, the greater the number of scientists in two cities, the more papers they publish and the more likely they are to collaborate, which shows a network trend of strong cooperation. Our conclusion is consistent with the results of published studies: the inter-regional scientific capacity has a positive role in promoting scientific cooperation [38,60].

7. Conclusions and Discussion

Based on the paper cooperation data of academicians of the Chinese Academy of Sciences collected in the CNKI, we used the complex network method and spatial statistics to characterize the scientific cooperation network of Chinese scientists and explore the proximity mechanism. The conclusions are as follows:

(1) The scientific cooperation network of Chinese scientists presented a multi-triangle skeleton with Beijing as the apex, where Beijing was the core of the network. The network hierarchy was obvious, with Beijing and Shanghai located in the core area of the scientific cooperation network of Chinese scientists. Then, 16 cities, including Changchun, Nanjing, Wuhan, Xi’an, Guangzhou, Lanzhou, Dalian, and Hefei, were located in the semi-periphery region of the scientific cooperation network of Chinese scientists. The rest of the cities were peripheral.

(2) The scientific cooperation of Chinese scientists was unbalanced in space, with the areas of Beijing–Tianjin–Hebei, the Yangtze River Delta, and the central-south region of Liaoning being the hot spots. The areas with high degree centrality were mainly distributed in provincial capitals and municipalities directly under the central government in Eastern China. The high weighted centrality was concentrated in some cities, and the two poles pattern of Beijing and Shanghai was observed. The spatial distribution of high betweenness centrality was scattered, presenting a spatial pattern of one superpower and multiple great powers.

(3) The negative binomial regression model accurately explained the proximity mechanisms of the scientific cooperation of Chinese scientists. We found that geographical proximity had a positive effect on scientific cooperation. For all proximity effects, geographic proximity had a positive impact on scientific collaboration. Educational proximity was the primary consideration for Chinese scientists to cooperate in scientific research. The closer the education level between two cities, the more likely scientists were to collaborate. Economic proximity and social proximity had significant positive effects on scientific cooperation. The influence coefficient of institutional proximity on scientific cooperation between scientists was negative and significant, indicating that scientific cooperation tends to occur among cities with different institutional types.

At present, globalization is increasing, so scientific cooperation across different specialties and different regions is increasingly occurring. Many top research results have been achieved through the close cooperation of different scientists. The scientific cooperation of academicians of the Chinese Academy of Sciences provides us with a model of scientific cooperation. At present, domestic scientific research should not only emphasize cooperation within and between units, but also strengthen the cooperation across cities, regions, and even countries to promote breakthroughs in major scientific projects.

The state should establish a scientific and technological resource sharing mechanism for the scientific cooperation of scientists, build a platform for scientific cooperation, strengthen information exchange and visit exchanges amongst scientists, and promote cooperative research between both sides and even multiple parties. The advantages of Beijing and Shanghai in terms of higher education resource agglomeration, sound scientific foundation, and numerous cooperative partners should be considered to promote the production of high-quality and high-level scientific achievements by scientists in these two cities. The transformation of scientific results should be a focus, turning Beijing and Shanghai into global scientific and technological innovation cities with international influence. The state should properly adjust the spatial layout and structural allocation of economic resources and higher education resources, as well as providing more relevant preferential policies to marginal cities in the scientific cooperation network of Chinese scientists to promote the scientific research level of the marginal cities and strengthen the scientific research links with the core cities.

The pertinence and selectivity of scientific cooperation should be strengthened for cities in semi-periphery and periphery areas of the network of scientific cooperation of Chinese scientists. Cities should take advantage of regional resources to build scientific characteristics of cities with characteristic research, strengthen cooperation with core cities, and enhance their level and status in scientific cooperation.

Young scientists should fully realize the importance of scientific cooperation and seek opportunities to learn in the field of high-level research institutions, improve research methods and build personal technical skills, build differentiated scientific advantages, strengthen scientific contacts with high-level scientists, and overall improve their scientific level.

We selected the cooperation data of academician papers collected from CNKI to discuss the complexity of the scientific cooperation network of Chinese scientists. The results showed that the domestic situation of the scientific cooperation network of Chinese scientists can be revealed through the CNKI database. Future research could use the Web of Science core citation database to reveal the international cooperation of Chinese scientists to supplement and improve the current research on the scientific cooperation of Chinese scientists. As the form of scientific collaboration of Chinese scientists is not limited to paper cooperation, it is also possible to depict the scientific cooperation network of Chinese scientists in the future using patents, research projects, and works to supplement and deepen this research.

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