The Effect of Geographical Proximity on Scientific Cooperation among Chinese Cities from 1990 to 2010

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Abstract

**Background:** The relations between geographical proximity and spatial distance constitute a popular topic of concern. Thus, how geographical proximity affects scientific cooperation, and whether geographically proximate scientific cooperation activities in fact exhibit geographic scale features should be investigated.

**Methodology:** Selected statistics from the ISI database on cooperatively authored papers, the authors of which resided in 60 typical cities in China, and which were published in the years 1990, 1995, 2000, 2005, and 2010, were used to establish matrices of geographic distance and cooperation levels between cities. By constructing a distance-cooperation model, the degree of scientific cooperation based on spatial distance was calculated. The relationship between geographical proximity and scientific cooperation, as well as changes in that relationship, was explored using the fitting function.

**Result:** (1) Instead of declining, the role of geographical proximity in inter-city scientific cooperation has increased gradually but significantly with the popularization of telecommunication technologies; (2) the relationship between geographical proximity and scientific cooperation has not followed a perfect declining curve, and at certain spatial scales, the distance-decay regularity does not work; (3) the Chinese scientific cooperation network gathers around different regional center cities, showing a trend towards a regional network; within this cooperation network the amount of inter-city cooperation occurring at close range increased greatly.

**Conclusion:** The relationship between inter-city geographical distance and scientific cooperation has been enhanced and strengthened over time.

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Data Availability: The authors confirm that all data underlying the findings are fully available without restriction. Relevant data are within the Supporting Information files. All cooperatively authored papers are available from the three famous citation database (SCI, SSCI, and A & HCI).

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Introduction

In the 21st century, along with the development and popularization of new information and telecommunication technologies, the spatial scale of people’s outreach has greatly increased; conversely, the obstacles to communication offered by spatial distance have become weaker. In Friedman’s view, the world is flat, meaning that people all around the world are now able to draw increasingly closer to one another, through the use of mobile phones, the internet, and open-source programming [1]. Some scholars have even proposed the “death of geography” or the “death of distance” [2–4]. However, whether geographical distance has really met its “demise” is a topic of common concern in many fields.

There are two views about the relationship between geographical proximity and spatial connection. One is that geographical space no longer plays a decisive role in actors’ communication, mainly because modern telecommunication and transportation technology can overcome spatial barriers in order to instead build links [5,6]. Another view suggests that despite globalization, geographical proximity is still a prime driving force behind actors’ interrelational activities – that is, many interactions still occur between geographically adjacent actors [7,8]. Researchers have undertaken multiple studies on the relationships between geographical proximity and entrepreneurs [6], enterprise cooperation [9,10], the corporate-university innovation connection [11], research institute cooperation [12], social contact [13], disease spread [14], and technology transfer [15], all of which concluded that geographical proximity did affect the formation of the relationship between these actors, albeit to varying degrees. However, in the era of the knowledge economy, surprisingly little attention has been paid to the relations between geographical proximity and scientific cooperation [16,17].

In recent years, with the development of scientometrics, the number of studies addressing knowledge transfer, scientific cooperation, and knowledge networks, using journal article data has gradually increased [18–21], helping research institutes to establish scientific alliances and promote the development of
Materials and Methods

Materials

With the development of bibliometrics and the establishment of periodical databases, studies of knowledge flow using statistics of published papers have become common [20,22,23]. Within that existing body of knowledge, cooperatively authored papers constitute important material in exploring the exchange of knowledge, cooperation, and knowledge networks [19,24,25]. In this paper, the degree of inter-city scientific cooperation is reflected by the number of cooperatively authored papers being produced between cities, which are considered instances of cooperation. This is a method that is widely used in research, due to the objectivity and availability of data. Each paper contains information about the authors’ institutes or (and) working locations; as a result, the Papers Database is highly suitable for studying the relation between inter-city cooperation and geographical distance.

In this paper, Chinese cities were selected to represent scientific cooperation network nodes. Compared with other countries, China is considered a superpower with representative features in science [26–28], due to its rapid development of scientific fundamentals. This is reflected by the 5,203 papers authored by Chinese researchers that were published in top international academic journals in 2010, a number which places China in second place in the world in terms of publication rates in such journals. This study used data on the number of published scientific research papers in 2010 in order to select the 60 most active research centers in China (Table 1). Almost all the capital cities and municipalities were selected, because they are national and regional scientific research centers. Here, although Taiwan is an inalienable part of China, little scientific cooperation occurs between its cities and cities from the mainland due to the administrative jurisdiction; thus, cities from Taiwan were not considered. It should be noted that Urumqi and Lhasa are capital cities of Xinjiang Uyghur Autonomous Region and Tibet Autonomous Region respectively, as well as two important research centers in western China, hence, in order to show the whole Chinese geographical network, these cities are also represented in the following figures which describe the Chinese inter-city scientific cooperation network. However, Urumqi and Lhasa are two isolated research centers without other case cities within 1000 km, so it is considered that these isolated centers have no possibility to establish relationships with nearby centers. As a result, in order to avoid possible errors in the results in terms of the correlations between cooperation levels and distances, Urumqi and Lhasa are excluded from the numerical analysis.

The cooperatively authored paper data came from the international periodicals database of the Web of Knowledge (http://isiknowledge.com/), which is one of a new generation of web-based academic information resource integration systems. This database includes three famous citation databases (SCI, SSCI, and A & HCI), and data for more than 8,500 of the most influential academic journals in the natural sciences, engineering, social sciences, arts, and the humanities; as such, it embodies the level and internationalization of scientific cooperation, and can represent high-level international research cooperation between Chinese cities. Given these advantages, data obtained from the international periodicals database of the Web of Knowledge should be differentiated from that which could be sourced from the Chinese domestic database. It should be noted that this study addresses the amount of cooperatively authored papers between cities, which is only very slightly affected by the active population of individual researchers. Given that there is no relevant statistical data on this, standardized calculations used in this study do not reflect the active research population.

Methods

(1) Constructing the inter-city scientific cooperation matrix. Two types of cooperatively authored papers exist which reflect forms of inter-city scientific collaboration. One type results from situations where individual co-authors belong to different cities, and the exchange of knowledge among them is done across cities. The other occurs when one author works in two cities, and knowledge is exchanged through his or her own migration. From the sample survey, it was found that the probability of the latter situation occurring was only 0.6%, which can be neglected. Given that the number of cooperatively authored papers being produced between two cities can be explored via the Web of Knowledge, and that the degree of inter-city scientific cooperation can also be represented by the number of cooperatively authored papers between two cities (here considered to constitute an instance of cooperation), an inter-city scientific cooperation matrix can be constructed using data from the Web of Knowledge [29]. Here, five different matrices – covering the years 1999, 1995, 2000, 2005, and 2010 – were built (Table S1).

(2) Establishing the inter-city spatial distance matrix for all 58 cities. With the help of GIS to calculate the linear distance between the 58 city points, the spatial distance matrix was established. Considering the great changes seen in inter-city transportation distances in the latest 20 years, as well as the vast territory of China, this paper examines only straight-line distances. In the 58×58 matrix, the minimum distance is 19 km from Guangzhou to Foshan, and the maximum distance is 3,232 km from Haikou to Daqing.

(3) Constructing a distance-cooperation computing model to calculate the total amount of inter-city scientific cooperation per unit distance interval. Taking into account that the maximum distance between the selected cities is 3,232 km and the width of Chinese territory from north to south and from east to west is approximately 3,600 km, the selected
### Table 1. The 60 selected node cities and their rank of indicators.

| Name       | RAP | RCU | RGDP | RPS | RRDS | Name       | RAP | RCU | RGDP | RPS | RRDS |
|------------|-----|-----|------|-----|------|------------|-----|-----|------|-----|------|------------|-----|-----|------|-----|------|------------|-----|-----|------|-----|------|------------|-----|-----|------|-----|------|
| Beijing    | 1   | 1   | 3    | 1   | 2    | Hohhot     | 25  | 28  | 178  | 83  | 63   |             |     |     |      |     |      |
| Nanjing    | 2   | 13  | 27   | 11  | 14   | Guiyang    | 41  | 25  | 118  | 70  | 102  |             |     |     |      |     |      |
| Shanghai   | 3   | 4   | 2    | 2   | 1    | Fuzhou     | 38  | 21  | 43   | 23  | 28   |             |     |     |      |     |      |
| Guangzhou  | 5   | 3   | 6    | 4   | 3    | Yinchuan   | 27  | 35  | 236  | 82  | 150  |             |     |     |      |     |      |
| Wuhan      | 7   | 2   | 13   | 9   | 11   | Xuzhou     | 30  | 58  | 21   | 40  | 32   |             |     |     |      |     |      |
| Hangzhou   | 11  | 19  | 18   | 6   | 8    | Yantai     | 42  | 41  | 48   | 58  | 21   |             |     |     |      |     |      |
| Chengdu    | 10  | 13  | 4    | 12  | 9    | Ningbo     | 29  | 33  | 32   | 14  | 15   |             |     |     |      |     |      |
| X’An       | 8   | 8   | 22   | 7   | 27   | Tangshan   | 39  | 52  | 34   | 220 | 17   |             |     |     |      |     |      |
| Chongqing  | 4   | 7   | 1    | 13  | 7    | Changzhou  | 33  | 45  | 102  | 21  | 31   |             |     |     |      |     |      |
| Tianjin    | 9   | 6   | 5    | 8   | 5    | Guilin     | 28  | 45  | 83   | 78  | 108  |             |     |     |      |     |      |
| Changchun  | 6   | 24  | 31   | 20  | 36   | Xining     | 32  | 45  | 223  | 204 | 193  |             |     |     |      |     |      |
| Changsha   | 13  | 9   | 46   | 17  | 16   | Daqing     | 40  | 70  | 174  | 55  | 40   |             |     |     |      |     |      |
| Lanzhou    | 14  | 25  | 142  | 52  | 104  | Zhenjiang  | 53  | 81  | 164  | 47  | 57   |             |     |     |      |     |      |
| Zhengzhou  | 16  | 15  | 20   | 22  | 20   | Haikou     | 56  | 41  | 233  | 103 | 204  |             |     |     |      |     |      |
| Shenyang   | 15  | 16  | 28   | 19  | 19   | Luoyang    | 37  | 122 | 53   | 44  | 46   |             |     |     |      |     |      |
| Harbin     | 12  | 9   | 8    | 18  | 29   | Qinhuangdao| 48  | 70  | 170  | 180 | 139  |             |     |     |      |     |      |
| Jinan      | 19  | 5   | 50   | 16  | 23   | Jingzhou   | 58  | 45  | 165  | 76  | 161  |             |     |     |      |     |      |
| Kunming    | 24  | 18  | 54   | 42  | 53   | Uhasa      | 45  | 96  | 282  | 235 | 280  |             |     |     |      |     |      |
| Nanchang   | 22  | 11  | 89   | 32  | 47   | Lianyungang| 50  | 122 | 113  | 86  | 98   |             |     |     |      |     |      |
| Hefei      | 26  | 12  | 35   | 24  | 30   | Wenzhou    | 34  | 70  | 15   | 38  | 34   |             |     |     |      |     |      |
| Qingdao    | 21  | 25  | 19   | 15  | 12   | Baotou     | 52  | 45  | 189  | 54  | 39   |             |     |     |      |     |      |
| Dalian     | 17  | 22  | 51   | 29  | 18   | Foshan     | 43  | 122 | 40   | 25  | 13   |             |     |     |      |     |      |
| Suzhou     | 18  | 29  | 9    | 5   | 6    | Dongguan   | 44  | 81  | 25   | 31  | 22   |             |     |     |      |     |      |
| Urumxi     | 56  | 30  | 167  | 87  | 81   | Zhongshan  | 57  | 81  | 166  | 39  | 62   |             |     |     |      |     |      |
| Nanning    | 54  | 23  | 44   | 48  | 61   | Quanzhou   | 55  | 31  | 26   | 66  | 24   |             |     |     |      |     |      |
| Taiyuan    | 31  | 19  | 124  | 26  | 69   | Jiaxing    | 46  | 81  | 107  | 28  | 48   |             |     |     |      |     |      |
| Shenzhen   | 20  | 52  | 10    | 3  | 4    | Zhuhai     | 47  | 41  | 251  | 65  | 100  |             |     |     |      |     |      |
| Xiamen     | 23  | 31  | 147  | 35  | 52   | Baoki      | 51  | 122 | 137  | 91  | 124  |             |     |     |      |     |      |
| Shijiazhuang| 35 | 16  | 11    | 27 | 25   | Lanzhou    | 49  | 58  | 134  | 73  | 86   |             |     |     |      |     |      |
| Jilin      | 45  | 52  | 76    | 112| 71   | Wuxi       | 36  | 38  | 10   | 55  | 10   |             |     |     |      |     |      |

Sources: All data are from 2011, the explanation of Abbreviations as follows:
- **RAP**: Rank of number of articles published, obtained from CNKI.
- **RCU**: Rank of number of colleges and universities, obtained from the 2012 China City Statistical Yearbook.
- **RGDP**: Rank of GDP, obtained from the 2012 China City Statistical Yearbook.
- **RPS**: Rank of population size, obtained from the 2012 China City Statistical Yearbook.
- **RRDS**: Rank of number of R&D staff, obtained from the website of the National Bureau of Statistics of China’s 2011 R&D Census Report (http://www.stats.gov.cn/tjgb/rdpcgb/index.htm).

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distance range was from 0 to 3,300 km. Because the average width of Chinese cities is approximately 100 km, the inter-city spatial distance was divided into 33 intervals, each one being 100 km. The statistical model of the cumulative amount of inter-city scientific cooperation at different spatial distance intervals was established as follows:

Figure 1. Evolution of scientific cooperation network among 60 Chinese cities from 1990 to 2010. The line between the city nodes suggests the degree of scientific cooperation. doi:10.1371/journal.pone.0111705.g001
| City         | Degree Centrality |  |  |  | Betweenness Centrality |  |  |  |  |
|--------------|-------------------|---|---|---|-------------------------|---|---|---|---|
|              | 1990  | 1995  | 2000  | 2005  | 2010  | 1990  | 1995  | 2000  | 2005  | 2010  |
| Beijing      | 455   | 961   | 2342  | 7417  | 16480 | 465.70| 494.83| 292.34| 237.08| 32.35 |
| Shanghai     | 316   | 413   | 1041  | 3356  | 7408  | 254.48| 189.90| 205.13| 132.51| 29.87 |
| Nanjing      | 93    | 298   | 647   | 1997  | 4264  | 109.54| 212.60| 104.14| 205.13| 41.23 |
| Tianjin      | 57    | 81    | 325   | 1195  | 2193  | 65.46 | 1.12  | 35.72 | 83.62 | 12.66 |
| Guangzhou    | 31    | 17    | 305   | 1124  | 3853  | 51.62 | 2.90  | 126.14| 36.71 | 56.19 |
| Wuhan        | 50    | 156   | 441   | 1275  | 3230  | 14.54 | 61.43 | 35.35 | 115.31| 59.43 |
| Chongqing    | 3     | 28    | 96    | 224   | 1235  | 0.33  | 2.00  | 6.36  | 7.46  | 8.00  |
| Zhengzhou    | 4     | 16    | 89    | 229   | 1033  | 0.00  | 0.00  | 1.98  | 4.88  | 10.25 |
| Shijiazhuang | 11    | 30    | 94    | 270   | 585   | 1.40  | 0.00  | 1.10  | 13.01 | 6.90  |
| Tangshian    | 0     | 9     | 47    | 91    | 0.00  | 0.00  | 0.00  | 0.94  | 0.59  |
| Qinhuangdao  | 0     | 6     | 18    | 77    | 189   | 0.00  | 0.99  | 0.00  | 4.70  | 3.69  |
| Jinan        | 20    | 39    | 244   | 850   | 1582  | 10.09 | 10.36| 12.89 | 45.07 | 8.32  |
| Qingdao      | 10    | 6     | 71    | 573   | 1582  | 5.20  | 0.00  | 210.3 | 53.56 | 14.60 |
| Yantai       | 2     | 9     | 27    | 147   | 474   | 0.00  | 0.00  | 10.62 | 7.51  | 2.39  |
| Wuxi         | 0     | 16    | 21    | 126   | 459   | 0.00  | 13.70| 4.38  | 7.85  | 11.82 |
| Zhenjiang    | 2     | 7     | 8     | 80    | 398   | 0.75  | 0.00  | 0.00  | 10.03 | 6.27  |
| Changzhou    | 1     | 1     | 10    | 51    | 258   | 0.00  | 0.00  | 0.00  | 0.12  | 4.61  |
| Suzhou       | 20    | 24    | 100   | 241   | 863   | 11.07 | 10.91| 7.63  | 0.64  | 67.64 |
| Xuzhou       | 4     | 4     | 32    | 126   | 320   | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  |
| Liangyungang | 0     | 0     | 3     | 24    | 119   | 0.00  | 0.00  | 0.00  | 0.05  | 1.59  |
| Hangzhou     | 58    | 81    | 310   | 1347  | 2748  | 20.90 | 30.45| 102.15| 85.39 | 19.71 |
| Ningbo       | 0     | 24    | 29    | 203   | 511   | 0.00  | 0.71  | 0.00  | 1.89  | 11.84 |
| Jiaying      | 0     | 1     | 2     | 28    | 114   | 0.00  | 0.00  | 0.00  | 0.00  | 0.82  |
| Wenzhou      | 2     | 11    | 10    | 141   | 488   | 0.00  | 5.00  | 0.14  | 7.39  | 3.97  |
| Fuzhou       | 13    | 54    | 87    | 265   | 903   | 9.25  | 4.24 | 11.11 | 28.51 | 7.44  |
| Xiamen       | 4     | 37    | 62    | 206   | 814   | 0.60  | 4.97  | 3.22  | 8.57  | 13.28 |
| Quanzhou     | 0     | 1     | 4     | 48    | 69    | 0.00  | 0.00  | 0.00  | 1.26  | 0.18  |
| Shenzhen     | 1     | 1     | 26    | 258   | 1129  | 0.00  | 0.00  | 0.44  | 3.32  | 17.82 |
| Dongguan     | 0     | 0     | 6     | 14    | 100   | 0.00  | 0.00  | 0.61  | 0.26  | 1.12  |
| Foshan       | 0     | 0     | 6     | 28    | 62    | 0.00  | 0.00  | 0.00  | 0.52  | 0.98  |
| Zhongshan    | 1     | 3     | 4     | 8     | 68    | 0.00  | 0.00  | 0.39  | 0.00  | 0.29  |
| Zhumai       | 0     | 3     | 2     | 23    | 50    | 0.00  | 0.00  | 0.00  | 1.61  | 0.47  |
| Haikou       | 0     | 3     | 11    | 70    | 243   | 0.00  | 0.00  | 0.00  | 9.89  | 4.10  |
| Taiyuan      | 6     | 24    | 87    | 321   | 784   | 44.00 | 3.29 | 5.66  | 8.63  | 8.78  |
| City         | Degree Centrality | Betweenness Centrality |
|--------------|-------------------|------------------------|
|              | 1990 1995 2000 2005 2010 | 1990 1995 2000 2005 2010 |
| Luoyang      | 1 4 16 25 340     | 0.00 1.21 0.66 0.00 3.13 |
| Jingzhou     | 1 2 9 30 2        | 0.00 0.00 0.00 0.00 0.00 |
| Changsha     | 9 84 160 582 1749 | 1.87 19.43 20.02 21.72 14.54 |
| Nanchang     | 6 17 42 165 909   | 0.84 1.64 1.45 3.07 7.30 |
| Hefei        | 30 170 505 866 2100 | 46.80 16.37 70.02 17.96 14.40 |
| Harbin       | 12 49 127 496 1758 | 0.00 18.20 9.96 10.05 17.45 |
| Daging       | 2 2 7 61 202      | 0.00 0.00 0.00 0.27 0.43 |
| Changchun    | 23 124 363 835 2015 | 5.77 5.11 104.07 26.81 23.81 |
| Jilin        | 2 2 9 56 90       | 0.00 0.00 0.00 0.51 1.38 |
| Shenyang     | 80 196 272 918 1948 | 18.10 89.59 38.84 23.63 19.35 |
| Dalian       | 14 67 157 612 1505 | 1.46 68.73 27.28 14.31 9.16 |
| Hohhot       | 1 7 10 57 329     | 0.00 0.83 0.33 0.37 2.33 |
| Baotou       | 0 3 5 28 141      | 0.00 0.33 0.00 0.96 0.93 |
| Yinchuan     | 3 3 8 20 133      | 0.00 0.00 0.29 0.00 0.43 |
| X‘ian        | 13 26 307 701 2033 | 3.95 5.45 36.63 12.37 14.87 |
| Baoji        | 1 10 7 4 23       | 0.00 0.00 0.00 0.00 0.10 |
| Lanzhou      | 46 118 376 647 1720 | 8.08 22.91 33.18 14.74 12.85 |
| Xining       | 1 6 18 71 274     | 0.00 0.00 0.00 0.10 2.08 |
| Chengdu      | 40 116 339 763 2189 | 5.80 41.92 17.39 15.84 12.08 |
| Guiyang      | 7 8 74 169 426    | 0.45 0.13 2.99 4.65 4.12 |
| Nanning      | 15 13 29 309 646  | 0.00 18.27 0.00 19.71 9.89 |
| Liuzhou      | 0 0 1 13 67       | 0.00 0.00 3.18 1.65 3.16 |
| Guillin      | 2 3 35 272 444    | 0.00 0.00 0.34 0.92 7.03 |
| Kunming      | 19 32 206 515 1245 | 6.30 1.99 6.93 12.83 5.49 |
| Urumqi       | 7 3 41 134 570    | 0.00 0.00 0.34 0.92 7.03 |
| Lasa         | 0 0 0 6 1         | 0.00 0.00 0.00 0.00 0.00 |

Note: Local Centrality ($C_{ad}$) measures the ability of a city to carry out scientific cooperation with other cities, using the following formula:

$$C_{ad} = N_a \sum_{j} R_{ad}$$

where $R_{ad}$ is the intercity network connectivity degree between city a and city i.

Betweenness Centrality ($C_{ab}$) was used to measure the controlling degree of a city on scientific knowledge. Its expression is as follows:

$$C_{ab} = \sum_{j,k} \frac{G_{jk}(a)}{G_{jk}}$$

where $G_{jk}$ indicates the number of geodesic paths between city j and city k; $G_{jk}(a)$ describes the number of geodesic paths between city j and city k, which pass city a. The geodesic path is the strongest connective path between two cities.

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where, $N_i$ is the total number of cooperation in the $i$-th bin and $i = (1, 2, ..., B)$; $D$ is the maximum distance for all links between cities, and $B$ is the total number of bins. $l_j$ is the number of links between distances $D \times i/B$ and $D \times (i+1)/B$.

**Results**

**Scientific cooperation network evolution**

Combined with the city’s location, 60 inter-city scientific cooperation matrices using data from 1990–2010 were used to develop a number of spatial evolution diagrams of the inter-city scientific cooperation network (Figure 1) and to explore the spatial characteristics of the network evolution. Judging from the size of the network (including the number of nodes), 46 cities made up the 1990 network, accounting for 76.67% of the total selected cities. In the 1995 network, that number increased to 54, accounting for 90% of the total selected cities; and in the 2000–2010 network, all of the selected cities were included. From these results, we can conclude that the size of the higher-level inter-city scientific cooperation network in China is expanding constantly. With respect to the level of cooperation, the average annual growth rate in inter-city cooperation was found to be 123.78%, suggesting a double growth trend. Specifically, we found 1,382 instances of inter-city cooperation to have occurred in 1990, 3,420 in 1995, 9,692 in 2000, 30,644 in 2005, and 77,558 in 2010. From the structure of the cooperation network revealed by the study, the network developed greater sophistication over time – in 1990, it maintained an obvious monocentric structure (the center was Beijing), but by 2000, it had adopted a polycentric pattern. In 2010, it had further developed towards a homogenized structure, in which it is difficult to distinguish the center of the network.

**Figure 2. Effect of geographical proximity on city-to-city scientific cooperation in China from 1990 to 2010.**

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Centrality is a measure of the extent of a city in the city network, reflecting the degree of importance that a given city has in the network. By calculating the local centrality of all the cities in the Chinese scientific cooperation network over the 5 years addressed by this study (1990, 1995, 2000, 2005, and 2010), we found the overall level of the network to have grown. Further, most of the cities' local centrality was found to have increased, especially that of super-cities like Beijing, Shanghai, and Guangzhou, indicating that most cities' ability to carry out scientific cooperation has been enhanced during the study period. Meanwhile, the betweenness centrality results show that the capability of some super-cites like Beijing, Shanghai, and Nanjing to control knowledge decreased obviously, while such capabilities improved greatly in some regional center cities of Midwest China, like Wuhan, Chongqing, and Zhengzhou (Table 2). As a result, we can conclude that the Chinese scientific cooperation network gathers around the center, that it is developing as a regional network, and that cooperation between spatially close cities is increasing greatly.

On the whole, the inter-city scientific cooperation network in China was found to expand, to strengthen, and to become more complicated during the study period. However, given that the relationship between geographical proximity and scientific cooperation cannot be derived from the spatial features of network evolution, further study of the spatial distance and the amount of cooperation was required.

**The effect of geographical proximity**

To explore the relationship between geographical proximity and scientific cooperation, and the changes that occur in that relationship, a fitting analysis of inter-city scientific cooperation at different distances was undertaken. Each fitting function was constructed using data on the amount of inter-city scientific cooperation in 33 distance intervals across the 5 years that made
up the study period (1990, 1995, 2000, 2005, and 2010) (Figure 2). Initially, an analysis was made of all the years, and by accumulating the amount of inter-city scientific cooperation of five years at each distance interval, a fitting function was obtained: \( Y = -0.0285x + 0.9871 \). This is a linear function with a negative slope and a relatively high fitting degree of 0.8194 (\( R^2 = 0.8194 \)). The result indicates that the distribution of city nodes was in line with the distance-decay regularity – specifically, the closer the city nodes were, the greater the inter-city scientific cooperation was, and the farther apart the city nodes were, the lesser the scientific cooperation was. In this paper, the greatest inter-city scientific cooperation occurred within a distance of 100–200 km, cumulated to 24,059; the least amount of inter-city scientific cooperation occurred within a distance of 3,200–3,300 km, cumulated to 0.

Next, a fitting analysis of the distance and the amount of cooperation was undertaken to further investigate any changes in the effects of geographical proximity on inter-city cooperation. From the fitting function and its correlation coefficient (\( R^2 \)) for each year, the impact of geographical proximity on inter-city cooperation was found to gradually increase. In the years of 1990 and 1995, the correlation coefficients (\( R^2 \)) were 0.3724 and 0.3853 respectively, which indicated a weak correlation between distance and cooperation. In 2000, the correlation coefficient was 0.3724, indicating that the effect of geographical proximity had begun to manifest itself. In 2010, the correlation coefficient soared to 0.7926, suggesting a more significant influence. From the slope of each fitting function, the absolute values were 0.0192, 0.0189, 0.0262, 0.0309, and 0.0316 respectively, illustrating the way in which the effect of geographical proximity on inter-city scientific cooperation was enhanced, year-by-year.

**Spatial scales in distance decay**

By examining the changing curve between the amount of scientific cooperation and inter-city distance, and the accompanying distance-cooperation distribution data, the spatial scale features of the change process can be discussed. It can be seen from the curve that the amount of inter-city scientific cooperation does not decrease continuously with increasing distance, and although the trend is in line with the distance-decay regularity, it is not a perfectly declining curve.

Firstly, comparing the changing curves for the five years studied, spatial distance with a high value-point was found to move towards greater intervals. From the view of relative values, assuming that when the amount of cooperation reaches 1/10 of that year’s highest value on the curve, it is the high value. Thus, the distance corresponding to the last high value in the 1990 curve was 1,600 km, and the distance in each curve of the following 4 years was 2,100 km, 2,200 km, 2,400 km, and 2,500 km respectively, thereby demonstrating a year-by-year increase. From the view of absolute values, when the cooperation amount reaches 1,000, it is the high value. Thus, the highest value in 1990 and 1995 did not meet the standard; in 2000, the distance corresponding to the last highest value was 1,500 km; and in 2005 and 2010, the distance was 2,600 km and 3,100 km respectively – also indicating a year-by-year increase (Figure 3).

**Table 3. Comparison of cooperation increment in different years at different distances.**

| Year       | Absolute growth value at close distance | Absolute growth value at long distance | Relative growth value at close distance | Relative growth value at long distance |
|------------|----------------------------------------|---------------------------------------|----------------------------------------|---------------------------------------|
| 1990–1995  | 1623                                   | 1459                                  | 4.7117                                 | 2.4793                                |
| 1995–2000  | 12099                                  | 3429                                  | 6.0907                                 | 4.5184                                |
| 2000–2005  | 36464                                  | 15411                                 | 3.0477                                 | 6.0907                                |
| 2005–2010  | 150549                                 | 80757                                 | 3.9948                                 | 4.5184                                |

Figure 4. The increments of inter-city scientific cooperation within different spatial distances.
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Table 3. Comparison of cooperation increment in different years at different distances.
Secondly, it can be seen from the five-year cumulated change curve and the other graphs that two different distance intervals obviously existed, and within each of them, when the distance changed, the amount of inter-city cooperation changed, with significant differences. Specifically, within the distance interval of 1500 km, the amount of inter-city cooperation was found to fluctuate with increases in distance and to remain around 0.75, which indicates a weak distance decay; but outside that distance interval (i.e., beyond 1500 km), the amount of inter-city cooperation was found to decrease continuously with increases in distance, suggesting a significant distance decay. When undertaking a fitting analysis of the data in the latter distance interval, we obtained a linear function - $Y = -0.0443X + 0.7603$ ($R^2 = 0.3813$), showing a more obvious law of distance decay.

Thirdly, by comparing the increments of inter-city cooperation in the five different years studied, the spatial scale corresponding to the high increment values can be explored (Figure 4). In the period 1990–1995, the highest increment (500) appeared at 1,500 km, and an increasing trend was not obvious. During the years 1995 to 2000, the highest increment (553) occurred at 200 km, and the increasing trend was only slightly significant. From the years 2000 to 2005, the increasing trend changed greatly, and the highest increment (3,871) occurred at 1,200 km. And in the years 2005–2010, the increasing trend showed a ladder form, with the highest increment (8,965) appearing at 1,400 km. In addition, the increments fluctuated at 9,000 within the distance of 0–2000 km, which can be regarded as a high increment distance interval. Hence, it can be seen that a high increment of cooperation can occur at different distance intervals, and a significant possibility exists that newly developed inter-city scientific partnerships will develop within a distance of 2,000 km. From the relative increment, it can be inferred that the relation increment changed greatly at close range, where the average increment was also higher; further, the relation increment changed only slightly at a distance, and the average increment was also lower.

In addition, in order to compare the cooperation increment changes at different distances in different years (Table 3), the chi-square test was used to check whether significant differences existed between the two situations. Here, 1,500 km was regarded as the long-distance threshold, and the chi-square test results are shown in Table 4. Significant differences were found to exist between the long-distance and the close-distance cooperation increment in all the years. Given the actual growth witnessed in the cooperation increment, the close cooperation evidenced during 1995–2000 increased significantly faster than the long-distance cooperation, although the amount of collaboration occurring at a close range from 2000–2005 and 2005–2010 grew at a slower pace than the amount of long-distance cooperation. This suggests that the cooperation network has been developing towards a regional network structure, while obvious growth in distant cooperation appeared gradually.

### Table 4. The chi-square test of cooperation increment change in different years at different distances.

| Year                  | 1990–1995 and 1995–2000 | 1995–2000 and 2000–2005 | 2000–2005 and 2005–2010 |
|-----------------------|-------------------------|-------------------------|-------------------------|
| chi-square value      | 291.018*                | 1126.313*               | 169.058*                |
| Sig                   | 0.000                   | 0.000                   | 0.000                   |
| result                | Significant difference  | Significant difference  | Significant difference  |

Note: * 0 cells (.0%) have expected count less than 5.

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**Discussion**

Why does the influence of geographical proximity on scientific cooperation become stronger with the development of information technology? First, the essence of inter-city scientific cooperation lies in collaboration among researchers. For researchers’ cooperation, as social actors, another important factor of contact is social proximity [30], a measure which refers to the extent to which researchers can accept each other’s social habits, customs, and languages. An important prerequisite for social proximity is geographical proximity. Second, greater opportunities for scientific collaboration can occur among cities at a close range, and cooperation chances are more likely when two actors are in close vicinity [31]. Cities in close vicinity tend to have the same regional background, such as the same provincial government jurisdiction, urban agglomeration with close economic ties, the same ecological zone, and the same watershed, which relates these cities with more common concerns and scientific issues that need to be solved through their cooperation. Furthermore, cities in the same area tend to have a similar local knowledge pool [32], which has higher availability and will provide more opportunities for scientific cooperation. Third, inter-city internet communication and transportation infrastructures are both being developed simultaneously. According to statistics, China’s internet penetration rate has increased from 8.5% in 2005 to 45.8% in 2013, and the track traffic mileage has grown from 413 km in 2005 to 2,400 km in 2013. While internet communication infrastructure can be of great help in promoting scientific cooperation at different distances, transportation infrastructure benefits face-to-face scientific cooperation at close range. Therefore, the development of information technology not only provides greater chances for researchers to collaborate with their counterparts at a distance, but it also enhances inter-city scientific cooperation in the close vicinity. Knowledge spillovers, knowledge transfer, and scientific cooperation are more likely to occur between nearby cites [33].

Why does a significant difference exist between the changes in distant and in nearby inter-city cooperation? Why do spatial scales, or phases, exist in the distance decay of scientific cooperation? First, from the perspective of economics, knowledge transfer must have a geographic upper bound, largely because the marginal costs of knowledge transmissions increase with distance [34]. Hence, differences would exist between cooperation within certain geographical boundaries, and cooperation with the areas beyond those boundaries. Second, from the perspective of cultural geography, three types of knowledge diffusion exist, namely: contagious diffusion, hierarchical diffusion, and relocation diffusion, among which hierarchical diffusion should be the key factor in forming such scale features [35]. It is easier to shape a hierarchy for countries with large land area, such as China. Third, from the sociological point of view, when choosing collaborators in the same spatial scale, researchers are inclined to consider non-spatial distance factors, such as complementarity due to homogeneity issues or competitive factors [36], because of the same regional
background, social environment, and local knowledge atmosphere. Fourth, transport would be an important factor affecting scientific researchers in their decisions about how far they are prepared to travel to carry out face-to-face communication. Two major options are high-speed railways and air travel; the former mode of transport is the better choice in this case, due to its convenience and price. If the longest tolerable travel time is six hours and the average speed of a high-speed railway is 250 km/h, then the distance between two cities that can be accessed by high-speed railway is 1500 km – this probably explains why 1500 km was found to be the distance split point.

**Supporting Information**

**Table S1 The standardized number of cooperated papers between 60 Chinese cities.** A) in 1990, B) in 1995, C) in 2000, D) in 2005, E) in 2005.

**References**

1. Friedman TL (2005) The World is Flat: A Brief History of the Twenty-first Century. New York: Farrar, Straus and Giroux. 25 p.
2. Graham S (1998) The end of geography or the explosion of place? Conceptualizing space, place and information technology. Prog Hum Geog 22: 163–185.
3. Agnes P (2000) The “end of geography” in financial services? Local embeddedness and territorialization in the interest rate swaps industry. Econ Geogr 76: 347–366.
4. Dymski GA (2009) The global financial customer and the spatiality of exclusion after the ‘end of geography’. Camb J Reg Econ Soc 2: 267–285.
5. Gluecker J (2007) Economic geography and the evolution of networks. J Econ Geogr 7: 619–634.
6. Ben Letafa S, Rabue Y (2013) Too close to collaborate? How geographic proximity could impede entrepreneurship and innovation. J Bus Res 66: 2071–2078.
7. Boekema F (2007) Do firms benefit from spatial proximity? Testing the relation between spatial proximity and the performance of small software firms in the Netherlands. Reg Stud 41: 868–869.
8. Singh J, Marx M (2013) Geographic Constraints on Knowledge Spillovers: Political Boundaries vs. Spatial Proximity. Manage Sci 59: 2056–2078.
9. Kolympiris C, Kalaitzandonakes N (2015) Geographic scope of proximity effects among small life sciences firms. Small Bus Econ 40: 1059–1086.
10. Luhkins AE (2003) Does geographic proximity matter? Evidence from clustered and non-clustered aeronautic firms in Germany. Reg Stud 37: 453–467.
11. Abramovsky L, Simpson H (2011) Geographic proximity and firm-university innovation linkages: evidence from Great Britain. J Econ Geogr 11: 949–977.
12. Katz JS (1994) Geographical Proximity and Scientific Collaboration. Scientometrics 31: 31–41.
13. Xie N, Dugan E (2012) The Impact of Geographic Proximity of Children on Life Satisfaction among Aging Parents. Gerontologist 52: 125–135.
14. Brownell J, Xierali I, Herrera AP, Calvo A (2012) Geographic Proximity of HRSA, VA, and DOD Clinics: Opportunities for Intergency Collaboration to Improve Quality. J Health Care Poor Und 23: 125–135.
15. Griffith R, Redding S, Simpson H (2009) Technological Catch-up and Geographic Proximity. J Regional Sci 49: 609–720.
16. Agrawal A, Goldfarb A (2000) Restructuring Research: Communication Costs and the Democratization of University Innovation. Amer Econ Rev 90: 1578–90.
17. Hesse BW, Sproull L, Kiesler S, Walsh JP (1995) Returns to science: Networks and scientific research in oceanography. Communs of the ACM 36: 90–101.
18. Kamnski J, Kirby A (2012) Bibliometrics and urban knowledge transfer. Cities 29: S3–S8.
19. Yu Q, Shao HF, Duan ZG (2011) Research groups of oncology co-authorship network in China. Scientometrics 89: 533–567.
20. Liu C, Shan W, Ye J (2011) Shaping the interdisciplinary knowledge network of China: a network analysis based on citation data from 1981 to 2010. Scientometrics 89: 89–106.

**Data S1**

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**Author Contributions**

Conceived and designed the experiments: HTM CLF. Performed the experiments: HTM GDL. Analyzed the data: HTM BP. Contributed reagents/materials/analysis tools: HTM GDL. Contributed to the writing of the manuscript: HTM.