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Articulating China's Science and Technology: Knowledge Collaboration Networks Within and Beyond the Yangtze River Delta Megalopolis in China

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Abstract: In this paper, we reconsider the defining but often overlooked 'hinge' function of megalopolises by analyzing how megalopolises have articulated national and international urban systems in the context of a globalizing knowledge economy. Taking the case of China's Yangtze River Delta (YRD) region, we particularly focus on knowledge circulation within and beyond the YRD region by analyzing the pattern and process of knowledge collaboration at different geographical scales during the 2004–2014 period. Results show that the structure of scientific knowledge collaboration as reflected by co-publications has been strongest at the national scale whereas that of technological knowledge collaboration as measured by co-patents has been strongest at the global scale. Despite this difference, the structure of both scientific and technological knowledge collaboration has been functionally polycentric at the megalopolitan scale but become less so at the national and global scales. The 'globally connected but locally disconnected' pattern of Shanghai's external knowledge collaboration suggests that the gateway role of the YRD megalopolis in promoting knowledge collaboration at different geographical scales will take time before it is fully realized.

Keywords: urban network; publication; patent; scale; gateway; Yangtze River Delta (YRD)

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1 Introduction

In a globalizing knowledge economy, it seems increasingly unlikely for individual cities or regions to be economically self-sustaining without reference to external sources of knowledge. To generate leading-edge knowledge, economic entities within individual regions usually need to rely upon both intra-regional and inter-regional collaboration. Here regions as economic agglomerations can be recast as a matter of 'local buzz' (internal collaboration) in 'global pipelines' (external collaboration) (Bathelt et al., 2004). In this sense, a high-level access to external (regional, national, and global) sources of knowledge is arguably of great significance to the competitiveness of regional economies (Amin and Thrift, 1995; Simmie, 2003; Bathelt et al., 2004; Coe et al., 2004).

From an urban network perspective, one approach to capturing the significance of external knowledge connectivity to regional development is providing an analysis of urban networks based upon intercity knowledge linkages. Within this literature, most studies have focused upon either national knowledge networks (Lv and Li, 2010; Lu and Huang, 2012; Andersson et al., 2014; Ma et al., 2015) or global knowledge networks (Matthiessen et al., 2002; 2010). Whereas these studies have benefited our understanding of knowledge circulation and transfer at the national and global scales, relatively

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little attention has been paid to knowledge networks at the megalopolitan scale and knowledge collaboration within and beyond megalopolises. The overlooking of this research field also exists in the recent resurgent interest in urban functionality and polycentric urban regions (PURs) which has mainly focused upon intercity firm linkages (Taylor et al., 2008; Hanssens et al., 2014): people flows (De Goei et al., 2010; Burger and Meijers, 2012) and transportation connections (Liu et al., 2016). Notable exceptions in this regard include the study of Wu and Lu (2015) which analyzes the network structure of knowledge interactions within the Yangtze River Delta (YRD) megalopolis based upon a gravity model and the studies of Li and Phelps (2016; 2017) that explore the patterns and processes of knowledge collaboration within and beyond the YRD megalopolis by drawing upon data on co-publications.

Exploring knowledge circulation within and beyond megalopolises is theoretically well-grounded. In fact, one can find its theoretical origin in the two defining but often overlooked functions that Gottmann (1957; 1961; 1976) ascribed to megalopolises—their being an 'incubator' of new knowledge and trends within national urban systems and a 'hinge' that articulates between national and global urban systems through trade linkages, cultural exchanges, and people flows. It is these two functions that have made megalopolises precisely fascinating in a globalizing knowledge economy. However, whereas Gottmann's legacy has been mainly conceived as contributing to debates on large-scale urbanized forms (Harrison and Hoyler, 2015), recent studies on economic functionality of urban networks have also largely neglected the articulation of PURs between national and global innovation systems. Nonetheless, Gottmann is not alone and the value of the hinge function of megalopolises has been recognized in recent years from several other perspectives. For instance, some studies in the world city networks literature have touched upon the articulation of world city networks with national and regional urban systems as can be reflected by the discussion of gateway cities (Rossi and Taylor, 2005; Hennemann and Derudder, 2014) and the relationship between world cities and their national urban systems (Ma and Timberlake, 2013). Other studies have highlighted the significance of megalopolises' relationships with the global or extra-local economy from the perspectives of economic development of urban regions (Scott, 2001; Florida et al., 2008): urban agglomeration economies (Phelps and Ozawa, 2003): and the globalization/city relationship (Short et al., 2000; Nijman, 2011).

Against the background of China's implementation of two national-level strategies of building an innovation-driven economy and promoting the development of urban agglomerations, analysis of knowledge collaboration within and beyond megalopolises is also of great practical significance as it integrates both strategies. In its 'Thirteenth-Five Year Plan (2016–2020)' and 'the Guidelines of National Innovation-Driven Development Strategy (2016)', the Chinese central government has indicated its commitment to promoting flows of innovation resources within some relatively developed urban agglomerations like the YRD megalopolis. The commitment can be also reflected by the recent promulgation of 'the Planning for the National Innovation Demonstration Area of Southern Jiangsu Province (2015–2020)'① which is the first national innovation demonstration area plan based upon urban agglomerations. Although these policy documents mainly focus upon facilitating intra-regional knowledge flows, it is natural to ask how megalopolises have contributed to China's integration into global knowledge systems since China has emerged as one of the world's leading countries in scientific and technological publications (National Science Board, 2016). In fact, some studies in the world city networks literature have already touched upon the integration of some major Chinese cities into world city networks through the lens of intra-firm linkages (Derudder et al., 2013).

By analyzing both scientific and technological knowledge collaboration, the current paper also seeks to extend the existing studies of Li and Phelps (2016; 2017) which have only focused upon analysis of scientific knowledge collaboration. While scientific knowledge is usually biased towards pure and science-oriented research and involves more codified knowledge, technological knowledge is often of applied and market-oriented nature and involves more tacit knowledge

① Southern Jiangsu Province is a key part of the Yangtze River Delta megalopolis which contains five cities: Suzhou, Wuxi, Changzhou, Nanjing, and Zhenjiang

(Partha and David, 1994; Stokes, 1997). Besides, the major aim of scientific activities is to add new knowledge to the existing 'stock of knowledge' and diffuse them as widely as possible whereas the community of technology wants to protect their gains from possession of private knowledge (Partha and David, 1994). Given these differences between scientific and technological knowledge, it could be expected that the collaboration patterns of scientific knowledge and technological knowledge might also differ to some extent.

Taking the case of China's Yangtze River Delta (YRD) megalopolis, the overarching aim of this paper is therefore to explore the extent to which it has acted as a hinge that articulates China's science and technology between national and global urban systems by analyzing the patterns and processes of knowledge collaboration within and beyond the YRD megalopolis. As China has been committed to promoting innovation and megalopolitan development, we hope that our research could offer an integrative perspective to understand how the YRD region can transform from a manufacturing-based megalopolis into an innovation-driven megalopolis.

2 Materials and Methods

2.1 Study area

The Yangtze River Delta (YRD) megalopolis lies in the eastern coastal area of China and was included by Gottmann (1976) as one of the world's six largest megalopolises. So far there have been several versions of the official delimitation of the YRD megalopolis. Here we stick to the 'Yangtze River Delta Regional Planning' in 2010 which designates the region as composed of three main areas: the Municipality of Shanghai, Jiangsu Province, and Zhejiang Province. Among the total 25 cities of the YRD megalopolis, there is one municipality (Shanghai), two provincial capitals (Nanjing of Jiangsu Province, Hangzhou of Zhejiang Province) and 21 prefecture-level cities (Fig. 1). The number of people permanently living in the YRD megalopolis almost reached 160 million in 2014, which is far beyond Gottmann's (1976) 25 million population threshold for a megalopolis.

Here it is worth mentioning the specifics of China's urbanization and political economy which could help foreign readers get a better understanding of our methodology and the following analysis of empirical results. First, unlike the functional urban regions in the European context, the boundaries of Chinese cities are politically defined based on the administrative jurisdiction systems. Typically, a prefecture-level city could cover an area of several thousand square kilometers and has a population of several million, implying that Chinese cities could function more like an intra-urban system. Second, the delimitation of megalopolises such as the YRD megalopolis is also the product of state planning which may not fully capture the functionality of the megalopolitan system. However, it is necessary to pre-define the boundary of the YRD megalopolis for analysis purpose. In fact, our empirical results based on co-authorship and co-patenting data indicate that the administrative YRD megalopolis is also ostensibly a functional region in that there are almost no major knowledge linkages with cities that fall outside the administrative region. Third, the structure of urban knowledge networks may be influenced by China's political economy. Cities with more privileged political status such as municipalities and provincial capital cities usually have more access to knowledge resources, e.g., universities and research institutes, high-tech firms, implying that their positionality in urban knowledge networks would also be prominent.

2.2 Data collection

Co-publications and co-patents which are two common indicators for measurement of knowledge collaboration in this line of literature are used in this paper to represent scientific knowledge collaboration and technological knowledge collaboration respectively (Matthiessen et al., 2010; Lu and Huang, 2012; Andersson et al., 2014; Ma et al., 2015). It goes without saying that the use of the two indicators has shortcomings. For instance, not all knowledge collaboration would end up with co-publications or co-patents (Griliches, 1990; Hoekman et al., 2009 for detailed discussions). However, their suitability for analysis of knowledge collaboration at higher geographical scales such as interurban, interregional, and international knowledge collaboration can be justified owing to the increased availability and accessibility of 'relational' databases on co-publications and co-patents. These databases usually contain a large amount of longitudinal and relational data which are useful for a variety of applications such as network analysis and evolutionary analysis. In fact, there have

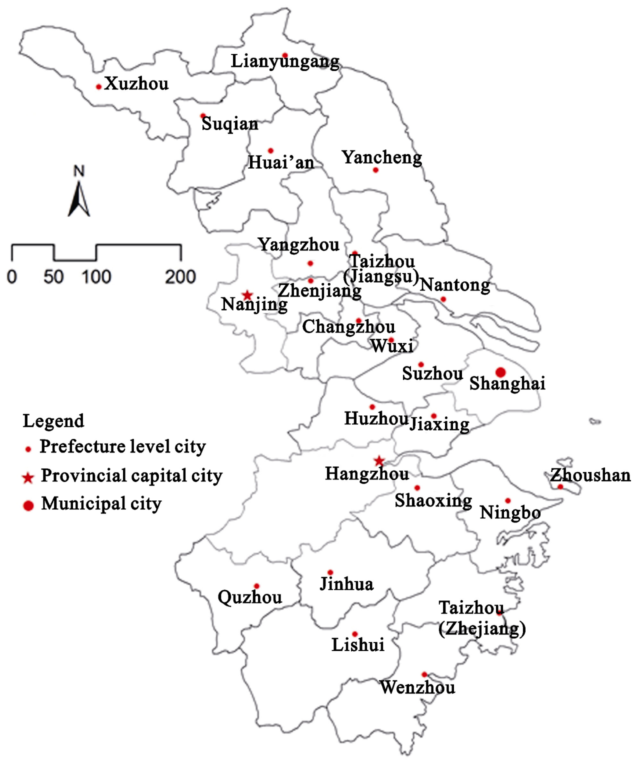

Fig. 1 Spatial distribution of Yangtze River Delta megalopolis

been calls for statistical measurement of knowledge and innovation for macro-scale studies focusing upon the geographical nature of knowledge collaboration (Gault, 2003; OECD, 2005; Shearmur, 2012).

Data on co-publications and co-patents were retrieved from the Web of Science (WoS) database and the World Intellectual Property Organization (WIPO) database respectively. The reasons for using the two international databases rather than Chinese domestic databases are as follows. First, Ren and Rousseau (2002) argued that the choice of the use of databases on co-publications and co-patents should be dependent on particular research focus. As the main goal of the current paper is to analyze knowledge collaboration at different geographical scales, it is necessary to use publications and patents achieved through international knowledge collaboration which are mainly published in English. Second, getting publications and patents included in these international databases is generally believed more difficult for Chinese researchers than is the case in Chinese domestic databases. This leads us to reject the idea of combining international databases and Chinese domestic databases as it would lead to a serious problem concerning the uniformity of data quality. Third, due to China's commitment to increasing the global visibility of its science and technology (Ren and Rousseau, 2002): the number of publications and patents contained in international databases has increased markedly. For instance, it has been reported that China has surpassed the US as the world's top country in terms of its share of global engineering publications and has closely followed the US in the output of scientific papers (National Science Board, 2016). Consequently, we believe that the two databases contain a substantially large number of papers and patents that could reflect a reasonable if not complete picture of knowledge collaboration within and beyond the YRD megalopolis.

Given the number of co-publications is substantially larger than that of co-patents, not all cities outside the YRD megalopolis are considered for analysis of scientific knowledge collaboration. Specifically, 39 cities are selected at the national scale under the criterion that each has more than 500 publications in 2014. Although this cut-off value is arbitrary, the list of cities covers almost all provincial capitals, municipalities, and other major cities. Besides, almost all the cities appear in the list of other studies on China's intercity scientific knowledge collaboration such as Lu and Huang (2012).

At the global scale, 133 cities are selected mainly based upon the world city list of Taylor et al. (2002) and supplemented by the list of the top 30 knowledge centers (Matthiessen et al., 2010). As most of these cities have a limited number of co-publications with the YRD cities, we believe that the lists could cover most cities that have knowledge collaboration with the YRD cities at the national and global scales.

Whereas the number of co-publications contained in the WoS database was found to be very limited before 2000, the WIPO database reported a very limited number of co-patents before 2004. Consequently, co-publications and co-patents used in this study were published from 2004 to 2014 to make results comparable. A three-year moving average centered on the middle year is adopted in this study to smooth fluctuations in the number of co-publications and co-patents. Accordingly, the analysis period of this study is from 2005 to 2013.

2.3 Methods

2.3.1 Network construction

Obviously, cities can not automatically generate knowledge linkages between themselves. The knowledge relationships between cities are maintained by a variety of economic entities such as people, firms, universities and research institutes (URIs) who create their cities' major external knowledge linkages. The detailed address information of researchers contained in co-publications and co-patents makes it possible to aggregate knowledge linkages between entities to the city level which can be further used to generate urban networks of knowledge collaboration at different geographical scales. It should be pointed out, however, that attention is only placed to linkages that are formed by at least one megalopolitan city. In other words, the urban network analyzed in this paper is an incomplete network as linkages between two cities which are both outside the megalopolis are not considered here.

2.3.2 Structure measurement

One commonly used indicator for measurement of the structure of urban networks is functional polycentricity (Burger and Meijers, 2012). Liu et al. (2016) summarizes that there are three main approaches to measuring functional polycentricity: 1) the regression approach based upon rank-size distribution; 2) the modeling approach comparing the observed polycentricity with expected 'pure' polycentricity; and 3) the network approach drawn upon social network methods. The modeling approach and the network approach are usually used for analysis of a complete network. However, knowledge networks at the national and global scales are incomplete in this paper. Consequently, the two approaches are unsuitable choices here. As for the regression approach, values of goodness-of-fit of regression lines are generally not high and differ a lot, which means imperfect use of data information and makes results less comparable. Besides, the slopes of regression lines which are the key indicators of functional polycentricity are negative, which are unsuitable for comparison as we generally expect positive signs of the degree of functional polycentricity.

In this study, functional polycentricity is defined to represent the distribution pattern of cities' external knowledge connectivity at different geographical scales. In this sense, it is essentially an indicator of inequality of cities' external knowledge connectivity. With this borne in mind, we measure the degree of functional polycentricity using the following expression:

$$DP_{\mathrm{F}} = 1 - G_{\mathrm{F}} \tag{1}$$

where DP_{F} refers to the degree of functional polycentricity of urban networks of knowledge collaboration at different geographical scale, G_{F} represents the Gini coefficient of the distribution of cities' external knowledge connectivity. Here we draw upon the concept of the Gini coefficient, one of the most widely used economic indicators of distribution disparity with values ranging from 0 (perfect equality) to 1 (perfect inequality). Cities' external knowledge connectivity is calculated using the following expression:

$$C_i = \sum\nolimits_j^n C_{ij} \, (i \neq j) \tag{2}$$

where C_i is external knowledge connectivity of a YRD city i at one geographical scale, C_{ij} denotes the knowledge linkages between city i and j which is represented by the number of co-publications or co-patents between the two cities.

3 Results

To explore how the YRD megalopolis has articulated China's science and technology at different geographical scales, a multi-scalar analysis is conducted by analyzing knowledge collaboration within and beyond the YRD megalopolis. The analysis consists of three sections. The evolution of the structure of knowledge collaboration within and beyond the YRD megalopolis is firstly explored. The degree of functional polycentricity of knowledge collaboration networks at different geographical scales is then measured and discussed. By further looking at Shanghai's external knowledge linkages at different geographical scales, the gateway role played by the YRD megalopolis in articulating China's science and technology between national and global urban systems is reconsidered.

3.1 Structural evolution of knowledge collaboration within and beyond the YRD megalopolis

Given space constraints, we only show the structures of scientific knowledge collaboration and technological knowledge collaboration in 2005 and 2013 (Fig. 2 and Fig. 3). The criterion for scientific knowledge collaboration is intercity links with 50 or more co-publications in 2005 and 200 or more co-publications in 2013. The criterion for technological knowledge collaboration is generally uniform in 2005 and 2013 which is intercity links with 4 or more co-patents. However, there are a large number of eligible cities at the global scale in 2013 if chosen under this criterion. To reduce the difficulties of visualization, we only show intercity links with 10 or more co-patents at the global scale in 2013.

3.1.1 Structural evolution of scientific knowledge collaboration

Overall, the strength of scientific knowledge linkages at each geographical scale has increased in general during the 2005–2013 period. This can be expected given China's rising share of the worldwide scientific outputs in recent years (Ren and Rousseau, 2002; National Science Board, 2016). However, a comparison of the strength of scientific knowledge collaboration at different geographical scales reveals that intercity scientific knowledge collaboration at the national scale is on average the strongest, followed by those at the global and megalopolitan scales. The structure of scientific knowledge collaboration at each geographical scale is discussed respectively as follows.

At the megalopolitan scale, the number of co-publications between the YRD cities and that of city pairs involved with collaboration have on average grown significantly during the study period. Two major conclusions can be drawn here. First, the collaboration pattern

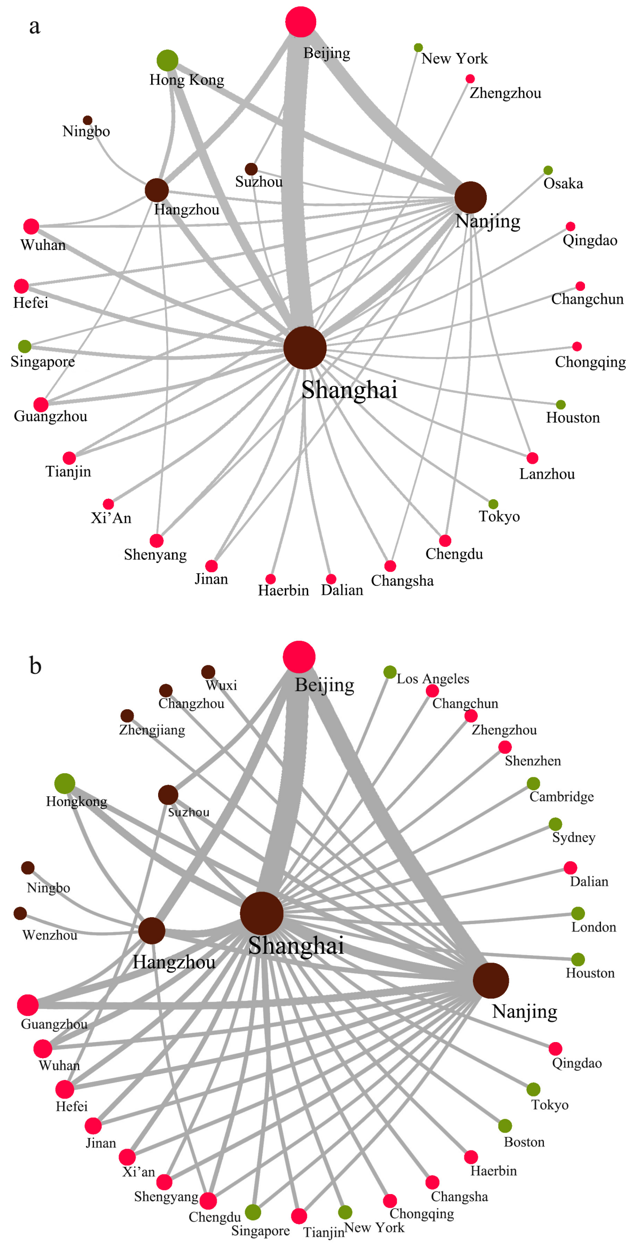

Fig. 2 Pattern of scientific knowledge collaboration within and beyond the YRD megalopolis in 2005 (a) and in 2013 (b). Thickness of lines is proportional to the number of intercity co-publications. Cities at different geographical scales are differentiated by colors (cities at the megalopolitan scale are in grey, the national scale red, and the global scale green. To simplify discussion, Hong Kong in China is treated as a global city.). The size of cities is also proportional to their external knowledge connectivity. Not all cities are shown due to limited spaces.

generally conforms to the politically-defined structure of the YRD megalopolis. Collaboration between the three largest cities (Shanghai, Nanjing and Hangzhou) dominates over other intercity links. Meanwhile, the three largest cities also have relatively strong links with other smaller cities of the region. According to the study of Andersson et al. (2014) which finds the structure of Chinese intercity scientific knowledge collaboration is politically-biased, it can be inferred that smaller YRD cities with modest knowledge resources tend to pursue economic development and upgrade their positions in urban networks through the lens of seeking collaboration with larger cities (usually capital cities) which have easy accesses to funds and research resources. Second, most intercity links have been generated between cities from the same province, except for those involved with Shanghai. For instance, Nanjing, the capital of Jiangsu Province, has maintained its megalopolitan-scale scientific knowledge collaboration mainly with cities from the same province in 2013, i.e., Changzhou, Zhenjiang, Wuxi and Suzhou (Fig. 2b). This finding is in line with the study of Andersson et al. (2014) which finds the geography of Chinese science has the same-province effect. One explanation could be regional protectionism in funding scientific knowledge collaboration. Despite the continuous commitment of the central government to promoting inter-provincial scientific collaboration, it has been argued that regional authorities at the provincial level are more likely to support and fund intercity scientific knowledge collaboration within the same province as they seek to maximize intra-provincial interests (Scherngell and Hu, 2011). Another explanation might relate to a new expansion strategy adopted by some localities with modest knowledge resources. To gain rapid scientific growth, these localities have attracted many renowned universities and research institutes (URIs) within their provinces to launch branches in their respective cities. Two notable examples are the intra-provincial Nanjing-Changzhou and Nanjing-Wuxi links in 2013 which did not exist in previous years. In their cases, both the localities of Changzhou and Wuxi have successfully attracted the establishment of branches of Nanjing University and Southeast University, the top two universities in Nanjing.

At the national scale, scientific knowledge collaboration has also strengthened markedly during the 2005–2013 period. The characteristics of its structure also bears some similarities with those at the megalopolitan scale. A notable feature is the above-mentioned politically-biased effect. As can be seen, most national-scale cities that have scientific knowledge collaboration with the YRD cities are capital cities or municipalities (e.g., Beijing, Guangzhou, Hefei). Particularly, there is a strong bias towards Beijing when the YRD cities seek scientific knowledge collaboration outside, which can be reflected by the strong linkages such as Shanghai-Beijing, Nanjing-Beijing, and Hangzhou-Beijing. The attractiveness of Beijing can also be expected; it holds China's two top-level universities (Tsinghua University and Peking University) and China's largest research organization (the Chinese Academy of Sciences, CAS) which has 98 research institutes, 11 branch offices, 2 universities, and 6 supporting organizations in China's 23 provinces (including municipalities and autonomous regions).

For scientific knowledge collaboration at the global scale, the most prominent feature is perhaps the dominant role of Shanghai over other YRD cities in generating global-scale knowledge linkages. This can be expected given Shanghai's position in China's opening-up policy and in its science system. Obviously, most of the global-scale intercity linkages are involved with Shanghai, whereas Nanjing and Hangzhou have no major international collaboration except for those with Hong Kong in China and the Singapore City. Another interesting finding is that it is Hong Kong in China and the Singapore City rather than London or New York in USA that have the strongest scientific knowledge collaboration with Shanghai, which is different from the findings based on intra-APS firm linkages (Taylor et al., 2014).

3.1.2 Structural evolution of technological knowledge collaboration

As in the case of scientific knowledge collaboration, technological knowledge collaboration within and beyond the YRD megalopolis has also strengthened during the study period (Figs. 3a and 3b). This finding is in line with other studies that have observed increasing strength of technological knowledge collaboration between metropolitan regions (provinces) at the national scale (Gao et al., 2011; Sun, 2016). Different from the structure of scientific knowledge collaboration, however, technological knowledge collaboration has been the strongest at the global scale, far ahead of those at the national and megalopolitan scales.

At the megalopolitan scale, an increasing number of YRD cities have been involved with technological knowledge collaboration (Figs. 3a and 3b). The above-mentioned same-province effect and political-bias can

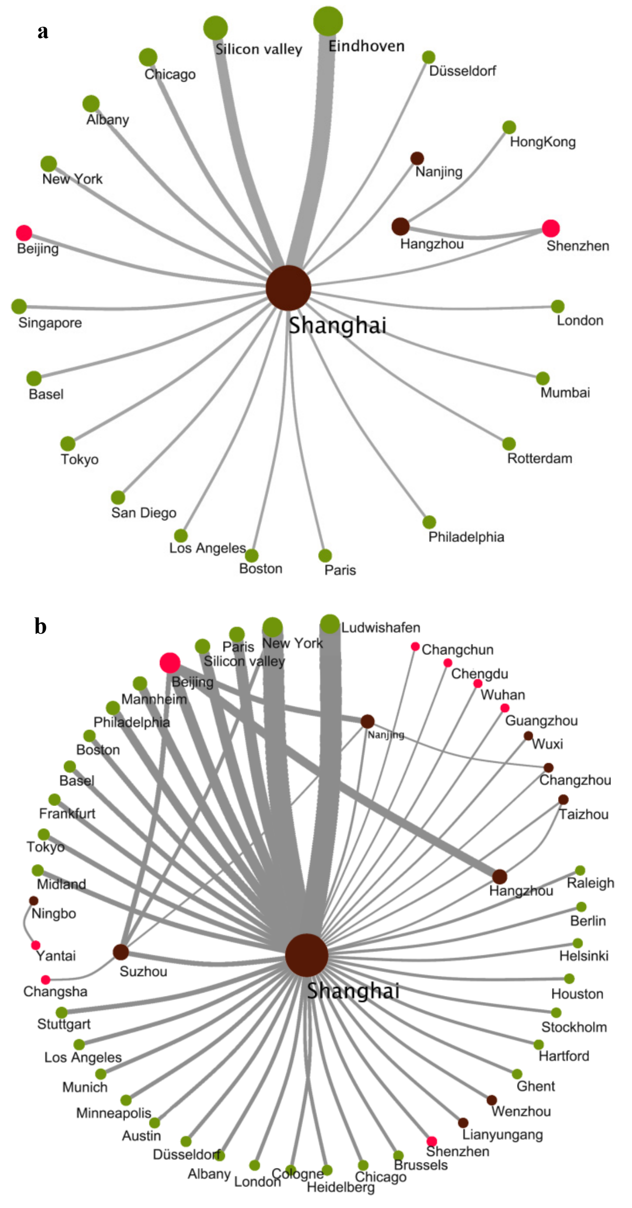

Fig. 3 Pattern of technological knowledge collaboration within and beyond the YRD megalopolis in 2005 (a) and in 2013 (b). Meanings of different colors and lines see Fig. 2

also be observed as most collaboration has been directed towards Shanghai and there is no major collaboration between cities respectively from Zhejiang Province and Jiangsu Province. Different from the structure of scientific knowledge collaboration, technological knowledge linkages among the three centers (Shanghai, Nanjing and Hangzhou) are relatively loosely connected. In fact, Shanghai has the strongest collaboration with Suzhou, followed by its collaboration with Lianyungang and Wenzhou. Whereas the Shanghai-Suzhou links are mainly developed by intra-firm collaboration of foreign multinational enterprises (MNEs): the latter two are maintained primarily by intra-firm collaboration of domestic enterprises. For instance, Lianyungang's stronger collaboration with Shanghai is due in large part to its two large-scale pharmaceutical companies (Jiangsu Hengrui Medicine Co., Ltd., Jiangsu Hansoh Pharmaceutical Co., Ltd.), both of which have Research and Development (R&D) centers in Shanghai.

The structure of technological knowledge collaboration at the national scale has been characterized by both political bias and market drivers. The political bias is reflected by the fact that most cities involved with national-scale collaboration are municipalities or capital cities, e.g., Shanghai, Nanjing and Hangzhou within the YRD megalopolis and Beijing, Guangzhou, Wuhan, Chengdu at the national scale (Fig. 3b). The market-driven nature is mainly represented by the presence of some non-capital but economically powerful cities which have been involved with technological knowledge collaboration (e.g., Shenzhen, Yantai). Take Shenzhen for instance, its collaboration with Shanghai is mainly developed by Huawei Technologies Co. Ltd., the world's largest telecommunications equipment manufacturer which is headquartered in Shenzhen and has R&D centers in Shanghai. This finding generally conforms to the study of Ma et al. (2015) which finds that both capital cities (or municipalities) and non-capital cities (usually economically strong) are key actors in China's city network driven by technological knowledge collaboration.

At the global scale, Shanghai has overwhelmingly dominated over other YRD cities in developing major technological knowledge collaboration. Two findings need to be highlighted here. First, the composition of cities that have global collaboration with Shanghai is relatively unstable. For instance, the Shanghai-Eindhoven linkage which has been mainly associated with Philips was the strongest global linkage in 2005. However, it has declined substantially these years and is even not qualifying to be shown in the figure in 2013. By contrast, recent years have seen the rise of Ludwigshafen and Paris which used to have relatively weak collaboration with Shanghai. Second, the composition of these cities is also diversified which includes both famous world cities (e.g., New York, London) and some smaller cities which are usually not seen as world cities (e.g., Ludwigshafen, Basel). Shanghai's linkage with these smaller cities is mainly due to intra-firm collaboration of some MNEs which are headquartered in these cities and have R&D centers in Shanghai. One notable example is BASF, the world's largest chemical producer which is headquartered in Ludwigshafen and has two manufacturing bases and one R&D center in Shanghai.

3.2 Functional polycentricity of knowledge collaboration within and beyond the YRD megalopolis

Before measuring the degree of functional polycentricity, it needs to decide the number of cities that should be considered in the measurement. Here we agree with the argument of Burger and Meijers (2012) that the measurement of functional polycentricity should be based on a fixed number of cities (usually from 3 to 5) rather than the total number of cities. In this study, we use the top four cities (Shanghai, Nanjing, Hangzhou, Suzhou) in terms of their external knowledge connectivity for both scientific and technological knowledge collaboration. The top three cities were not used because the measurement of the Gini coefficient could be more precise based on larger number of cities. However, the composition of the top five cities is unstable which is unsuitable for comparison purposes as we generally expect to observe the evolution of functional polycentricity within a consistent group of cities. For scientific knowledge collaboration, the top four cities generally account for 68% of the region's total scientific knowledge connectivity at the megalopolitan scale, 86% at the national scale, and 94% at the global scale. For technological knowledge collaboration, the top four cities on average make up 65% of the region's total technological knowledge connectivity at the megalopolitan scale, 81% at the national scale, and 95% at the global scale.

3.2.1 Functional polycentricity of scientific knowledge collaboration

Fig. 4 shows the results of the degree of functional polycentricity of scientific knowledge collaboration at different geographical scales during the 2005–2013 period. The R^2 values of Lorenz curves upon which the results are based are all over 0.99 which are generally larger than those generated by the regression approach based on rank size distribution. Two major conclusions can be drawn here. First, the degree of functional polycentricity at the megalopolitan scale is in general the highest, followed by those at the national and global scales. The result is in line with the other studies which find a decreasing degree of functional polycentricity as the geographical scale increases (Taylor et al., 2008; Hanssens et al., 2014). In fact, the result can also be expected if we look back to the structure of scientific knowledge collaboration within and beyond the YRD megalopolis which is more evenly distributed at the megalopolitan and national scales than at the global scale.

Second, the degrees of functional polycentricity at different geographical scales have all been on the rise, albeit to varying degrees. Specifically, the increase in the degree of functional polycentricity at the megalopolitan and global scales has been relatively modest, whereas that at the national scale has been the highest which rose from 0.576 to 0.678. The modest increase in the degree of functional polycentricity at the megalopolitan scale can be expected given that it has already been at a high level (over 0.76). However, it still suggests that the structure of scientific knowledge collaboration within the YRD megalopolis has become more functionally polycentric; a finding which is in line with other studies based upon other types of intercity linkages (De Goei et al., 2010). The degree of functional polycentricity at the national scale has been approaching that at the megalopolitan scale due to its rapid increase in recent years. This implies that Shanghai's dominant role in developing scientific knowledge collaboration with cities at the national scale has been weakening. In fact, recent years have seen active engagement of other major YRD cities like Nanjing and Hangzhou in national knowledge collaboration, which also implies that the structure of scientific knowledge collaboration at the national scale has been evolving towards becoming more functionally polycentric. While having been rising modestly, the degree of functional polycentricity at the global scale has declined slightly since 2010, implying that Shanghai's dominant role in generating global knowledge collaboration has been strengthening recently. Given the not-so-strong degree of functional polycentricity and its recent decline, it might be argued that the current structure of scientific knowledge collaboration at the global scale can hardly be viewed functionally polycentric. In fact, Shanghai generally accounts for 45% of the total global scientific knowledge connectivity of the top cities.

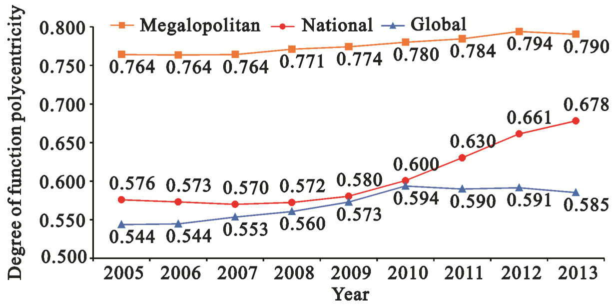

Fig. 4 Functional polycentricity of scientific knowledge collaboration at different geographical scales

3.2.2 Functional polycentricity of technological knowledge collaboration

Fig. 5 shows the results of the degree of functional polycentricity of technological knowledge collaboration at different geographical scales during the 2005–2013. As in the case of scientific knowledge collaboration, the R^2 values of Lorenz curves upon which the results are based are all over 0.99, indicating perfect goodness-of-fit of regression lines. Besides, that the degree of functional polycentricity decreases as the geographical scale increases can also be confirmed in the case of technological knowledge collaboration. However, the change in the degree of functional polycentricity of technological knowledge collaboration at different geographical scales has differed a lot during the 2005–2013 period.

At the megalopolitan scale, the degree of functional polycentricity has increased steadily from 0.593 in 2006 to 0.718 in 2010, followed by a slight decline from 2010 to 2013. In general, this suggests that the structure of technological knowledge collaboration within the YRD megalopolis has become more functionally polycentric.

As in the case of scientific knowledge collaboration, the degree of functional polycentricity of technological knowledge collaboration at the national scale has also experienced the most significant increase (from 0.469 in 2006 to 0.677 in 2013) compared with those at other geographical scales. Moreover, it has been quite close to that at the megalopolitan scale in recent years, suggesting an increasingly functionally polycentric structure of technological knowledge collaboration between the YRD cities and cities at the national scale.

At the global scale, the degree of functional polycentricity of technological knowledge collaboration has experienced marked fluctuations. It declined from 0.357 in 2005 to 0.323 in 2007 and then steadily climbed to 0.348 in 2011 and decreased again to 0.305 in 2013 which has been the lowest during the 2005–2013 period. The result implies that technological knowledge collaboration of the YRD megalopolis at the global scale has been predominantly involved with Shanghai, which can be also observed in Fig. 3a and Fig. 3b. In fact, Shanghai accounts for nearly 90% of the total global technological knowledge links of the top four cities. Overall, the relatively low and fluctuated degree of functional polycentricity has provided little evidence for a functionally polycentric structure of technological knowledge collaboration between the YRD cities and cities at the global scale.

3.3 Gateway role of YRD megalopolis in articulating China's science and technology

The above analysis of the structural evolution and functional polycentricity of knowledge collaboration at different geographical scales has already shed some light on how the YRD megalopolis has articulated China's science and technology between national and global urban systems. For instance, we have observed the presence of the trans-scalar geography of knowledge collaboration with in and beyond the YRD megalopolis, although there are some differences in the structure and the degree of functional polycentricity between scientific and technological knowledge collaboration. However, this alone can not provide a full understanding of the knowledge gateway role of the YRD megalopolis which is generally expected to be represented by its primate city–Shanghai. Arguably, a gateway city of a megalopolis should be one that is well connected with cities both within and beyond the megalopolis. In this sense, we need to have a further look at Shanghai's external knowledge connectivity within and beyond the YRD megalopolis which is often neglected by most studies that have analyzed functional polycentricity at

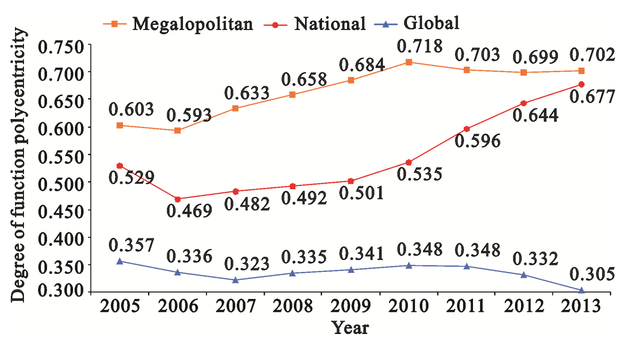

Fig. 5 Functional polycentricity of technological knowledge collaboration at different geographical scales

different geographical scales.

In fact, the substantial differences in the distribution of Shanghai's external knowledge connectivity at different geographical scales have already been touched upon in the above analysis. In absolute terms, whereas the result of the structural evolution of scientific knowledge collaboration has suggested that Shanghai on average has the strongest scientific knowledge connectivity at the national scale which is followed by those at the global and megalopolitan scales, that of technological knowledge collaboration has obviously shown that Shanghai has more and stronger collaboration with cities at the global scale which is followed by those with cities at the national and megalopolitan scales. In relative terms, the result of the degree of functional polycentricity of both scientific and technological knowledge collaboration has implied that Shanghai tends to strengthen its dominant role in knowledge collaboration as the geographical scale at which it operates increases. This is especially the case for technological knowledge collaboration given its weak and fluctuated degree of functional polycentricity at the global scale.

The reasons for the dominance of Shanghai's external knowledge connectivity over other cities have been partly mentioned in our above discussion of the structural evolution of both scientific and technological knowledge networks. Overall, Shanghai's dominance can be attributed to the large number of URIs and MNEs it holds. While the former has been major actors for scientific knowledge collaboration, the latter has been main economic entities for technological knowledge collaboration. By 2014, Shanghai has held 68 schools of higher education, much higher than the figures for Nanjing (44) and Hangzhou (38). Moreover, many of its URIs are nationally and globally renowned such as Fudan University, Shanghai Jiaotong University, Chinese Academy of Sciences Shanghai Branch, which have accounted for most of Shanghai's national and global knowledge connectivity. In addition to URIs, it has been well documented that there has been an overconcentration of R&D centers of MNEs in Shanghai. For instance, 78 out of the 199 foreign R&D establishments compiled by von Zedtwitz (2004) were in Beijing whereas another 61 in Shanghai. Notable examples are Intel Corporation and Nokia Corporation which have R&D subsidiaries in both Shanghai and Beijing.

To get a closer inspection of Shanghai's external knowledge connectivity at different geographical scales, Table 1 shows the total number of cities at each geographical scale among the top 40 cities that have the largest knowledge links with Shanghai in selected years (2005, 2009, 2013). As we can see, the number of the top 40 cities at each geographical scale has been generally stable during the 2005–2013 period.

The structure of Shanghai's external knowledge connectivity can be generally summarized as 'globally connected but locally disconnected', despite some differences between the structures of scientific and technological knowledge links. Obviously, there has been a mismatch between the global and local reach of Shanghai's knowledge collaboration. One may argue that the limited number of megalopolitan cities in Table 1 is related with the small number of cities within the YRD megalopolis. Nonetheless, the 'globally connected but locally disconnected' structure still holds because of the relatively weak knowledge linkages between Shanghai and those involved megalopolitan cities. In other words, although Shanghai has strengthened its knowledge collaboration with cities at different geographical scales over the last decade, its knowledge collaboration with other YRD cities (especially those non-capital cities) has remained relatively the weakest compared with its knowledge collaboration with cities at the global and national scales.

Recalling that a gateway city of a megalopolis should function not only as a window open to the outside world but also as a bridge connecting the outside world with the inside cities of the megalopolis, it could be argued that the YRD megalopolis may still have a long way to go before its knowledge collaboration being 'glocally connected' and its knowledge gateway role being fully realized; a role that requires Shanghai to develop knowledge collaboration not only with cities beyond the YRD megalopolis but also with cities within the YRD megalopolis. The current structure of Shanghai's external

Table 1 Number of cities at different geographical scales that have the strongest knowledge links with Shanghai (top 40)

Scale	Scientific knowledge collaboration			Technological knowledge collaboration		
	2005	2009	2013	2005	2009	2013
Megalopolitan	5	6	5	4	2	4
National	21	22	21	3	2	2
Global	14	12	14	33	36	34

knowledge connectivity implies that Shanghai will function just like the sort of mega-city described by Castells (2000) as 'globally connected and locally disconnected'. However, to articulate China's science and technology at different geographical scales requires the YRD megalopolis to function more like the 'buzz-and-pipeline' model that Bathelt et al. (2004) develop to explain knowledge learning processes within and between clusters.

For the YRD megalopolis, the current 'globally connected but locally disconnected' structure of Shanghai's external knowledge connectivity could undermine the development of its knowledge system. Whereas 'globally connected' may be beneficial for the knowledge development of mega-cites themselves as they are solely exposed to global and national resources, 'locally disconnected' may be detrimental to the overall knowledge development of megalopolises where mega-cites are located. One key feature of today's megalopolises should be their outstanding accumulation and agglomeration of economic mass and knowledge bases. While 'globally connected' ensures that newly-created knowledge elsewhere in the world can quickly find their ways to the YRD megalopolis, 'locally disconnected' may lead to insufficiency or even failure of translating and spreading new knowledge within the YRD megalopolis. Moreover, as 'globally connected' generally favors Shanghai, it is likely that a cumulative effect would occur whereby less developed cities within the YRD megalopolis lag ever further behind Shanghai.

4 Discussion and Conclusions

In an era of a globalizing knowledge economy, knowledge circulation within and beyond individual regions has been increasingly important for their sustainable development. This study draws upon the recent resurgent interest in the functional aspect of megaregions to analyze the pattern and process of knowledge collaboration networks within and beyond China's Yangtze River Delta (YRD) megalopolis. In contrast to studies that have primarily focused upon economic and transportation functionality of intercity linkages within an urban network (e.g., Burger and Meijers, 2012; Liu et al., 2016) and those that have analyzed intercity knowledge collaboration at the national and global scales (Matthiessen et al., 2002; 2010; Lu and Huang, 2012; Andersson et al., 2014; Ma et al., 2015), our study focus on intercity knowledge collaboration at different geographical scales sheds light on how the YRD megalopolis has articulated China's science and technology between national and global urban systems. In doing so, we have also re-highlighted the two defining but often overlooked functions that Gottmann (1961; 1976) ascribed to megalopolises as 'hinges' and 'incubators'.

Drawing upon data on co-publications and co-patents, the empirical results can be summarized as follows. First, the strength of knowledge collaboration at different geographical scales has generally been on the rise over the last decade. Besides, the structure of knowledge collaboration has remained relatively stable over the time. However, there are still some differences between the structures of scientific knowledge collaboration and technological knowledge collaboration. Whereas the former is generally strongest at the national scale, followed by those at the global and megalopolitan scales, the latter is prominently strongest at the global scale, followed by those at the national and megalopolitan scales. While these differences may be caused by the different nature of scientific knowledge and technological knowledge which has been discussed above, they also indicate the complexity of intercity linkages which reminds us to be cautious when generalizing the structures of urban networks based upon different types of intercity linkages (Burger et al., 2014).

Second, the degree of functional polycentricity of knowledge collaboration has increased in general over the last decade, except for that of technological knowledge collaboration at the global scale which has been markedly fluctuated. Besides, the degree of functional polycentricity of both types of knowledge collaboration decreases as the geographical scale at which they are measured increases, which confirms the findings of studies based upon other types of intercity linkages (Taylor et al., 2008; Hanssens et al., 2014). However, the degree of functional polycentricity of technological knowledge collaboration has been in general lower than that of scientific knowledge collaboration at each geographical scale (especially at the global scale). Nonetheless, the result suggests that Shanghai's dominant role in knowledge collaboration becomes more prominent at higher geographical scales.

Third, the structure of Shanghai's knowledge collaboration within and beyond the YRD megalopolis can be generally described as 'globally connected but locally disconnected'. Over the last decade, Shanghai, the primate mega-city of the YRD megalopolis, has maintained relatively the weakest knowledge collaboration with other YRD cities (especially those non-capital cities) than with cities at the national and global scales. This, combined with the results of the structural evolution and functional polycentricity of knowledge collaboration, suggests that the YRD megalopolis may still have a long way to go before fully shouldering the gateway role in promoting knowledge collaboration at different geographical scales.

Two policy implications are derived from the empirical results. First, although intercity knowledge collaboration is essentially a bottom-up process promoted by knowledge flows and exchanges between people and firms, governments could also encourage such collaboration by providing more top-down institutional arrangements. Greater attention need to be paid to enhancing the ability of less favored cities in developing knowledge collaboration with major cities. A 'globally connected but locally disconnected' structure of knowledge collaboration could hinder the overall development of a region's knowledge system in the long term. Second, the knowledge-based understanding of the YRD megalopolis also provides some evidence on a potential transformation of its development mode from manufacturing-based to innovation-driven, highlighting the importance of building an innovation-driven megalopolis which is in line with China's two national-level strategies of promoting the development of urban agglomerations and building an innovation-driven economy.

Recalling that cities can not automatically form knowledge collaboration which is in fact generated between various types of economic entities such as people and firms within cities, one direction for future research agendas in this vein could be micro-level analysis of the mechanisms behind the macro-level pattern and process of knowledge collaboration within and beyond the YRD megalopolis. Such micro-level mechanism analysis would help answer questions like why does a certain pair of cities have more knowledge linkages than other pairs of cities and why does a given city have more external knowledge connectivity than other cities?

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