

Knowledge and the evolving megalopolis: the knowledge polycentricity of the Yangtze

River Delta Region, China

Abstract: Inspired by the two defining but often overlooked features of megalopolises as ‘hinges’ and ‘incubators’, this paper presents a multi-scalar and dynamic analysis of the knowledge polycentricity of China’s Yangtze River Delta Region. Using data on publications and co-publications from 2000 to 2014, the results show that the structures of knowledge production and knowledge collaboration within and beyond the region have, to differing degrees, become more polycentric. Whereas the region has acted as an ‘incubator’ of knowledge at the megalopolitan scale, its ‘hinge’ role in knowledge collaboration has been mainly played at the national scale.

Keywords: Megalopolis; Polycentricity; Urban networks; Knowledge collaboration;

The Yangtze River Delta Region

JEL classifications: D85, O19, R12

INTRODUCTION

Research interest in the concepts of ‘polycentricism’ and ‘polycentricity’ has grown recently (DAVOUDI, 2003; MEIJERS, 2008; BURGER and MEIJERS, 2012; BURGER et al., 2014). Nevertheless, the increasing popularity of polycentricity has seemingly made the concept one of the most ambiguous and stretched concepts in analytical and planning circles. The ambiguity stems from the fact that polycentricity could have different meanings at different geographical scales, from different

analytical perspectives and at different development stages. Recent studies have resulted in some progress in conceptual clarification of the polycentricity concept. For instance, DAVOUDI (2003) observes the scale-dependent nature of polycentricity which exists at the intra-urban, inter-urban and inter-regional scales. BURGER and MEIJERS (2012) distinguish between morphological and functional polycentricity and discuss the way that both can be measured and compared.

Despite these contributions made to overcoming some of the analytical and empirical ambiguities of polycentricity, there still remains room for the concept to be further explored. First, the fact that polycentricity can be viewed as a spatial *process* indicates the extent to which an urban region is polycentric can change over time. Like cities, urban regions are not born polycentric, but evolve to become more so. Here it may be important to distinguish the different modes – centrifugal, incorporation and fusion - by which polycentric urban regions emerge (CHAMPION, 2001) with accompanying questions of whether it is meaningful to speak of polycentric urban regions (PARR, 2004). Without a comparison-in-time perspective, one is left with a partial understanding of the way in which any given polycentric urban region (PUR) has evolved. Nevertheless, most empirical studies have predominantly measured polycentricity at one point in time (van OORT et al., 2010; BURGER and MEIJERS, 2012; HANSSSENS et al., 2014; LIU et al., 2016). Notable exceptions are the studies of De GOEI et al. (2010) and VASANEN (2012) that have scrutinized the changing configurations of PURs.

Second, a recent scientometric analysis of polycentricity in urban studies by van

MEETEREN et al. (2016a) finds that the literatures on intra-urban, inter-urban and inter-regional polycentricity are loosely connected and far apart. For PURs, however, analyzing functional polycentricity merely at the megalopolitan scale may not lead to a full understanding of this new urban form emerging with continued urbanization and globalization. According to SWYNGEDOUW (2004), the intertwined processes of globalization and localization have transformed into what he dubs the ‘glocalization’ process whereby economic activities are becoming simultaneously localized and transnational. It can be argued that both internal intercity linkages *within* a particular megalopolis and external intercity linkages *beyond* that same megalopolis are equally important to understanding its development. Indeed, this argument can find its origin in the ‘hinge’ or ‘hub’ role that GOTTMANN (1976) ascribed to megalopolises.

Third, despite multiple types of intercity linkages being explored in analysis of functional polycentricity, comparatively few studies have attempted to examine the role played by intercity knowledge collaboration in driving the formation of urban networks within and beyond megalopolises. In economic geography, however, some studies have analyzed intercity or interregional knowledge collaboration at the national (MA et al., 2014; ANDERSSON et al., 2014) and international scales (HOEKMAN et al., 2009; MATTHIESSEN et al., 2010). In fact, the knowledge (or ‘incubator’) function of megalopolises was also highlighted by GOTTMANN (1976), together with the aforementioned ‘hub’ or ‘hinge’ role, as two defining features of megalopolises. However, the two crucial roles played by megalopolises are often neglected in the vast literature on PURs.

Fourth, although recent years have seen an increasing number of studies on the polycentric development of China's megalopolises, most studies have relied upon data on intercity firm linkages (ZHAO et al., 2015; ZHANG and KLOOSTERMAN, 2016) and intercity transportation linkages (LUO et al., 2011; LIU et al., 2016), while paying little attention to examining the polycentric development of megalopolises' knowledge system. Exploring the knowledge subsystem of megalopolises and the extent to which its structure maps onto those of other subsystems (e.g., those based on commuting, firm linkages and transportations connections) can contribute to a better understanding of megalopolises in a globalizing knowledge economy.

In light of the above-mentioned research gap, a recent study of LI and PHELPS (2016) analyzes functional polycentricity of China's Yangtze River Delta Region at different geographical scales in 2014 from the perspective of intercity knowledge collaboration. However, their study does not touch upon the polycentric structure of the knowledge production system of the megalopolis and how functional polycentricity within and beyond the megalopolis has evolved over time. Building upon the analysis of LI and PHELPS (2016), the current paper examines the polycentricity concept in the Chinese context. In particular, it focuses on the two overlooked functions (incubator and hub) of megalopolises from a *dynamic* perspective. Taking the case of China's Yangtze River Delta Region, this paper analyzes the polycentric structure of the region's knowledge *production* ('incubator') as well as knowledge *collaboration* within and beyond the region ('hub'), exploring the way in which polycentricity evolves over time.

The remainder of this paper is structured as follows. First, it reviews briefly the evolution of the megalopolis concept with a particular focus on its two important but often neglected functions, after which the research region, data collection and methodology are introduced. The empirical results of a multi-scalar and dynamic analysis of knowledge polycentricity are then presented. The paper concludes with a discussion of major findings and some suggestions for future research agendas.

KNOWLEDGE POLYCENTRICITY: RECASTING MEGALOPOLIS IN A GLOBALIZING KNOWLEDGE ECONOMY

The evolving concept of megalopolis

The foundations upon which studies on large-scale urbanization processes have been conducted are usually attributed to the work of GEDDES (1915), MUMFORD (1938) and GOTTMANN (1957) on the term of megalopolis (see BAIGENT (2004) for a detailed comparison of their studies). However, it is worth noting that it was GOTTMANN (1957, 1964) who first positively promoted megalopolis as a new urban form. Before Gottmann, the term megalopolis was originally proposed to reflect the development stage of urban expansion/sprawl by GEDDES (1915) and MUMFORD (1938), usually with negative overtones from a morphological view. While continuing to emphasize morphology in the conception of megalopolis, GOTTMANN (1964, 1976) also touched upon the functional aspects of megalopolises in his later studies by describing a megalopolis as a *hinge or hub* connecting cities within and beyond

megalopolitan areas and an *incubator* of new trends, knowledge and innovation.

Although scholarly and policy interest in megalopolis had faded by the early 1980s, recent years have seen a resurgent interest in this concept, usually under the headings of urban regions, mega-city regions and megaregions. However, Gottmann's legacy is primarily read as a major contribution to the debates on evolving urban forms (VICINO et al., 2007; LANG and KNOX, 2009), whereas his emphasis on the functional aspects of megalopolises is often overlooked in the present day focus on large-scale urbanization processes. As HARRISON and HOYLER (2015: 7) write, 'while Gottmann's work has traditionally been read for its contribution to informing debates around mapping and planning the evolving urban form, its structure and its anatomy, dig beneath the surface and you will find a putative relational economic geography with incipient ideas about the functioning of the urban system which he went on to develop and expand upon in subsequent works'. The following section discusses how the two functions (hinge and incubator) of megalopolises are usually ignored and why they remain important in today's analysis of megalopolitan areas.

The overlooked functions of contemporary megalopolitan regions

Since the 2000s the focus of megalopolises in the European context has been associated with the concepts of urban networks and polycentricity. Partly inspired by the work on world city networks (TAYLOR et al., 2002), there has been an increasing interest among European scholars to adopt a functionally-dominant approach to large-scale urbanization processes (HALL and PAIN, 2006; TAYLOR et al., 2008;

BURGER and MEIJERS, 2012; BURGER et al., 2014). One of the focal points of this interest is the analysis of PURs from the perspective of urban networks. However, even in these studies, Gottmann's identification of the two important functions of megalopolises is still only partially acknowledged, let alone explored. This is not surprising because the explanatory frameworks of PURs found in recent studies are generally developed in the context of interurban networks rather than megalopolises themselves. In other words, the departure point of most studies on polycentricity and urban networks has been intercity linkages and economic linkages in particular rather than the roles that megalopolises are playing in a globalizing knowledge economy.

To be specific, on the one hand, most empirical studies on PURs have focused merely on intercity linkages within megalopolises without consideration of their connection to the global economy which is most closely associated with the hub function of megalopolises (e.g., De GOEI et al., 2010; VASANEN, 2012; BURGER and MEIJERS, 2012; BURGER et al., 2014). Note, however, that measuring polycentricity merely at the megalopolitan scale may not capture important aspects of the emergence of mega-city regions as new urban forms in contemporary processes of globalization. Some notable exceptions are the studies of HALL and PAIN (2006), TAYLOR et al. (2008) and HANSSSENS et al. (2014). However, these studies pay little attention to analyzing the articulation of mega-city regions with national and global urban systems.

Although not mentioning the hub role of megalopolises explicitly, some studies have highlighted the significance of megalopolises' relationship with the global

economy from several different perspectives. The first perspective is on the globalization/city relationship. Drawing upon a concept that itself dates back earlier (e.g. BIRD, 1983), SHORT (2000), NIJMAN (2011) and PAIN (2011) develop the idea of cities - especially primary cities - of megalopolises as gateways connecting other cities with the rest of the world, though BIRD'S (1983) observation of the slow recognition for such gateways despite their irresistible rise remains true. The second perspective is on economic development of urban regions. FLORIDA et al. (2008: 460) argue that 'urban mega-regions are coming to relate to the global economy in much the same way that metropolitan regions relate to national economies'. The third perspective is on agglomeration economies of urban regions. PHELPS and OZAWA (2003: 598) write that while the expanding geographical scale at which agglomeration operates 'has much to do with changes in the internal economies and the mobility of individual people and businesses, it also has to do with changes in the geographical extent of external economies open to collectivities of people and businesses'.

On the other hand, despite studies on flows of people (HALL and PAIN, 2006; De GOEI et al., 2010; BURGER and MEIJERS, 2012), firm linkages (TAYLOR et al., 2008; HANSSENS et al., 2014; BURGER et al., 2014), information exchanges (HALL and PAIN, 2006) and transportation connections (LUO et al., 2011; LIU et al., 2016), relatively little is known about the polycentric structure of a megalopolis' knowledge system which is closely related to Gottmann's description of their incubator function. A closer inspection of these common types of intercity linkages also helps explain why the hub function of megalopolises is often neglected since

most types of intercity linkages can only exist at the megalopolitan scale. In fact, the above-mentioned notable exceptions that have analyzed the multi-scalar nature of functional polycentricity have predominantly relied upon evidence relating to intra- and inter- firm linkages between cities which exist at different geographical scales (e.g. HALL and PAIN, 2006; TAYLOR et al., 2008; HANSSENS et al., 2014). Even where only the type of intercity linkage is concerned, it has also been argued that ‘a region may appear polycentric and spatially integrated with respect to one type of functional linkage but monocentric and loosely connected with respect to another type of functional linkage’ (BURGER et al., 2014: 818). Given this multiplexity of intercity linkages, there is also a need to account for knowledge collaboration as a type of intercity linkage in the functionally-dominated approach to megalopolises. The next section justifies the use of knowledge collaboration in analysis of polycentric megalopolises in a globalizing knowledge economy.

Intercity knowledge collaboration within and beyond megalopolitan regions

Recent studies on the geography of knowledge have increasingly challenged a traditional view that knowledge collaboration is spatially bounded and pointed to the trans-scalar nature of knowledge collaboration. These studies differ from each other in terms of the geographical scale at which knowledge collaboration is considered (e.g., national, continental and global) and the spatial unit of analysis upon which knowledge collaboration is constructed (e.g., clusters, cities, regions and nations). Most studies have focused on one type of scale-unit combination which includes

inter-cluster linkages at the global scale (BATHELT and LI, 2013), intercity knowledge collaboration at the national (MA et al., 2014; ANDERSSON et al., 2014) and the global scales (MATTHIESSEN et al., 2010), interregional (or inter-provincial) knowledge collaboration at the national (SCHERNGELL and HU, 2011) and the continental scales (HOEKMAN et al., 2009). Note, however, that few studies have touched upon the analysis of intercity knowledge collaboration at the megalopolitan scale, let alone the comparison of intercity knowledge collaboration at different geographical scales.

In fact, no matter which type of scale-unit combination is concerned, cities or regions per se cannot automatically become connected with each other. In terms of intercity knowledge collaboration, it is economic entities (e.g., people, firms, universities and research institutes) within cities that collaborate and cities here act as nodes hosting these entities (albeit that urban institutions may support the development of such connections). By aggregating individual knowledge collaboration to the city level, one can then construct urban networks of knowledge collaboration. In this sense, intercity knowledge networks resemble to a large extent those based upon other types of intercity linkages. The major difference, as discussed above, however is that intercity knowledge collaboration exists at different geographical scales while most other types of intercity linkages (e.g., commuting flows) are confined to the megalopolitan scale. Recall that this trans-scalar nature of knowledge collaboration can be used to analyze the hub function of megalopolitan regions. Besides, examining the evolution of urban networks entails time series data

on intercity linkages, a requirement which cannot be met in connection with most types of linkages. However, longitudinal data on knowledge collaboration have been increasingly available and easy to access.

THE RESEARCH REGION, DATA AND METHODS

The Yangtze River Delta Region (YRDR)

The YRDR was forecast by GOTTMANN (1976) forty years ago as one of the six largest megalopolises emerging around the world. Since China's opening up in the 1980s, the region has grown into a highly urbanized area and one of the largest economic, financial and transportation hubs in China. Since 2010 when the Chinese government began to highlight the innovation-driven strategy for the country's development, the YRDR has accelerated its transition of development mode from manufacturing towards innovation. It is in this context that the current study on the knowledge polycentricity of this region is conducted.

The YRDR is officially composed of three provinces (municipalities) with a total number of twenty-five cities. They include one province-level city (Shanghai) under the direct management of the central government, two provincial capitals (Nanjing of Jiangsu province and Hangzhou of Zhejiang province) and twenty-two prefecture-level cities (see Figure 1).

Figure 1 should be inserted around here

Data

Knowledge production is a process whereby tacit and codified knowledge are interacted and converted (NONAKA et al., 2000), which has always made the measurement of knowledge one of the challenges confronting studies on the geography of knowledge. Generally, survey-based data and secondary data based on co-publications and co-patents are two common types of data in empirical studies on knowledge collaboration. Whereas the former has typically been used to analyze the detailed geography of knowledge concerning individual or several cities (SIMMIE, 2003), the latter has been widely used in studies on knowledge networks between cities and regions (e.g., HOEKMAN et al., 2009; ANDERSSON et al., 2014).

As our focus is on the geography of knowledge interaction at macro-geographical scales, secondary data on co-publications and co-patents are more suitable and feasible¹. Further, we rely solely upon data on co-publications in this study for the following reasons. First, whereas co-patents are usually believed to be market driven, co-publications have been found to be spatially and politically biased by ANDERSSON et al. (2014) in their studies on China's intercity knowledge networks. In this sense, analyzing urban networks based on co-publications is more likely to present a true picture of the current Chinese urban system. Second, partly due to its market driven nature, we found that the number of intercity co-patents has fluctuated significantly during the last two decades, which has made it difficult to observe the structural evolution of the YRDR's knowledge system. Third, the inclusion of co-patents in our analysis based on co-publications would play a trivial role in

network structures as the number of co-patents is substantially smaller than that of co-publications.

According to REN and ROUSSEAU (2002), the selection of databases on publications should be dependent on the particular research focus. In line with other studies on Chinese intercity knowledge networks (e.g., MA et al., 2014; ANDERSSON et al., 2014), we use Web of Science Core Collection (WoS) rather than Chinese domestic databases for the following reasons. First, analyzing knowledge collaboration at the global scale, which is a major focus in our analysis, requires the use of publications written through international collaboration which are mainly published in English and included in international databases such as WoS. Second, one could argue that WoS is biased towards publications written through international collaboration as those written through collaboration at the regional and national scales are mainly included in Chinese domestic databases. However, we do not intend to compare the absolute number of co-publications at different geographical scales. The degree of polycentricity is essentially a relative index reflecting the distribution disparity of cities' total publications and co-publications at each geographical scale. Third, as China has been committed to increasing international visibility of its research outputs (REN and ROUSSEAU, 2002), the number of publications written by Chinese authors in WoS has risen markedly. In fact, we retrieved more than 610,000 publications from WoS which were written by at least one author living in a city of the YRDR during the 2000-2014 period². We believe such a large number of observations could provide us with a reasonable if not full

picture of intercity knowledge collaboration within and beyond the region. Fourth, the combination of Chinese domestic databases and WoS, which seems a trade-off to include more papers published in Chinese, has a major problem in the uniformity of data quality. It is commonly believed that getting published in WoS is on average more difficult for Chinese authors than in their domestic databases and thus could require more genuine knowledge collaboration between co-authors.

Despite the aforementioned reasons, we also recognize the limitations of using WoS in this study. According to HASSINK (2007), using only one language to describe and explain the diversity of worldwide phenomena has serious limitations. In this sense, the use of WoS would inevitably lose some information on knowledge interaction between Chinese authors.

Given the substantial number of cities that are located outside the YRDR, not all these cities are considered. As for cities at the national scale, there is a criterion that each city should have over 500 publications in 2014. Although it is an arbitrary threshold value, 39 cities including almost all provincial capital cities, municipalities and other major cities are included in the analysis. The reliability of cities in this list is also supported by the fact that almost all these cities appear in other studies such as MA et al. (2014). Cities at the global scale are selected mainly based on the world city list of TAYLOR et al. (2002)³. The catalogue is supplemented with the top 30 world knowledge centers of MATTHIESSEN et al. (2010), which yields a total number of 133 world cities.

Knowledge collaboration is defined as a pair of unique cities occurring in each

publication. The occurrence of cities that are both located within the YRDR is regarded as knowledge collaboration at the megalopolitan scale. Similarly, if one city is from the YRDR and the other is located outside the region but within China, then the occurrence of cities is defined as knowledge collaboration at the national scale. The same rule applies to knowledge collaboration at the global scale. The frequencies of the occurrence are then counted to measure collaboration strength. The external connectivity of each city is the *sum* of their co-publications with all other cities at each geographical scale. Given space constraints, Figure 2 shows selected intercity knowledge links at different geographical scales in 2000 and 2014.

Figure 2 should be inserted around here

Measuring knowledge polycentricity

Knowledge polycentricity in this study is defined as the polycentric structure of a region's knowledge production and the knowledge collaboration within and beyond that region. Following BURGER and MEIJERS' (2012) approach to morphological and functional polycentricity, knowledge polycentricity can be further classified into attribute polycentricity and functional polycentricity. Whereas the former refers to the distribution inequality of cities' total publications, the latter represents the distribution inequality of cities' external connectivity at different geographical scales. Here attribute polycentricity acts as an indicator for the position of a city in the megalopolitan knowledge production system while functional polycentricity reflects the position of a city in knowledge collaboration systems within and beyond the

megalopolis.

The regression method based on rank-size distribution of cities' connectivity has been widely adopted in measurement of polycentricity (e.g., BURGER and MEIJERS, 2012; BURGER et al., 2014). Although the method is easy to implement, values of goodness-of-fit of regression lines are usually not high which could result in the loss of some data information. Besides, the negative sign of the slope is poorly suited to comparison since people generally expect a positive sign of the degree of polycentricity.

This study draws upon the concept of Gini coefficient, the most commonly used indicator of income inequality which ranges from 0 (perfect equality) to 1 (perfect inequality). In addition to a positive sign, the Lorenz curve which is the best-fitting regression line of the Gini coefficient usually has a high R-square value. The degree of polycentricity can be calculated by adopting the following expression.

$$DP_A = 1 - G_A$$

$$DP_F = 1 - G_F$$

where DP_A and DP_F refer to the degree of attribute and functional polycentricity of the region's knowledge system, while G_A and G_F represent the Gini coefficients of the distribution of cities' total publications and external connectivity respectively. Note that the higher the values of DP_A and DP_F , the more polycentric the region's knowledge system.

THE EVOLUTION OF THE YRDR'S KNOWLEDGE POLYCENTRICITY

Attribute polycentricity of knowledge production of the YRDR

In line with BURGER and MEIJERS (2012), the degree of attribute polycentricity is calculated based on the top four cities with the highest number of publications, while the degree of functional polycentricity is measured based on the top four cities with the highest external connectivity⁴. The top four cities are Shanghai, Nanjing, Hangzhou and Suzhou. As Table 1 shows, they account for a significant proportion of the region's total publications and knowledge links at the national and global scales, although their share of regional knowledge links is relatively low. Figure 3 shows the results of the degree of attribute polycentricity and functional polycentricity at different geographical scales during the 2000-2014 period. The R-squared values of Lorenz curves upon which the results are based are all over 0.99, indicating perfect goodness-of-fit of regression lines.

Table 1 should be inserted around here

Figure 3 should be inserted around here

The degree of attribute polycentricity increased from 0.549 in 2000 to 0.651 in 2014, indicating that the structure of the YRDR's knowledge production has become more polycentric. The ever-increasing degree of attribute polycentricity also suggests that the disparity in the number of total publications of the top four cities has been narrowing gradually. In fact, the number of publications in 2000 by authors in

Shanghai (the first city) was over two times that of those in Nanjing (the second) and twenty-eight times that of those in Suzhou (the fourth). However, the situation changed markedly in 2014. Although Shanghai's dominant role still remains unshakeable, it became less prominent as its number of publications was less than 1.5 times that of Nanjing and around seven times that of Suzhou.

Recalling that attribute polycentricity functions as an indicator for the position of a city in the knowledge production system of the YRDR, we can see that the role played by three other cities (i.e., Nanjing, Hangzhou and Suzhou) has strengthened in relative terms and may be part of the story of China's recent emergence as a leading nation in science (ZHOU and LEYDESDORFF, 2006). Guided by a series of policies such as 'Medium- and Long-Term Plan for Development of Science and Technology' (MINISTRY OF SCIENCE AND TECHNOLOGY, 2006), research resources have been focused on less developed cities and regions as there is still significant inter-regional disparity of research systems in China (OECD, 2007; NIU et al., 2011). As a result, universities and research institutes at these three cities which traditionally have had fewer research resources than their counterparts in Shanghai are likely to have benefited from the greater funding opportunities provided by central government and local authorities.

Functional polycentricity of knowledge collaboration within and beyond the YRDR

As Figure 3 shows, the change in the degree of functional polycentricity of the YRDR's knowledge system at different geographical scales has differed a lot during

the 2000-2014 period. At the megalopolitan scale, there has been a stable increase in the degree of functional polycentricity from 0.717 to 0.796, implying that the structure of intercity knowledge collaboration within the YRDR has been more functionally polycentric. The result is in line with studies on the functionally polycentric structures of other subsystems of megalopolises. For instance, De GOEI et al. (2010) provide some evidence for urban network development in the Greater South East region of United Kingdom based on commuting patterns. ZHAO et al. (2015) find an increasing degree of functional polycentricity of the YRDR based on intercity firm linkages. However, caution should be exercised when drawing the conclusion that the YRDR has generally been more functionally polycentric given the multiplexity of functional polycentricity (BURGER et al., 2014). Urban networks are diverse and complex (van MEETEREN et al., 2016b), so generalization of their structures could require a substantial discussion of mechanisms which is beyond the scope of this paper.

At the national scale, the degree of functional polycentricity has risen markedly from 0.554 to 0.683 although with a slight decline between 2003 and 2008. The result implies that the structure of knowledge collaboration between cities within the YRDR and cities at the national scale has been on its way towards becoming more functionally polycentric and that the disparity in national knowledge links of cities within the YRDR has been narrowing gradually. For instance, the national knowledge links of Shanghai were sixteen times those of Suzhou in 2000 but this ratio had declined to just five times by 2014. This finding conforms to the study of HONG

(2008) which finds a decentralizing process of knowledge collaboration center among Chinese provinces.

At the global scale, we can obviously see the significant fluctuations that have been associated with the degree of functional polycentricity, although it has grown slightly from 0.535 to 0.562. The result indicates that the structure of knowledge collaboration between cities within the YRDR and cities at the global scale can hardly be considered functionally polycentric at present although it has been evolving slowly towards to becoming so. In fact, the global knowledge links of the YRDR has been mainly dominated by Shanghai. In 2014, for instance, Shanghai accounted for 51.1% of the total global knowledge links of the top four cities.

Comparing attribute and functional polycentricity

A comparison between attribute and functional polycentricity as well as a comparison between functional polycentricity at different geographical scales helps us get a better understanding of the polycentric structure of knowledge production and knowledge collaboration within and beyond the YRDR.

First, the structure of intercity knowledge collaboration within the YRDR is more polycentric than that of knowledge production of the YRDR. Recent years have even seen a larger degree of functional polycentricity at the national scale than that of attribute polycentricity. Although the finding conforms to BURGER and MEIJERS (2012), it differs somewhat from HALL and PAIN (2006) and LIU et al. (2016). The different approaches to measuring the degree of polycentricity and the focus on

different subsystems of megalopolises could be the two reasons explaining the difference. However, the result itself is of significance as it partly reflects the ever-increasing intercity knowledge collaboration in China. In other words, it has been increasingly common for universities and research institutes to collaborate with their counterparts in other cities rather than relying solely upon their own resources.

Second, the degree of functional polycentricity decreases as the geographical scale increases. In other words, the structure of intercity knowledge collaboration within the YRDR is most polycentric, followed by that of knowledge collaboration of cities in the YRDR and cities at the national scale and that of knowledge collaboration of cities in the YRDR and cities at the global scale. This is consistent with other studies such as HALL and PAIN (2006), TAYLOR et al. (2008) and HANSSENS et al. (2014). The finding implies that the regional and national knowledge linkages of cities in the YRDR are more evenly distributed than their global knowledge linkages which, as can be supposed, are dominated by Shanghai.

The incubator and hinge roles played by the YRDR in knowledge production and collaboration

Given the complexity and diversity of megalopolises, it could be difficult to examine the incubator and hinge roles of the YRDR through a comprehensive analysis of its different subsystems. Nonetheless, the multi-scalar and dynamic analysis of the polycentric structure of knowledge production and knowledge collaboration within and beyond the YRDR has already provided some evidence relating to the two

important roles of the region.

In terms of the ‘incubator’ role, it can be argued that the YRDR has been acting as an incubator of knowledge at the megalopolitan scale. Moreover, the polycentric structure of the region’s knowledge production indicates that the ‘incubator’ role is fulfilled not only by its primate city—Shanghai, but also by other major cities like Nanjing, Hangzhou and Suzhou. In fact, Shanghai only accounted for 37.2% of the region’s total publications in 2014, dropping from 52.5% in 2000. Apart from the aforementioned policies encouraging a more balanced distribution of research resources, rises in the number of universities and research institutes hosted as well as in their economic strength are other two factors that may also account for the emergence of these three ‘incubator’ centers. For instance, the number of higher education institutes in Nanjing has grown from 38 in 2004 to 59 in 2014 which is now quite close to that of Shanghai. As most of the public research institutes are funded by local governments in China (SCHERNGELL and HU, 2011), cities with stronger economic performance are more likely to become ‘incubator’ centers. This helps to explain why Hangzhou and Suzhou (which, compared with the situation of Nanjing, have less number of higher education institutes but larger GDP) have also become ‘incubator’ centers.

The ‘hinge’ role played by the YRDR in knowledge collaboration is mainly performed by Shanghai at the national scale. As Figure 2 shows, Shanghai’s national knowledge links are the strongest, followed by its international and regional links. This is, to some extent, in line with the analysis of TANG and ZHAO (2010) which

finds that Shanghai's international inter-firm linkages are significantly larger than its regional linkages. In fact, Shanghai has been replaced by Nanjing as the city with the strongest regional knowledge links since 2012. This supports an argument that 'some centers fulfil a global or national function, while other centers fulfil a more regional or local function' (BURGER and MEIJERS, 2012: 1132). In the study of LI and PHELPS (2016), they explain the emergence of Nanjing as a regional hub of knowledge collaboration by referring to the spatial political bias and same-province effect in China's intercity knowledge collaboration (ANDERSSON et al., 2014). Here regional protectionism may be another explanation. Although the central government has promoted inter-provincial scientific collaboration, it has been claimed that regional authorities at the provincial level - which aim to maximize intra-provincial benefits - prefer to encourage and fund knowledge collaboration between cities from the same province (CHEN and ZHANG, 2003; SCHERNGELL and HU, 2011).

In terms of the YRDR's 'hinge' role in knowledge collaboration at the global scale, it should be noted that Shanghai has strengthened its knowledge links with international cities during the 2000-2014 period as reflected by the increase in the number of the top fifteen global knowledge links that are involved with Shanghai. However, instability in the degree of functional polycentricity at the global scale, the weakening regional knowledge links and the relatively low international knowledge links of Shanghai all suggest that the YRDR may still have a way to go before fulfilling the sort of 'hinge' role in knowledge collaboration that Gottmann saw as part of the functional properties of megalopolitan areas at the global scale.

CONCLUSION

This study builds upon the recent resurgent interest in the concept of polycentricity which has been understood from different perspectives. One perspective that has gained popularity in recent years is the measurement of polycentricity by distinguishing between morphological and functional polycentricity (BUEGER and MEIJERS, 2012). However, many of the contributions to the measurement of polycentricity have adopted a static approach, focused merely on economic and commuting linkages of megalopolises and been conducted solely at the megalopolitan scale. This study, therefore, aims to shed light on the polycentric development of the structure of knowledge production and knowledge collaboration within and beyond one of China's megalopolises—the Yangtze River Delta Region (YRDR).

In doing so, the often overlooked functions of megalopolises as 'hinges' and 'incubators' which were stressed by GOTTMANN (1976) forty years ago are re-highlighted in this study. Meanwhile, in contrast to intercity economic and transportation linkages that have been mainly adopted in studies on polycentricity and urban networks of China's megalopolises (e.g., LIU et al., 2016; ZHAO et al., 2015; LUO et al., 2011), intercity knowledge collaboration upon which this study focuses enables us to observe the polycentric development of the YRDR's knowledge system and its relationship with other knowledge systems at the national and global scales.

The empirical results confirm that the knowledge perspective helps to understand the process of polycentric development of megalopolises. During the 2000-2014 period, the structure of the region's knowledge production and knowledge

collaboration within and beyond the region has generally become more polycentric although to different degrees. Specifically, whereas the structure of global knowledge links of cities in the YRDR is least polycentric, the structure of regional knowledge links of cities in the YRDR is most polycentric which is followed by the structure of the region's knowledge production and the structure of their national knowledge links.

The empirical results, together with a comparison of the strength of intercity knowledge collaboration at different geographical scales, also suggest that the 'incubator' and 'hinge' roles are played by the YRDR at different geographical scales. While the YRDR has been an incubator of knowledge at the megalopolitan scale, the YRDR's hinge role in knowledge collaboration has been mainly played at the national scale and it may take some time for the region to act as a knowledge hinge at the global scale.

The framework of this study clearly has limitations. Nevertheless, it is our hope that this will open a new research agenda that encourages elements of theoretical and empirical integration of relatively weakly connected bodies of literature. These include notably, the world city networks literature and the polycentric urban regions literature⁵ discussed here. However, our emphasis upon *process* and upon *knowledge linkages* also opens questions relating to evolutionary economic geography and the geography of global cluster networks (BATHELT and LI, 2013). For instance, it opens questions of how the polycentric structure of knowledge production and knowledge collaboration within and beyond megalopolises co-evolves with the structures of other subsystems of megalopolises and of the particular mechanisms behind the evolution

of knowledge polycentricity? Taken together, these bodies of literature may provide distinct and partially complementary perspectives on the ‘hub’ and ‘incubator’ functions of megalopolises in a globalizing knowledge economy.

In terms of data, methods and cases, future research might explore the use of data on co-patents to reveal the patterns of knowledge collaboration within and beyond megalopolises and the results could serve as a comparison with those based on co-publications. Besides, a comparative study on the development of knowledge polycentricity of China’s other megalopolises is necessary to see whether the findings based on the YRDR could be generalized or whether they differ from each other.

ACKNOWLEDGEMENTS

The authors would also like to thank the editor and two anonymous referees for their very helpful and constructive comments. However, the authors take sole responsibility for their views. The first author would also like to acknowledge the China Scholarship Council for award No. 201406090167.

NOTES

1. While relying upon secondary data, we admit the limitations of measuring knowledge by codified forms. For instance, tacit knowledge which is mainly related to face-to-face contacts cannot be recorded by publications or patents. Besides, not all research leads to publications or patents. However, it has also been acknowledged that publications and patent are of great value for macro-scale studies on the geography of knowledge, as they often contain detailed information

on researchers' addresses and data on publications and patents are continuous and easy to access (see also Hoekman et al. (2009)).

2. This period is selected because the WoS database only reported a very small number of co-publications before 2000.
3. The world city list of Taylor et al. (2014) which covers over 500 cities is not used. On the one hand, it is extremely time-consuming to search co-publications between the YRDR cities and these world cities. On the other hand, the number of co-publications is very limited even between the YRDR cities and most of the 133 world cities selected in this study. As a result, it is believed that the 133 world cities included in the analysis can cover most of the world cities that have meaningful knowledge collaboration with the YRDR cities.
4. We did not use the top three and the top five cities for the following reasons. First, measurement of Gini coefficient could be more precise based on four cities than that based on three cities. Second, the composition of the top five cities keeps changing. However, it could be better to observe the evolution of cities' relative importance within a stable structure of urban hierarchy.
5. There are some studies that have already noticed the relationship between world city networks and national urban systems (see TAYLOR and DERUDDER, 2016 and MA and TIMBERLAKE, 2013).

REFERENCES:

ANDERSSON D. E., GUNESSEE S., MATTHIESSEN C. W. and FIND S. R. (2014)

The geography of Chinese science, *Environment and Planning A* 46, 2950-71.

BAIGENT E. (2004) Patrick Geddes, Lewis Mumford and Jean Gottmann: divisions over 'megalopolis', *Progress in Human Geography* 28, 687-700.

- BATHELT H. and LI P. F. (2013) Global cluster networks--foreign direct investment flows from Canada to China, *Journal of Economic Geography* 14, 45-71.
- BIRD, J. (1983) Gateways: slow recognition but irresistible rise', *Tijdschrift voor Economische en Sociale Geografie* 74: 196-202
- BURGER M. and MEIJERS E. (2012) Form Follows Function? Linking Morphological and Functional Polycentricity, *Urban Studies* 49, 1127-49.
- BURGER M. J., Van der KNAAP B. and WALL R. S. (2014) Polycentricity and the multiplexity of urban networks, *European Planning Studies* 22, 816-40.
- CHAMPION, A.G. (2001) 'A changing demographic regime and polycentric urban regions: consequences for the size, composition and distribution of city populations', *Urban Studies* 38: 657-677
- CHEN C. T. and WANG T. (2003) The influence to the local S&T legislation from the view of CASToperation mode forum on science and technology in China, *Forum on Science and Technology in China* 4, 3-6. (In Chinese)
- DAVOUDI S. (2003) Polycentricity in European spatial planning: from an analytical tool to a normative agenda, *European Planning Studies* 11, 979-99.
- De GOEI B., BURGER M. J., Van OORT F. G. and KITSON M. (2010) Functional Polycentrism and Urban Network Development in the Greater South East, United Kingdom: Evidence from Commuting Patterns, 1981-2001, *Regional Studies* 44, 1149-70.
- GEDDES P. (1915). *Cities in evolution: An introduction to the town planning movement and to the study of civics*. London: Williams & Norgate.

- GOTTMANN J. (1957). Megalopolis or the Urbanization of the Northeastern Seaboard. *Economic Geography* 33, 189-200.
- GOTTMANN J. (1964) *Megalopolis: The Urbanized Northeastern Seaboard of the United States*. MIT Press, Cambridge, MA.
- GOTTMANN J. (1976). Megalopolitan systems around the world. *Ekistics*, 243, 109-13.
- HALL P. G. and PAIN K. (2006). *The polycentric metropolis: learning from mega-city regions in Europe*. Routledge.
- HANSSENS H., DERUDDER B., Van AELST S. and WITLOX F. (2014) Assessing the functional polycentricity of the Mega-City-Region of central Belgium based on advanced producer service transaction links, *Regional Studies* 48, 1939-53.
- HARRISON J. and HOYLER M. (Eds.). (2015). *Megaregions: Globalization s New Urban Form?* Cheltenham: Edward Elgar Publishing.
- HASSINK R. (2007) It's the language, stupid! On emotions, strategies, and consequences related to the use of one language to describe and explain a diverse world, *Environment and Planning A* 6, 1282-87.
- HOEKMAN J., FRENKEN K. and van OORT F. (2009) The geography of collaborative knowledge production in Europe, *The Annals of Regional Science* 43, 721-38.
- HONG W. (2008) Decline of the center: The decentralizing process of knowledge transfer of Chinese universities from 1985 to 2004, *Research Policy* 37, 580-95.
- LANG R. and KNOX P. K. (2009) *The New Metropolis: Rethinking Megalopolis*,

Regional Studies 43, 789-802.

LI Y. and PHELPS N. (2016). Megalopolis unbound: Knowledge collaboration and functional polycentricity within and beyond the Yangtze River Delta Region in China, 2014. *Urban Studies*, DOI:10.1177/0042098016656971.

LIU X., DERUDDER B. and WU K. (2016) Measuring polycentric urban development in China: An intercity transportation network perspective, *Regional Studies* 8, 1302-15.

LUO Z., HE H. and GENG L. (2011) Analysis of the polycentric structure of Yangtze River Delta based on passenger traffic flow, *Urban Planning Forum* 2, 16-23 (In Chinese).

MA H., FANG C., PANG B. and LI G. (2014) The effect of geographical proximity on scientific cooperation among Chinese cities from 1990 to 2010, *PLoS One* 9, e111705.

MA X. and TIMBERLAKE M. (2013) World city typologies and national city system deterritorialisation: USA, China and Japan, *Urban Studies* 2, 255-75.

MATTHIESSEN C. W., SCHWARZ A. W. and FIND S. (2010) World cities of scientific knowledge: Systems, networks and potential dynamics. an analysis based on bibliometric indicators, *Urban Studies* 47, 1879-97.

MEIJERS E. (2008) Measuring polycentricity and its promises, *European Planning Studies* 16, 1313-23.

MINISTRY OF SCIENCE AND TECHNOLOGY (2006) Medium- and long-term plan for development of science and technology in China,

http://www.gov.cn/jrzq/2006-02/09/content_183787.htm. (In Chinese)

- MUMFORD L. (1938). *The culture of cities*. London: M. Secker and Warburg.
- NIJMAN, J. (2011) *Miami: Mistress of the Americas*. Philadelphia: University of Pennsylvania Press.
- NIU F., LIU W., LIU Z. et al. (2011) Relationships between public scientific & technological resources and regional economic development in China, *Economic Geography* 4, 541-47. (In Chinese)
- NONAKA I., TOYAMA R., & KONNO N. (2000) SECI, Ba and leadership: a unified model of dynamic knowledge creation, *Long range planning* 1, 5-34.
- ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT (OECD) (2007) OECD Reviews of innovation policy China. Synthesis Report. OECD, Paris.
- PAIN K. (2011) 'New Worlds' for 'Old'? Twenty-First-Century gateways and corridors: Reflections on a European spatial perspective. *International Journal of Urban and Regional Research* 6, 1154-74.
- PARR, J. (2004) 'The polycentric urban region: a closer inspection', *Regional Studies* 38: 231-40.
- PHELPS N. A. and OZAWA T. (2003) Contrasts in agglomeration: proto-industrial, industrial and post-industrial forms compared, *Progress in Human Geography* 27, 583-604.
- REN S. and ROUSSEAU R. (2002) International visibility of Chinese scientific journals, *Scientometrics* 53, 389-405.

- SCHERNGELL T. and HU Y. (2011) Collaborative Knowledge Production in China: Regional Evidence from a Gravity Model Approach, *Regional Studies* 45, 755-72.
- SHORT J. R., BREITBACH C., BUCKMAN S., & ESSEX J. (2000) From world cities to gateway cities: Extending the boundaries of globalization theory. *City: analysis of urban trends, culture, theory, policy and action* 3, 317-40.
- SIMMIE J. (2003) Innovation and Urban Regions as National and International Nodes for the Transfer and Sharing of Knowledge, *Regional Studies* 37, 607-20.
- SWYNGEDOUW E. (2004) Globalisation or 'glocalisation' Networks, territories and rescaling, *Cambridge Review of International Affairs* 17, 25-48.
- TANG Z. and LI T. (2010) Economic globalization and transformation of urban systems in the Yangtze River Delta Region: Interlocking network and value-added hierarchy, *Urban Planning Forum* 1, 29-34. (In Chinese)
- TAYLOR P. J., CATALANO G. and WALKER D. R. F. (2002) Measurement of the World City Network, *Urban Studies* 39, 2367-76.
- TAYLOR P. J., EVANS D. M. and PAIN K. (2008) Application of the Interlocking Network Model to Mega-City-Regions: Measuring Polycentricity Within and Beyond City-Regions, *Regional Studies* 42, 1079-93.
- TAYLOR P. J. and DERUDDER B. (2016) *World city network: A global urban analysis*. Routledge.
- van MEETEREN M., POORTHUIS A., DERUDDER B. and WITLOX F. (2016a) Pacifying Babel's Tower: A scientometric analysis of polycentricity in urban research, *Urban Studies* 6, 1278-98.

- van MEETEREN M., NEAL Z. and DERUDDER B. (2016b). Disentangling agglomeration and network externalities: A conceptual typology, *Papers in Regional Science* 1, 61-80.
- van OORT F., BURGER M. and RASPE O. (2010) On the economic foundation of the urban network paradigm: spatial integration, functional integration and economic complementarities within the Dutch Randstad, *Urban Studies* 47, 725-48.
- VASANEN A. (2012) Functional polycentricity: examining metropolitan spatial structure through the connectivity of urban sub-centers, *Urban Studies* 49, 3627-44.
- VICINO T. J., HANLON B. and SHORT J. R. (2007) Megalopolis 50 Years On: The Transformation of a City Region, *International Journal of Urban and Regional Research* 31, 344-67.
- ZHANG X., & KLOOSTERMAN R. C. (2016) Connecting the 'workshop of the world': Intra-and extra-service networks of the Pearl River Delta city-region. *Regional Studies*, 50(6), 1069-81.
- ZHAO M., ZHONG Y. and XU G. (2015) Polycentric progress of the three major city regions in China, 2001-2009, *Economic Geography* 35, 52-59. (In Chinese)
- ZHOU P. and LEYDESDORFF L. (2006) The emergence of China as a leading nation in science, *Research Policy* 35, 83-104.

Table 1 The top four cities' publications and knowledge links at different geographical scales and their respective shares of the total

Year	Total publications		Regional connectivity		National connectivity		Global connectivity	
	Top 4	Share	Top 4	Share	Top 4	Share	Total	Share
2000	8461	95.3%	542	80.2%	1710	95.6%	1173	97.3%
2001	9832	94.0%	732	79.4%	2042	93.0%	1282	94.8%
2002	11342	92.7%	869	75.6%	2343	91.7%	1577	94.9%
2003	14304	92.9%	1280	72.8%	2967	92.4%	1973	95.2%
2004	19059	91.4%	1740	73.4%	4533	91.6%	2607	95.3%
2005	24115	90.5%	2157	70.4%	5536	89.6%	3121	95.0%
2006	29142	89.1%	2779	71.1%	6754	89.2%	3889	94.2%
2007	33757	88.2%	3035	68.7%	7126	87.7%	4052	93.3%
2008	39966	87.8%	3786	69.9%	8678	87.6%	5026	94.1%
2009	47073	85.8%	4799	67.8%	10119	85.2%	6088	92.8%
2010	45997	85.0%	5452	66.8%	12014	85.5%	8242	92.6%
2011	55126	82.6%	7002	65.3%	15105	84.7%	11638	93.9%
2012	63818	82.8%	8831	64.3%	19482	84.6%	18118	94.6%
2013	74771	82.9%	11490	64.7%	24361	84.6%	19873	93.2%
2014	82692	82.0%	13220	62.9%	27868	82.2%	24003	93.0%

Figure 1 The Yangtze River Delta Region

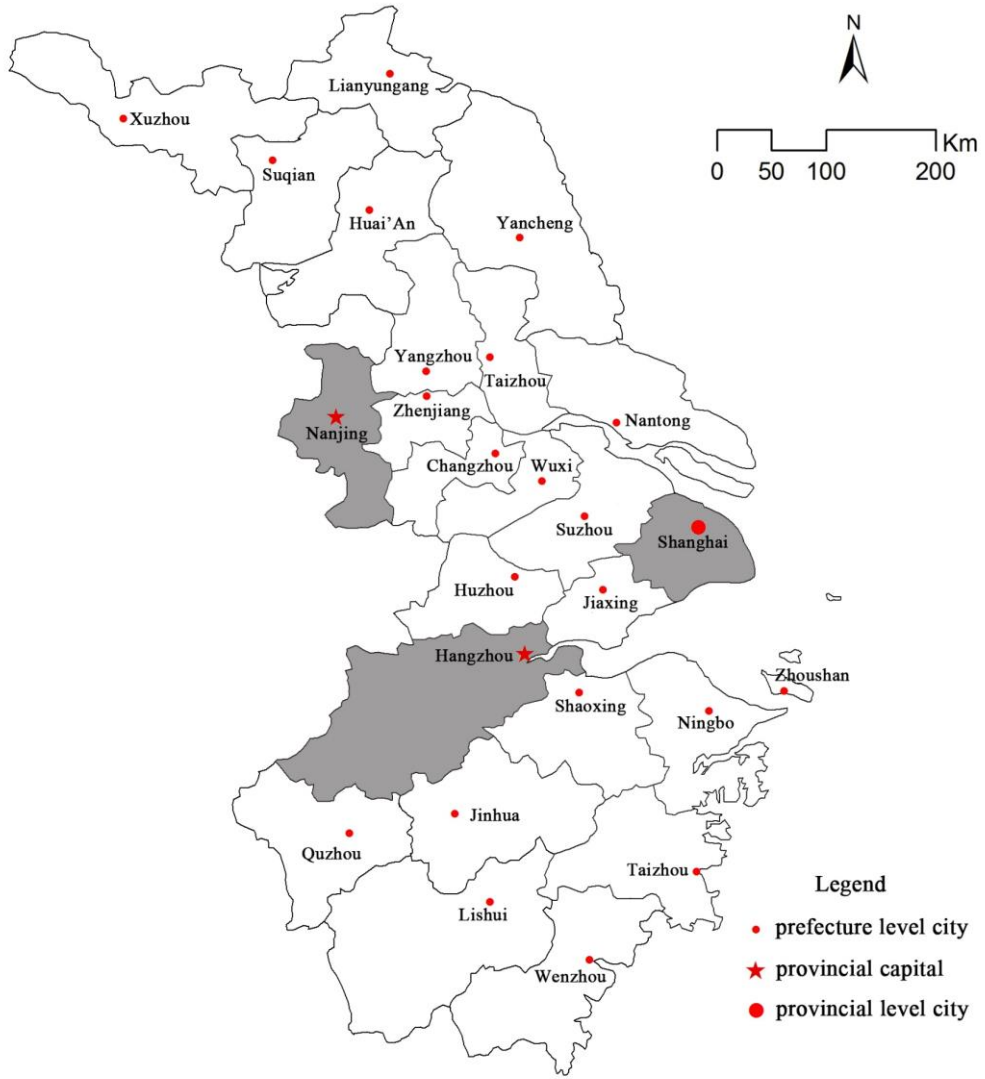


Figure 2 The top fifteen intercity knowledge links at different geographical scales in 2000 and 2014

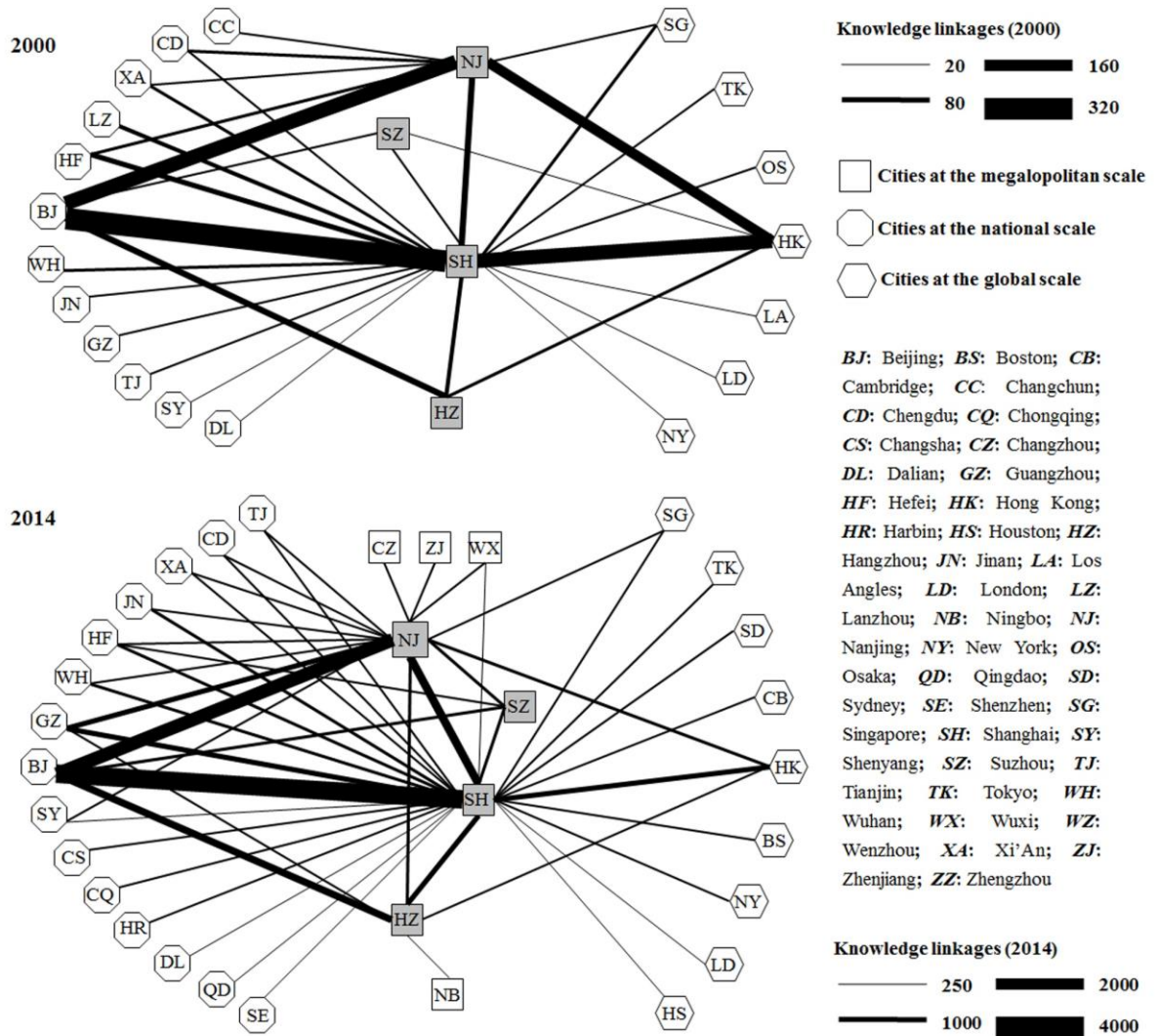


Figure 3 The degree of attribute and functional polycentricity at different geographical scales of the YRDR's knowledge system, 2000-2014

