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Article

An analysis of the evolution of Chinese cities in global scientific collaboration networks: Manuscript prepared for special issue on 'China's internationalization and changing role in the world'

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An analysis of the evolution of Chinese cities in global scientific collaboration networks

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Abstract: This paper examines the emergence of China – now the world’s largest source of scientific publications – in global science from the perspective of the connectivity of its major cities in interurban scientific collaboration networks. We construct collaboration networks between 526 major cities (including 44 Chinese cities) for 2002–2006 and 2014–2018 based on co-publication data drawn from the Web of Science. Both datasets are analyzed using a combination of different centrality measures, which in turn allows assessing the shifting geographies of global science in general and the shifting position of Chinese cities therein in particular. The results show that: (1) on a global scale, the bipolar dominance of Europe and North America has waned in light of the rise of Asia-Pacific and especially China. Most Chinese cities have made significant gains in different centrality measures, albeit that only a handful of cities qualify as world-leading scientific centers. (2) The rise in connectivity of Chinese cities is therefore geographically uneven, as cities along the East Coast and the Yangtze River corridor have become markedly more prominent than cities in other parts of China. The uneven trajectories of Chinese cities can be traced back to changing institutional, economic, and geopolitical contexts. (3) Evolution in the global scientific collaboration network exhibits strong ‘Matthew Effects’, which can be attributed to the path-dependent nature of knowledge

production and preferential attachment processes in scientific collaboration.

Keywords: Global science, Scientific collaboration, Network centrality, Evolution, Network analysis, China

1 Introduction

The epicenter of global science has shifted several times throughout history, from Renaissance Italy to Britain, France and Germany, before crossing the Atlantic to North America in the early 20th century. Today, the geographies of global science are again shifting: the rapid emergence of Asia-Pacific as a new scientific powerhouse on the back of Japan’s earlier ascendancy makes it increasingly apt to speak about a tripolar world of science instead of the erstwhile North America-Europe near-duopoly. China is arguably the most notable new scientific hotspot (Xie et al., 2014). Since the onset of its reform and opening-up in 1978, the country has witnessed a wide range of profound economic and social changes. This includes a massive expansion of R&D investments, the reconstruction of higher education systems, policies toward fostering global engagement, and also a more prominent and significantly altered role for science. According to Web of Science data, China overtook the United States in terms of the total number of scientific publications in 2020 and has thus – from the perspective of the inter-state system – become the world’s largest source of science for this specific indicator.

A major driving force underlying the changing geographies of global science is the rise of multiscale scientific collaboration networks (Adams, 2012). Myriad country-level studies have shown that the rapid rise of China is evidenced not only by its increasing total scientific output, but also and perhaps above all by its fast-expanding cross-border collaborations (Gui et al., 2019; Leydesdorff et al., 2013; Ribeiro et al., 2018; Zheng et al., 2012). However, from a geographical point of view these are fairly crude assessments that may hide variegated patterns within countries. One way out of this conundrum is through city-level analyses as cities are key incubators of scientific production. For example, all the top Chinese

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research universities and institutes are concentrated in major urban areas (Cao et al., 2022; Andersson et al., 2014). Recent research has firmly established that the role of cities in the global economy is co-defined by their positions within multiple networks of interurban flows of capital, people and knowledge (Derudder & Taylor, 2018; Derudder & Taylor, 2020). Against this backdrop, this paper starts from the observation that the geographies of China's rise in global science can be illustrated and analyzed through its cities and their positions in interurban scientific collaboration networks.

Taking advantage of the co-publication data obtained from the Web of Science, we seek to further our understanding of the changing position of China in global science from the perspective of interurban scientific collaboration networks. We address three complementary questions: (1) How have the network positions of Chinese cities in global scientific collaboration networks changed over time? (2) What are the differences between Chinese cities in terms of their changing trajectories in global scientific collaboration networks? (3) How do these changes and differences in Chinese cities relate to their national/local economic and political contexts?

The remainder of this paper is organized as follows. The next section positions our analysis in the economic geography literature by reviewing the extant research on urban innovation, collaboration networks, and China's engagement in global science. The third section describes our data and methods. In the fourth section, we analyze the changing positions of Chinese cities in the global scientific collaboration networks. In the final section, we provide an overview of our major findings.

2 Conceptual background

2.1 Science and urban innovation

A limited number of cities/regions have become international symbols of knowledge-based development, which has led scholars and policymakers to explore the 'secrets' behind their success (Asheim & Coenen, 2005; Etzkowitz, 2012; Markusen, 1996; Liefner et al., 2021; Kroll & Neuhäusler, 2020). Economic geographers point to the (resurging) importance of space and place as key economic factors, highlighting that much of the variation across different cities/regions in performance and growth largely depend on a few relatively immobile and exclusive elements: knowledge bases, innovation capacity and institutional structures (Bathelt & Cohendet, 2014; Breschi &

Malerba, 2001; Cooke & Leydesdorff, 2006; Malmberg & Maskell, 2002). An extensive body of literature outlines the geographical dimensions of innovation and puts cities/regions at the center of innovative and entrepreneurial activities as providers of proximity, density and diversity that facilitate innovators to interact, collaborate and compete (Duranton & Puga, 2004; Florida et al., 2017). However, the processes of urban innovation and the mechanisms through which they foster urban economic growth and competitiveness are more complex than mere agglomeration economies undergirded by notions such as 'face-to-face' interactions or 'being there' (Asheim & Gertler, 2005). Studies on 'regional innovation systems' or 'triple helix clusters' adopt a systems approach to explain the geography of innovation and shed light on its inherent complexity (Asheim & Gertler, 2005; Cooke, 1992; Leydesdorff & Etzkowitz, 1996). The main proposition of this strand of research is that urban innovation is realized through combinations of different types of knowledge bases and a network of various actors, and underpinned by a place-specific institutional framework (Asheim & Coenen, 2006). In terms of knowledge bases, three different yet interrelated types of knowledge are involved in the processes of urban innovation across various industries and sectors: analytical (science-based), synthetic (engineering-based), and symbolic (creative-based) knowledge (Asheim, 2007). In terms of innovation actors, cities/regions can be viewed as densities in networks with three interconnected and interpenetrative dynamics: the intellectual capital of universities, the wealth creation of industries, and their participation in local institutions (Leydesdorff & Deakin, 2011).

Science has thus long been acknowledged as a fundamental component of the knowledge-based development of cities/regions. Basic research is not tied to a particular product or country and can be combined in unpredictable ways and used in different fields, which means that it often spreads more widely and remains relevant for a longer time than applied knowledge (Stephan, 1996). The relation and lag between basic scientific research and its economic added value is complex and extensive, but the impact is clear (Stephan, 1996). Asheim (2007) distinguished two different types of regional innovation systems, namely the institutional regional innovation system and the entrepreneurial regional innovation system. The institutional regional innovation system relies more on exploitive innovation around synthetic knowledge bases (engineering-based) and aims to further promote existing specialization advantages, as is often the case in German and Nordic regions. The entrepreneurial regional innovation system, in contrast, depends

on exploratory innovation with their analytical knowledge bases (science-based) and pursuing radical changes in emerging fields, such as Silicon Valley. Importantly, science-based innovation systems are more flexible and adjustable and are less likely to end up in ‘lock-in’ situations than traditional innovation systems evolving out of erstwhile technological trajectories (Asheim & Coenen, 2006). Today, some of the most disruptive enterprises such as Tesla and Neuralink are powered by the most cutting-edge and complex science. Thus, it could be argued that science-based knowledge is of importance for regional economic development.

A knowledge-intensive city/region is dependent on its universities, which are often viewed as a source of new technologies, skilled human capital, and new spin-off firms (Etzkowitz, 2012; Feldman & Kogler, 2010). For instance, MIT and Stanford play vital roles in Boston and Silicon Valley respectively, fostering a dynamic of science-based innovation with the concentration of intensive academic research generating regional economic effects through university-industry interactions and start-up enterprises. In these cases, universities are characterized by their entrepreneurship which become an explicit objective alongside teaching and fundamental research: transferring and commercializing science and technology (Etzkowitz, 2012; Leydesdorff & Zawdie, 2010). Universities are therefore not simply providers of basic scientific findings and technological breakthroughs in the early stages of knowledge creation. Rather, to ensure sustained innovation, industries might return to universities and access new sources of academic research when their technological paradigms are exhausted (Cai & Liu, 2015; Leydesdorff & Deakin, 2011).

2.2 Interurban collaboration networks and globalizing science

Urban settings facilitate local buzz and learning in knowledge creation processes (Florida et al., 2017). However, the knowledge stock of a city is limited, and sustained innovation cannot solely depend on the localized interactions among the same members in the same milieu (Bathelt et al., 2004). There is a danger of technological lock-in for cities when intraurban knowledge exchanges become crowded and redundant over time (Gargiulo & Benassi, 2000). This can be offset through interurban collaboration linkages, or ‘translocal pipelines’, as these can provide cities with opportunities and advantages that are not found within the local environment, including (1) opportunities to access new sources of external knowl-

edge, which is important in cutting-edge fields where science and technology change rapidly and drastically (Bathelt et al., 2004), and (2) access to a wider and larger pool of specialties and professionals (Kerr, 2010). Once a pipeline has been established, the partners at both ends can exploit the benefits through reciprocity, knowledge spillovers and unexpected inspiration and, simultaneously, externalize increasing costs, reduce information redundancy, and minimize the risk of lock-in (Batten, 1995).

Empirical studies have corroborated these theoretical observations: there is ample evidence that interurban knowledge collaboration can foster innovation at different geographical scales and in geographical entities by means of complementary mechanisms. For instance, drawing on co-patent data, Guan et al. (2015) found that the importance of a city in interurban collaboration networks is positively related to its innovation performance, with this relation moderated by inter-country collaboration networks. Drawing on co-publication data, in turn, Gui et al. (2018) found that countries with higher degree centrality, more structural holes and higher level of small-worldness present stronger innovation levels. Cao et al. (2022) examined the impact of interregional and intraregional scientific collaboration network on innovation capacity of Chinese cities based on co-publication data, and found that both types of collaboration links can promote cities’ innovation levels.

One key element of the rising importance of collaboration networks is that science today has become so big, and knowledge bases so complex, that many cutting-edge scientific breakthroughs are collective work emanating from large, well-funded teams involving many scientists in different cities across different countries – examples include the discovery of gravitational waves and the first picture of a black hole (Simonton, 2013). There is empirical evidence that internationally co-authored publications are on average more innovative and highly cited (Wagner et al., 2019). As this global scientific network is spatially organized and ordered, its geographical patterns are often utilized to illustrate and explain the uneven development of global science (Hennemann et al., 2012). Drawing on co-publication data, many scholars have found that the global share of interurban and international co-authored scientific publications has increased significantly (Leydesdorff et al., 2013; Ribeiro et al., 2018; Wagner et al., 2017), even though there is also evidence that the lion’s share of scientific collaboration is still domestic (Maisonobe et al., 2016). Maisonobe et al. (2016) found that cities in developing economies rely more on international collaboration than those in developed economies, suggesting the impor-

tance of accessing global scientific collaboration networks in the processes of building and promoting national innovation systems.

2.3 Global engagement of Chinese science

China's rise in global science since the reform and opening-up in 1978 has been nothing short of remarkable. Prior to that, the national science system was severely devastated by the political turmoil during the Cultural Revolution (1966–1976). Universities, colleges and research institutes, which are often seen as places of free speech and new ideas, were closed, dismissed and abandoned. Scientists, academics and educators were widely persecuted. Upon becoming China's leader in 1978, Deng Xiaoping started rebuilding the national science and higher education systems by emphasizing that 'science and technology are the primary productive forces'. This also entailed exploring a strategy of 'global engagement for national purposes', integrating global participation and national enhancement in the national science system (Marginson, 2021a). Similar to his more tolerant attitude toward the market economy and global engagement, he encouraged Chinese research institutes and scientists to engage in global scientific communities as long as they were under the party's control within China (Vogel, 2011). The Chinese science and higher education system especially started undergoing tremendous changes from the mid-1990s to the early 2000s onwards. The number of college students and researchers have significantly expanded since the central government shifted its policy of elite higher education to that of mass higher education. Meanwhile, there was a strong wave of recentralization processes in which the Chinese government merged hundreds of specialized colleges into dozens of large, comprehensive research-oriented universities with the purpose of 'building world-class universities' (Huang, 2015). This practice can be seen as a policy package aiming at steering and promoting engagement in global science, including urging academics to increase both the quantity and quality of publications in international journals, sponsoring researchers and students to go abroad for scientific training and collaboration, attracting Chinese returnees or foreign professors from overseas, and increasing international exchange students to/from other countries (Yang & You, 2018).

Because of China's top-down system and political control over science and education, the top research universities that have been assigned with missions to build world-class universities are exclusively concentrated in

(provincial) capital cities or more economically developed cities. These cities constitute the backbone of the Chinese scientific system (Andersson et al., 2014). Based on Web of Science data, the number of scientific publications produced in the 34 (provincial) capital-level cities accounted for 86.61 % of the national total in 2020. More recently, many Chinese cities, such as Beijing, Shanghai, Guangzhou and Nanjing, declared their ambitions of building 'global innovative centers' with a series of policies aiming, among other things, at promoting openness to external sources of science and encouraging international scientific collaborations (Xie et al., 2014). From a network perspective, a city that occupies a more important and influential position in interurban scientific collaboration networks is more likely to access, share, and (re)combine the complementary and heterogeneous resources that are crucial for new scientific findings (Cao et al., 2022). As a consequence, it is reasonable to envisage that the geographies of globalizing science in general and the rise of China in particular can, to a large extent, be depicted and explained through its cities and the inter-urban collaboration networks through which they are interconnected.

3 Data and methods

3.1 Data

In the existing literature, co-publication data are widely used as proxy of scientific collaboration activities (Leydesdorff et al., 2013; Newman, 2001). Our co-publication data was obtained from the Web of Science Core Collection database. The publication data indexed in this dataset contain detailed information on author names and affiliations, which allows us to geolocate bipartite collaborative relations in publications. Because there is a time lag between actual research activities and publication date, we use 5-year time windows for 2002–2006 and 2014–2018. The reason we chose these periods is that, as mentioned before, the national science and higher education system started undergoing significant changes and had not stabilized until the early 2000s. We restricted our data collection to the three databases provided by the Web of Science: Science Citation Index (SCI) Expanded, the Social Sciences Citation Index (SSCI), and the Arts & Humanities Citation Index (A&HCI). In addition, only journal articles with at least two institutions located in different cities are retrieved. Meanwhile, we only retain research articles and manuscripts that are less clearly related to scientific inno-

vation: book reviews, retractions, corrections, et cetera, were excluded.

We based our selection of cities on the research carried out in the context of the Globalization and World City (GaWC) network. This leads to a total of 526 major cities, all of which are either capital cities, cities with a population of more than 1 million, or cities hosting a headquarter office of major producer services (Taylor & Derudder, 2016). There are 44 Chinese cities in the dataset. Between 2002 and 2006, 6,331,122 papers were indexed in the Web of Science, with researchers located in one of the 526 GaWC cities involved in 4,170,530 of them (65.87 % of the global total). Between 2014 and 2018 period, 70,129,349 papers were indexed in the Web of Science, with researchers located in one of the 526 GaWC cities involved in 54,834,137 papers (78.19 % of the global total). This suggests that the 526 selected cities are indeed major science hubs and can, to a large extent, depict the backbone of global science.

In our study, an interurban knowledge collaboration link is defined as the co-occurrence of two different cities in a publication (Neal, 2014). Consequently, a publication involving n different cities has $n(n-1)/2$ interurban collaborative links. By aggregating individual collaboration links, we construct global scientific collaboration networks for both periods. The end product is a 526×526 matrix with $526 \times (526-1)/2 = 138,075$ valued dyads for both periods. In 2002–2006, there were 1,936,318 pairwise collaborative connections among the 526 cities, while there were 13,526,217 pairwise collaborative connections in 2014–2018. It is worth noting that not only international but also intranational collaboration linkages of cities are included in the calculations, as the interpretations of cities' importance in the global scientific collaboration networks should be embedded in the contexts of their respective national innovation systems.

3.2 Degree centrality as a measure of cities' positions in global scientific collaboration networks

Topologically privileged cities in global science are at the center of networks of knowledge, putting other cities in a state of dependence (Sheppard, 2002). In many empirical studies on innovation networks, degree centrality is arguably the most prominent indicator of cities' connectivity. Degree centrality measures the number of direct partners a city has in the collaboration network. In the context of an interurban scientific collaboration network, degree centrality of a city can reflect its importance, pri-

ority and power in accessing, sharing and integrating different sources of knowledge (Ahuja, 2000; Gui et al., 2019; Matthiessen et al., 2010). To facilitate comparison of cities' relative position, degree centrality is expressed as a percentage of the most connected city, so that it ranges from 0 % (no collaboration links) to 100 % for London (the most connected city).

3.3 Standardized change of degree centrality

We apply a measure of 'standardized change' developed in Derudder et al. (2010) to investigate the shifting patterns of cities in the networks. The reason for adopting this measure rather than directly comparing cities' degree centrality for the two periods is that neither absolute nor relative measures allow for a clear-cut analysis of change: all cities have gained much connectivity in absolute terms, while London cannot increase its degree centrality in relative terms as it has a value of 100 % in both periods. The measure of 'standardized change' tackles this problem by gauging a city's change relative to the entire distribution. The standardization consists of two consecutive transformations. First, we calculate the standardized degree centrality of cities (SDC) for both periods:

$$SDC_a = \frac{n \cdot DegreeCentrality_a - \sum_i DegreeCentrality_i}{\sqrt{n \cdot \sum_i \left[DegreeCentrality_i - \frac{1}{n} \sum_i (DegreeCentrality_i) \right]^2}} \quad (1)$$

For both periods, this operationalization generates an open number sequence pivoting on zero. Second, the standardized degree centrality change (SDCC) is obtained by another standardization procedure based on changes of standardized degree centrality between two periods:

$$SDCC_a = \frac{n \cdot [SDC_a(2014-2018) - SDC_a(2002-2006)] - \sum_i [SDC_i(2014-2018) - SDC_i(2002-2006)]}{\sqrt{n \cdot \sum_i \left[[SDC_i(2014-2018) - SDC_i(2002-2006)] - \frac{1}{n} \sum_i [SDC_i(2014-2018) - SDC_i(2002-2006)] \right]^2}} \quad (2)$$

Through these transformations, the standardized change of degree centrality can be understood as a z-score. For example, cities with positive values larger than 2 have witnessed exceptional gains of degree centrality compared to the rest of the distribution, while cities with a value of 0 have witnessed connectivity change perfectly in line with overall patterns of change in the distribution. Note that

this is a distribution-standardized measure: a negative value does not imply a city has fewer collaborative links, but rather that the rise in the number of links in this city has been less profound.

3.4 Other centrality measures as complements

In addition to degree centrality, other types of centrality metrics are widely applied to examine the positionality of cities in urban networks, such as eigenvector centrality, betweenness centrality, and closeness centrality. Different measures of centrality reflect different dimensions of cities' network features and can be used to assess the different positions they occupy and the roles they play. Eigenvector centrality weights a city's degree centrality proportional to that of its direct partners so that cities strongly connected to other central cities are proportionally more central than those tied to less central cities. Betweenness centrality examines the extent to which a city acts as an intermediary and its function as a gatekeeper in knowledge exchange between separated communities. Closeness centrality describes the mean of the shortest geodesic distance of a city to other cities, reflecting its connectivity to other knowledge pools. In this study, these three different centrality measures are used alongside degree centrality to capture the changing positions of Chinese cities in the networks. All centrality measures are normalized by dividing each by their respective maximum values and expressing this ratio as a percentage.

4 Changing positions of Chinese cities in the global scientific collaboration networks

4.1 Changing positions of top Chinese cities: Beijing, Shanghai, Taipei, and Nanjing

Figures 1(a) and (b) show the geographical patterns of the global interurban scientific collaboration networks in both periods. Nodes in the maps denote cities, with node size proportional to their degree centrality. Edges denote the interurban collaborations with edge thickness scaled to the number of co-publications between two cities. During 2002–2006, the network showed a globally dispersed yet regionally concentrated geographical pattern.

At the global scale, two core regions – North America and Europe – formed a bipolar or trans-Atlantic axis in the network. The degree centrality of cities in the two core regions accounted for 76.32% of the global total. However, during 2014–2018, the global pattern of scientific collaboration underwent some major changes. The number of cities involved in international collaboration increased from 499 to all 526, while the total number of bilateral ties among cities also witnessed a significant rise from 50,875 to 85,664; meanwhile, the average degree centrality increased from 7,823.50 to 43,511.98, and the network density increased from 0.42 to 0.70, which corroborates earlier research pointing to the extensive and intensive globalization of science (Gui et al., 2019; Leydesdorff et al., 2013; Wagner et al., 2017). In addition, the rise of cities in the Asia-Pacific region and the Global South was prominent, and the global scientific collaboration network once dominated by the Europe–North America duopoly has been gradually replaced by a more multipolar structure with intense collaborative ties interlinking Europe, North America, Pacific Asia, but also Australia/New Zealand and parts of South America. The network also showed some modest signs of decentralization, as evidenced by a slight decrease in the Gini coefficient of the degree centrality distribution from 0.69 to 0.65 and the tie strength from 0.76 to 0.71.

Although all cities have witnessed significant gains in degree centrality, the growth is geographically uneven. Figure 1(c) illustrates the standardized change in cities' degree centrality. Asia-Pacific cities in general and Chinese cities in particular show positive standardized changes, suggesting that their growth in degree centrality has been faster than the average, while most North American cities show negative standardized changes, implying that their growth in degree centrality has been slower. European cities exhibit a mixed pattern, with Eastern European cities gaining prominence. Cities in Sub-Saharan Africa registered medium gains in connectivity; a similar pattern can be found in Latin America and South Asia.

Table 1 lists the most connected cities in the networks in both periods, also listing their population-weighted connectivity. The former indicates a city's overall scientific collaboration capacity, while the latter indicates the relative prowess of this collaboration capacity in light of its overall agglomeration capacity. In terms of connectivity, 8 out of 10 cities are located within North America and Europe, and most of the cities have remained the same in both periods. In terms of population-weighted connectivity, relatively smaller cities such as Boston, Baltimore, and Philadelphia stand out, showing their specialized roles in scientific research (networks). Beijing and Tokyo

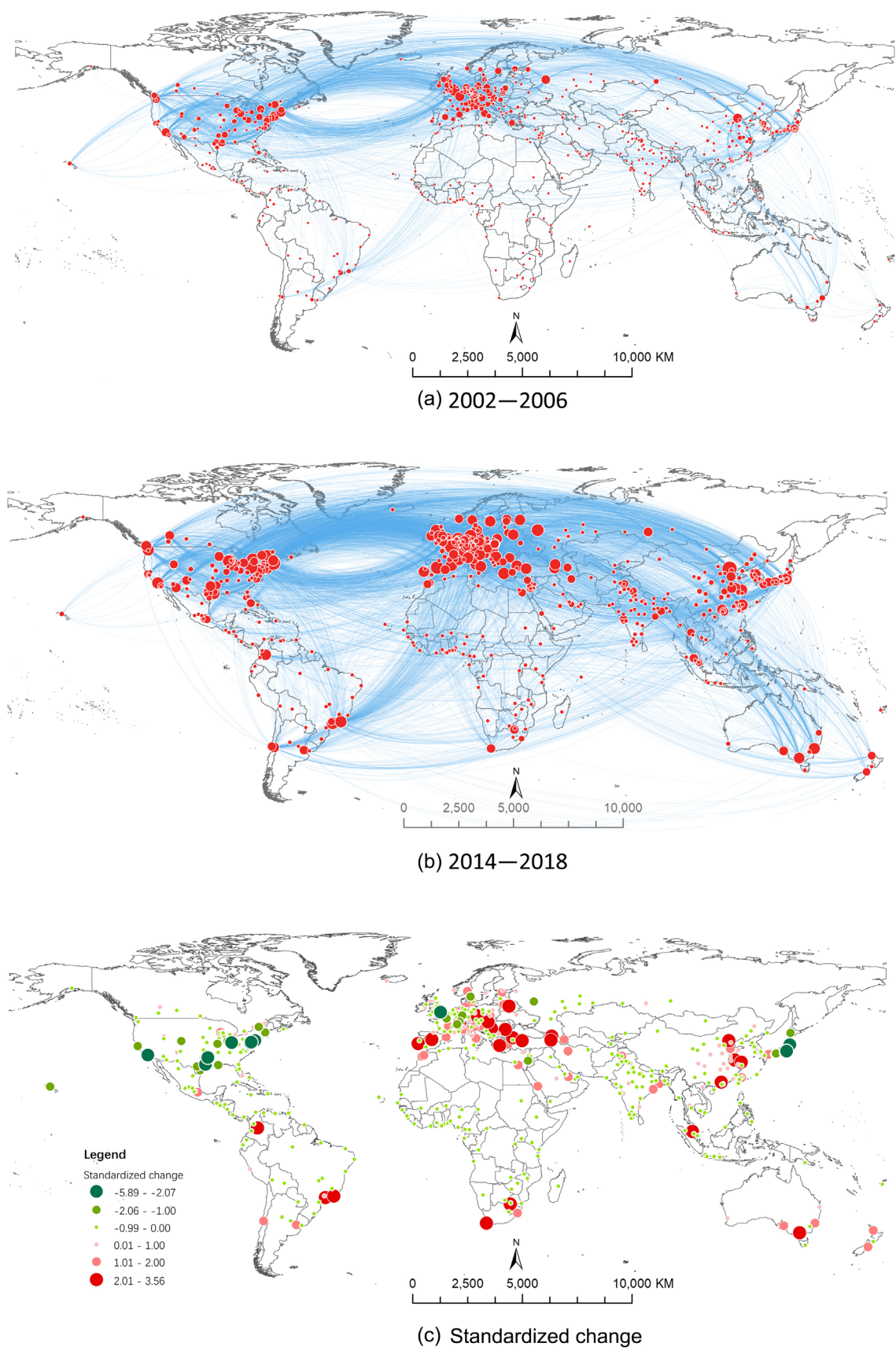


Figure 1: Distribution of cities' degree centrality and standardized change in the global scientific collaboration networks

are the only Asian cities making it into the top 10. Nonetheless, Beijing's rise from 6th to 2nd position stands out, and the city has been clearly become a hotspot for international scientific collaboration. As the nation's capital, Beijing houses China's most prestigious universities like Tsinghua University and Peking University, as well as its most important state-sponsored scientific organizations such as the Chinese Academy of Science. According to our dataset, in 2018, the Chinese Academy of Science and its affiliated university (University of the Chinese Academy of Science) produced 71,069 papers and accounted for 1.56 % of the global total, making it the most productive scientific institution not only in China but also around the globe. In addition, the control and coordination centers of China's scientific system, such as the Ministry of Science and Technology and the National Natural Science Foundation committee, which play a central role in global engagement and national building of Chinese science, are also located in the city (Marginson, 2021b). Because of this profound resource allocation and priorities of sharing national policy benefits, Beijing's collaboration links with scientists in other cities are much more developed (Andersson et al., 2014). Beijing's dominance in the networks evidences the important role of the top-down system and political decisions in shaping Chinese entanglements in global science. Another influential factor that is responsible for this pattern is the continued importance of *Guanxi*, the culture of interpersonal networking governing Chinese social practices. *Guanxi* networks are grounded in Confucian doctrines about the 'proper' structure of interpersonal relations in a community with mutual commitment, reciprocity, and trust, and which requires constant investment in the estab-

lishment and maintenance of personal bonds before any other collaboration, business, and political relations can develop (Chen & Chen, 2004). Jonkers (2010) found there is an intangible network connecting the most prestigious Chinese scientists in the most authoritative institutions who often hold great power in making decisions of the allocation of research funds and acceptance of papers in scientific journals. Thus, involving Beijing-based scientists/institutions in a project application or a manuscript would, to some extent, increase the possibility of success. Although there have been efforts to eliminate *Guanxi* in the scientific system for the past few years, it is still influential.

Shanghai's rise in the networks is also notable. Shanghai not only has a strong and globalized economic base and science-related resources, but is also a frontrunner in China's global engagement in science and technology. Shanghai was one of the earliest open port cities in colonial times, during which some Western powers established a number of missionary schools and hospitals that later evolved into some of the best universities in China, such as Tongji University (founded by Germans in the 1900s) and St. John's University (founded by Americans in the 1880s and split and merged into Fudan University, Shanghai Jiaotong University and East China Normal University in 1949). The colonial history is still influential in maintaining international collaborations among these top universities and their Western founders (Xu, 2006). Furthermore, since the reform and opening-up, an experimental development strategy called the 'exchange market for science and technology' has been explored on the east coast of China, within which Shanghai was one of the first beneficiaries. Relying on its locational advantage, vast hinter-

Table 1: Most connected cities in the global scientific collaboration networks

Rank	City	Connectivity% (2002–2006)	Connectivity per 1000 people	City	Connectivity% (2014–2018)	Connectivity per 1000 people
1	London	100.00	13.69	London	100.00	47.22
2	New York	77.76	7.38	Beijing	87.52	22.10
3	Boston	74.16	18.42	Boston	82.22	81.39
4	Tokyo	69.20	8.00	New York	79.91	18.10
5	Paris	68.40	6.98	Paris	69.16	26.97
6	Beijing	62.77	5.45	Chicago	56.39	27.13
7	Los Angeles	56.45	4.80	Rome	53.42	54.14
8	Baltimore	52.15	24.99	Madrid	53.36	35.26
9	Philadelphia	51.83	16.03	Milan	52.21	70.95
10	Chicago	48.76	5.88	Barcelona	48.38	37.79
...	...	...	...	...	...	...
	Taipei (48)	21.8	18.41	Shanghai (22)	39.4	18.77
	Shanghai (50)	21.6	6.49	Taipei (31)	36.7	28.12
				Nanjing (47)	29.9	15.63

Note: global rankings (top 50) of Chinese cities are in the brackets

land and favorable policies, Shanghai soon became the most attractive hotspot for foreign investments, through which it established close scientific and technological collaborations with transnational enterprises in the form of joint ventures. Today, in addition to investments, many transnational enterprises have set up R&D branches and facilities in Shanghai and have consolidated their R&D collaborations with Shanghai, which further enhanced Shanghai's position in the global scientific collaboration networks (Chen, 2006).

Taipei also registered significant gains. Of course, Taipei's (changing) position in global scientific collaboration networks is detached from the mainland system because of longstanding political conflicts. After the civil war in 1949, Taiwan embarked on the road to capitalism with investment and support from the US. During the 1960s to 1990s, it seized the opportunities of industry and technology transfers from developed countries earlier than the mainland, thus establishing an advantageous position in science and technology in Pacific Asia. In this process, Taiwan has built, maintained and been strengthening close collaborations with their western partners, especially in the fields of ICT (Liu et al., 2012). In the period 2002–2006, the US, Japan and European cities contributed the most external to Taipei's collaborations (68.14 %), while the mainland cities only contributed 18.06 %. Although the people-to-people non-governmental exchanges across the strait in the form of academic collaborations have been encouraged in recent years, the share of the mainland cities in Taipei's external collaboration linkages dropped down to 12.52 % in 2014–2018, implying the continuation of Taipei's relatively independent trajectory in terms of engagement in global science. This is also evidenced by the measure of population-weighted connectivity: in 2002–2006, the population-weighted connectivity of Taipei (18.41) is higher than that of Beijing (5.45) and Shanghai (6.49) – even though this gap narrowed in 2014–2018 – suggesting the scientific research activities in Taipei were more intensive than its mainland counterparts.

Nanjing's gain of degree centrality in the networks is also remarkable. In terms of economic scale, population size and geographical location, Nanjing is not comparable to Beijing, Shanghai and Taipei, or with some of the other first-tier cities in Mainland China. Nonetheless, Nanjing is often acknowledged as the city where China's higher education system originated, which can be traced back to the Han dynasty around 30 B.C. when the emperor set up the first higher education institution for Confucianism. During the Ming Dynasty, the Imperial College of Nanjing established by the empire was the largest higher education institution around the world in the 15th century, and

it was the first college that set up different disciplines. Meanwhile, Nanjing is also the birthplace of China's modern science and education: in the late Qing dynasty of the 1860s, a number of government-sponsored higher education and research institutions had been established in Nanjing during the 'Westernization Movement', aiming to introduce modern sciences and industries from Western countries. The influence of this historic legacy of education and science is profound. Today, Nanjing is the third most important city in terms of the number of higher education institutions and state-sponsored research institutions, following Beijing and Shanghai, and it is the second most productive city with respect to publications and patents.

In Table 2, we list the top cities according to the other three centrality measures (eigenvector, betweenness and closeness centrality) in the global scientific collaboration networks during the two periods. At first glance, all Chinese cities in the lists have witnessed growth in the three centrality measures, albeit in different ways. Compared to degree centrality, the major Chinese cities lose their relatively strong positions in the eigenvector centrality ranking. This suggests that although these Chinese cities have become more connected in the network, the collaborative partners they have established seem are on average less important. For example, in 2002–2006, the number of collaborative ties of Beijing between the other top 20 global cities (in terms of degree centrality) accounted for 13.23 % of its total, while this share was 37.09 % for New York and 43.67 % for London. By 2014–2018, however, the ranks of Chinese cities in eigenvector centrality have raised significantly, implying that they become not only more connected in the network but also more important to other well-connected cities.

In terms of betweenness centrality, Beijing towers over other Chinese cities, suggesting its strong broker function as a knowledge gatekeeper in the collaboration network, searching for and collecting external sources of new knowledge through 'global pipelines', while decoding and diffusing knowledge to its regional/domestic cities with 'local buzz' (Bathelt, 2007; Morrison et al., 2013). Interestingly, Hong Kong also presents a higher score in betweenness centrality albeit that this has decreased over time. The gatekeeping role of Hong Kong can be traced back to its relative political-institutional autonomy from the mainland control on the one hand, and its ongoing close connections with Commonwealth countries on the other hand (Ma & Li, 2018; Postiglione, 2013). In terms of closeness centrality, Beijing once again stands out, indicating its larger accessibility and informational advantage in the network. Two other mainland cities, Shanghai and Nanjing also have witnessed significant gains in closeness

Table 2: Other forms of centrality measures in the global scientific collaboration networks

2002–2006						
Rank	City	Eigenvector	City	Betweenness	City	Closeness
1	New York	100.0	London	100.0	London	100.0
2	Boston	94.6	Paris	61.4	Paris	93.8
3	London	88.3	Tokyo	52.7	Tokyo	91.4
4	Philadelphia	71.5	Washington	45.6	New York	91.2
5	Los Angeles	71.0	Geneva	43.1	Washington	91.0
6	Baltimore	69.6	New York	41.7	Atlanta	89.9
7	Chicago	65.8	Atlanta	41.2	Geneva	89.5
8	Paris	58.3	Boston	37.6	Boston	88.9
9	Houston	56.0	Beijing	37.6	Baltimore	88.2
10	Seattle	53.1	Newcastle	35.6	Montreal	88.1
...	...	...	...	...	...	...
	Beijing (22)	36.5	Hong Kong (36)	22.7	Beijing (18)	87.5
	Taipei (74)	16.2	Taipei (42)	20.2	Hong Kong (59)	85.4
	Shanghai (93)	13.6	Shanghai (53)	17.6	Taipei (69)	84.2
			Nanjing (55)	17.1	Shanghai (91)	78.6
2014–2018						
Rank	City	Eigenvector	City	Betweenness	City	Closeness
1	London	100.0	London	100.0	London	100.0
2	Boston	91.7	Beijing	89.5	Beijing	98.6
3	New York	90.9	New York	74.3	New York	98.6
4	Paris	69.3	Paris	73.6	Paris	98.4
5	Beijing	66.0	Washington	69.4	Washington	97.8
6	Chicago	62.7	Madrid	69.1	Boston	97.8
7	Milan	57.9	Boston	69.0	Atlanta	97.3
8	Rome	57.6	New Delhi	68.9	Toronto	97.3
9	Madrid	56.1	Atlanta	66.3	Tokyo	96.7
10	Barcelona	54.0	Barcelona	63.4	Madrid	96.5
...	...	...	...	...	...	...
	Shanghai (31)	36.9	Shanghai (19)	54.6	Shanghai (43)	90.8
	Taipei (44)	32.9	Hong Kong (59)	40.5	Hong Kong (56)	86.3
	Nanjing (59)	28.6	Nanjing (65)	39.4	Taipei (66)	85.7
	Hong Kong (99)	21.0	Taipei (69)	38.7	Nanjing (73)	83.8

Note: global rankings (top 100) of Chinese cities are in the brackets

centrality. In comparison, the changes of Hong Kong and Taipei are relatively modest and stable, implying that they have developed relatively fewer new partners (both direct and indirect) during our period of study.

4.2 Changing positions of other Chinese cities

Figure 2 presents the geographical patterns of (changes in) the degree centrality distribution of the 44 Chinese cities. In 2002–2006, cities with notable degree centrality were mainly located in well-developed coastal megaregions on the Mainland, including the Beijing-Tianjin-Hebei region, the Yangtze River Delta region, and the Guangdong-Hong

Kong-Macao Greater Bay Area. This is not surprising because the three coastal regions not only have stronger economic bases and science-related resources but were also the first movers involved in a series of national experiments related to opening-up and global engagement. Since the opening-up in 1978, an experimental development strategy called ‘exchange market for science and technology’ was explored in Guangdong province, by which external capital and technologies mostly from Hong Kong and Taiwan were encouraged and introduced under the form of joint-venture enterprises. The success of this strategy implied that it was soon implemented in the Yangtze River Delta and Beijing-Tianjin-Hebei regions. For the past few decades, the three regions have witnessed significant progress in science and technology and have been

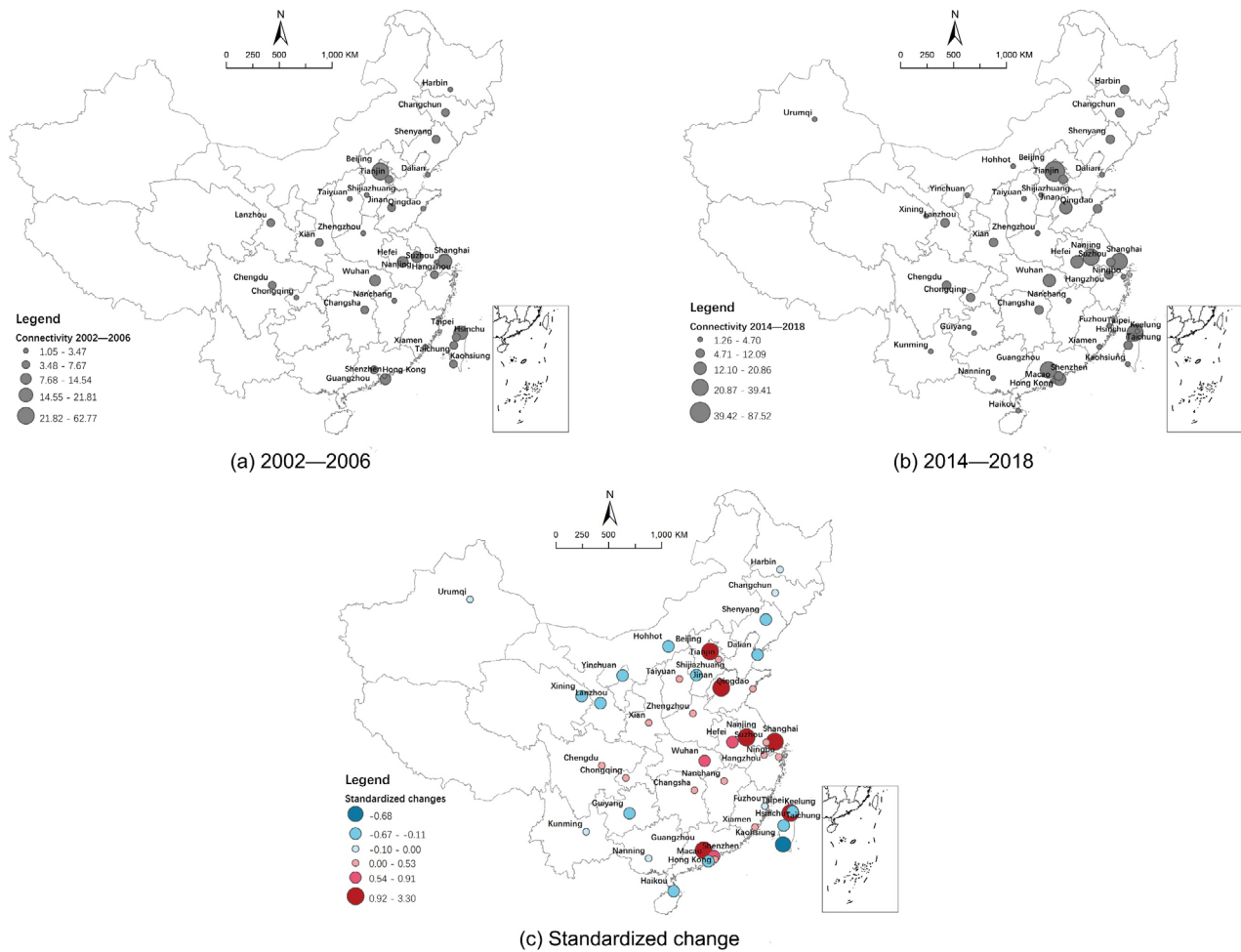


Figure 2: Distribution of cities' degree centrality and standardized change in Chinese urban system

transforming from ‘world factories’ into ‘world innovators’ in recent years.

Meanwhile, some cities in western and northern China are also fairly well connected to the network, such as Chongqing, Xi'an and Lanzhou in the west, and Shenyang, Changchun, and Harbin in the north. These cities lack the above-described locational advantages and have lost part of their economic significance after the opening-up. They once hosted some of the most important scientific institutions and advanced industrial sectors in the early years of the Communist Party regime. After the collapse of the Sino-Soviet alliance in 1962 and the ensuing hostilities, the Chinese government was forced to adopt a ‘third front’ defense strategy that consisted of relocating some of the nation's heavy industries and top-secret sci-tech institutions, particularly military-related, to peripheral mountainous or deserted regions to elude possible military attacks. Even today, these ‘remote’ cities still hold great advantages in some specific sectors, such as automobile and aircraft engineering, nuclear science, and space

technology, and therefore have maintained their places in scientific collaboration networks.

In 2014–2018, all cities registered observable growth in degree centrality, yet the overall structure of its geographical pattern did not fundamentally change. The overall gains of degree centrality of Chinese cities do not necessarily mean they have been integrating into the global scientific collaboration network at the same pace. The results of standardized change show that ‘faster’ gains are mostly concentrated along the east coast and the Yangtze River. However, there is an exception: as a core city in the Beijing-Tianjin-Hebei region, Shijiazhuang shows signs of declining importance. This finding implies that Beijing, although it is the most connected city in the network, provides limited benefits and spillovers to its regional neighbor and casts something of an ‘agglomeration shadow’ that impedes balanced regional development (Cao et al., 2022).

In addition to the coastal regions, cities in the middle and upper reaches of the Yangtze River also showed

sizable connectivity gains, above all Wuhan, Changsha, Hefei, Chengdu, and Chongqing. Although these cities did not benefit from the earlier stages of the opening-up policy, in the past two decades they have started benefiting from nationwide rebalancing strategies, such as ‘The Rise of Central China’ and ‘The Development of the Western Region’. These plans aimed at narrowing the economic gap with the eastern parts of China and included an emphasis on knowledge transfers from the east. More recently, a newly issued transregional plan by the central government – ‘Outline of Yangtze River economic belt development’ – is designed to pursue a balanced, integrated, and sustained regional economy. One of its main goals is to accelerate the knowledge spillovers of the Yangtze River Delta region towards regions alongside the middle and upper reaches, while exploring and incubating new opportunities for science and technology advancement in those regions. For instance, with a large scale of investment and preferential policies, Wuhan has now become China’s most innovative and productive center for photoelectron science and related industries; Chongqing has also emerged as a new frontrunner in computer science, information technology and integrated circuit industry.

Furthermore, cities like Zhengzhou, Xi’an, and Taiyuan have also recorded observable connectivity gains, although they have not yet been targeted by national-level strategic plans. A possible explanation is that the intensification of local investments, the densification of infrastructure networks, and the relative geographical proximity to the coastal areas and Yangtze River (Delta region) enable them to benefit from those developed regions in many respects, such as knowledge spillovers, mobility of scientists, and investments.

The remainder of the cities, which are distributed across less-developed inland or peripheral areas, show different degrees of decline in standardized degree centrality, meaning their integration into the global scientific collaboration network is relatively ‘slower’. Taken together, the changing geography of the degree centrality of Mainland cities in collaboration networks parallels the development trajectory of China’s science and China’s economy at large.

Finally, the importance of Taiwanese cities in the network has declined significantly, except for Taipei. This should of course be interpreted carefully in light of the longstanding political conflict and differences in socio-institutional contexts between Taiwan and the mainland. Unlike mainland cities, Taiwan’s science capacity did not start from scratch, as some of the Western countries had been continuously providing scientific and technological input since the Kuomintang party retreated from the mainland to Taiwan in 1949. Thus, the margins of further con-

nectivity gains for Taiwanese cities are relatively smaller than for mainland cities.

5 Conclusions

In the past four decades, China has become a major contributor to global science and therefore an important player in global scientific collaboration networks. Prior to the 1980s, world science was dominated by the Europe-North America duopoly. Against the backdrop of economic globalization, informatization, and the rise of ‘big science’, a number of erstwhile developing countries, particularly China, have put tremendous efforts into engaging global science through collaboration, fostering a more complex multipolar global scientific landscape. The rise of China in global science rests on sustained high investment by the state since the reform and opening-up, targeted deployment of international connections, and focused national system building (Marginson, 2021a). China’s role in global science has been widely debated in bibliometric studies, yet it is still insufficiently understood from a geographic perspective.

Cities are science generators, as they provide both tangible and intangible assets for knowledge creation (Duranton & Puga, 2004; Florida et al., 2017). However, in era of ‘big science’, building translocal collaboration linkages is necessary as the local knowledge stock of a city is limited (Bathelt et al., 2004). Therefore, positionally advantaged cities in a broader interurban collaboration network are at the center of, and control, networks of knowledge (Matthiessen et al., 2010). This study used this as a starting point to investigate the evolution of China’s role in global science through the lens of interurban scientific collaboration networks. The results reveal several trends. First, on a global scale, the shift of gravity of the global scientific collaboration network from the Europe-North America duopoly towards Asia in general and China in particular is very visible. Based on the measure of degree centrality and closeness centrality, Beijing, Shanghai, Taipei and Nanjing occupy important positions in the network. The eigenvector centrality measure, however, suggests that their importance in the network is largely derived from collaborations with less-connected cities. The results of betweenness centrality reveal Beijing and Hong Kong’s roles as China’s knowledge gatekeepers.

Second, the wholesale rise in connectivity of Chinese cities is geographically uneven. Beijing in particular and cities along the east coast and the Yangtze River more generally have gained more significance than other parts

of China. The development trajectories and the changing geographical pattern of Chinese cities in the global scientific network are embedded in China's changing institutional, economic, and geopolitical contexts (Andersson et al., 2014).

Third, although there are ups and downs among cities in the global scientific network and China's national system, the overall structure of the Europe-North America duopoly and East Coast-Yangtze River corridors have not been fundamentally changed (Gui et al., 2019). In the global scientific collaboration network, different cities are interconnected by collaborative links among researchers through which heterogeneous scientific knowledge elements across different technological, sectoral, regional and national contexts are combined and recombined (Strambach & Klement, 2012). Although knowledge is sometimes believed to be easily transferred across geographical space in the age of globalization and informatization (Castells, 1996), empirical evidence suggests that urban resources include place- and context-specific knowledge of both tacit and codified nature that is largely geographically immobile, so that the landscape of science is spiky rather than flat (Asheim & Isaksen, 2002). Existing scientific knowledge is a building block for further knowledge accumulation and production. The cumulative and path-dependent nature of scientific production accounts to a large degree for the spatial concentration of scientific activities in which cities specialize in particular scientific fields (Heimeriks & Boschma, 2013). This process is accompanied by the ever-growing global research networking and the 'preferential attachment' mechanism therein (Wagner & Leydesdorff, 2005), which tends to favor a small group of world-class scientific hubs (Gittelman, 2007; Matthiessen et al., 2010). Therefore, the evolution of cities in the global scientific collaboration network presents a self-reinforcing 'Matthew Effect'.

We acknowledge this study has several limitations and blind spots, some of which can be addressed in future research. First, co-publication data only captures a specific part of scientific collaboration activities, and we only collect those linkages from the subset of Web of Science indexed papers. Data on exchange scholars and co-funding projects could be employed to enrich the future research. Second, there is plenty of evidence that cities' connectivities in collaboration networks are closely – even if unevenly so – related to their economic size, and this could be further examined through explanatory models.

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