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RESEARCH ARTICLE

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Polycentricity measurement of China's urban agglomerations considering internal and external connections

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Abstract

This paper uses Baidu migration data to obtain the intercity trips between cities in China. Taking intercity travel as a functional connection between cities, taking into account the internal and external intercity travel connections of urban agglomerations, an improved rank scale distribution method was used to quantitatively measure the form and function of the Beijing-Tianjin-Hebei, Yangtze River Delta, Pearl River Delta, middle reaches of the Yangtze River, Chengdu-Chongqing, Central Plains, Guanzhong, and Harbin-Changchun urban agglomerations. It is found that, firstly, there are differences in the Functional Polycentricity presented by the internal and external connections of urban agglomerations, which are related to the economic development of urban agglomerations and central cities. Secondly, there are differences between Morphological Polycentricity and Functional Polycentricity of the eight urban agglomerations measured by the internal and external connections, indicating that the external connections have a significant impact. The internal and external connections of urban agglomerations are important functional connections of urban agglomerations. The study of urban agglomerations should not ignore the internal or external connections, and the overall consideration can more comprehensively reflect the polycentric characteristics of urban agglomerations. The internal and external connections of urban agglomerations are important functional connections, and the study of urban agglomerations should not ignore internal or external connections. Overall consideration can better reflect the polycentirccharacteristics of urban agglomerations.

Keywords Polycentricity, Urban agglomeration, Internal and external connections, Rank-size, Intercity trips

1 Introduction

Polycentricity has long been regarded as an advanced stage of urban agglomeration development, and it is also a hot topic in academic research. As globalization brings about uneven regional development, the role of polycentricity in achieving synergy and functional complementarity among different cities has become the goal of urban agglomerations and city regions to seek balanced development (Hall & Pain, 2006). A large number of relevant studies have shown that polycentric regions have advantages over monocentric regions, which can ensure the balanced development of the region and alleviate the excessive concentration of the economy and population (Meijers, 2007; Meijers & Romein, 2003; Parr, 2004).

Since China's Reform and Opening-up Policy in the 1980s, the Chinese central government has attached great importance to urban economic development and promoted the government's assessment system with GDP as the core, which has led governments at all levels to fully promote their economic development for their political achievements. Although 40 years of practice has significantly promoted the rapid development of China's

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urban economy, it has also brought about "competition" among Chinese local city governments (Ma, 2002). These Chinese cities will support local economic development by formulating direct or indirect administrative policies, such as formulating preferential policies for urban investment promotion or restricting foreign investment in local enterprises (Gu et al., 2012). The free circulation of development factors in the region is restricted by administrative intervention, which restricts the process of regional integration. With the advancement of China's new urbanization strategy, it has become a national strategy to promote regional development through urban agglomerations and achieve the integration and development of different regions.[1] The integrated development of China's urban agglomerations is consistent with the development goals of polycentric regions in other countries. Therefore, the polycentricity of urban agglomerations is an important indicator for judging the development of regional integration.

Most of the developed countries in the world have made a lot of progress in the research on the polycentricity of major urban areas. A typical example is the EU PLOYNET project led by Hall and Pain, which measured the polycentricity of eight European mega-urban regions (Hall & Pain, 2006). In comparison, relevant research in China mainly focuses on the polycentricity of the Beijing-Tianjin-Hebei, Yangtze River Delta, and Pearl River Delta urban agglomerations, which cannot fully reflect the degree of polycentric development of urban agglomerations in China (Luo et al., 2011; He et al., 2021; Wen & Thill, 2016). Liu et al. (2016) calculated the polycentricity of 22 urban agglomerations in China, but the scope of major urban agglomerations is not consistent with the latest national planning.

The change in the measurement method of polycentricity from the dimension of spatial form to measure the dimension of urban scale to the dimension of functional connection represented by the "flow" between cities is called the "Paradigm Shift" (Burger & Meijers, 2012). Current "flow" data are mainly divided into two types of "flow" —— "flow" simulated by traditional quantitative models and the real "flow" measured from physical environments. 1) Since the early research could not directly observe the real "flow", the static data was transformed into an abstract "flow" with the help of traditional quantitative models such as mathematical models, gravitational models, and radiation models. The method was relatively mature, and socioeconomic statistics were public and easy to obtain (Taylor et al., 2002). 2) The real "flow" refers to the measured flow of people, logistics, capital flow, and other data, such as real commuting, recreation and other residents' traffic travel data between cities, commercial investment amount between cities, and other data. Some early studies tried to use postal data as information "flow" and traffic surveys as traffic "flow" to represent the real "flow" between cities (Green et al., 1955; Mitchelson & Wheeler, 1994). However, the traditional traffic survey method has targeted content. It can not only directly analyze the interconnection between cities, but also make up for the shortcomings of the traditional quantitative model method. The disadvantage is that the survey workload is extremely high and the cost is extremely high, especially for domestic traffic survey data. It is limited to the inner city, and no cross-city travel is investigated, and the results of the investigation are usually kept secret. Some studies obtain passenger frequency data, and use high-speed rail, highway, and other public passenger frequencies instead of traffic "flow", but the samples are incomplete and unevenly distributed. With the development of information technology and the advent of the Internet age, the threshold for obtaining measured "flow" data has been significantly lowered. For example, measuring traffic "flow" with mobile positioning big data (Ratti et al., 2006). The flow of information is represented by mobile phone calls or the Internet (Camagni et al., 1994).

Contemporary cities and urban agglomerations are no longer entities that operate independently, but there is an increasing interaction of multiple functional types with each other, and each city has more functional connections with the "external world" (Lambregts, 2009; Wall, 2009). At present, the measurement method of polycentricity pays more attention to the internal connection of urban agglomeration, mainly because it is difficult to obtain the external connection of urban agglomeration synchronously. There is a lack of relevant research to measure the polycentricity of urban agglomerations taking into account both internal and external connections, as well as the differences in internal and external connections.

This paper uses Baidu's national migration data as real "flow" data to identify the internal and external connections of major urban agglomerations in China and measure the polycentricity of urban agglomerations.

2 Research methods

2.1 Polycentric form

Most relevant studies divide the polycentricity into three levels: 1) the metropolitan area composed of cities and suburbs; 2) the polycentric urban area composed of

[1] On November 18, 2018, the Central Committee of the Communist Party of China and the State Council issued the "Opinions of the Central Committee of the Communist Party of China and the State Council on Establishing a More Effective New Mechanism for Regional Coordinated Development".

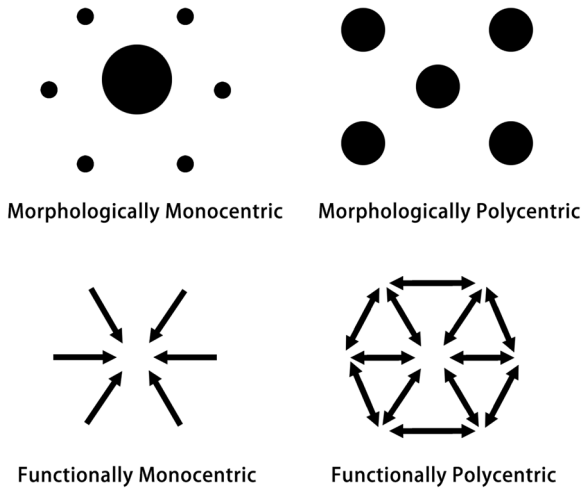

Fig. 1 Morphological Polycentricity and Functional Polycentricity. Source: Burger & Meijers (2012)

multiple balanced metropolitan areas, such as the Randstad in the Netherlands, the Rhine-Ruhr area in Germany and the Kansai region of Japan; 3) several polycentric urban areas form a polycentric area. For example, the Randstad in the Netherlands, the Rhine-Ruhr area in Germany, and Brussels-Flanders tend to form a transnational polycentric macro-region (Batten, 1995; Dieleman & Faludi, 2010). The spatial scale of urban agglomerations in China is between urban regions and regions.

Describing the spatial structure of urban agglomerations with functional connections changes the measurement of spatial structure from spatial forms represented by agglomeration scales such as population size, employment, and economy to functional connections represented by "flow spaces" such as traffic flow and information flow. Polycentricity will shift from "Morphological Polycentricity" to "Functional Polycentricity" (Burger & Meijers, 2012). Morphological Polycentricity represents the accumulation scale of each city, reflecting the absolute importance; while Functional Polycentricity represents the ability of each city's surrounding areas to provide functions such as goods, services, and jobs, reflecting the relative importance (Fig. 1). This article will combine Morphological Polycentricity and Functional Polycentricity to reflect the polycentricity of urban agglomeration.

2.2 Polycentricity measurement method

There are usually two methods for measuring polycentricity: the network density method based on social network analysis and the improved rank-size distribution method.

The network density method uses the network density to reflect the degree of interdependence between central cities and proposes to measure polycentricity by the standard deviation of the amount of attraction between network nodes and network density (Green, 2007). This approach employs functional linkage data, further considering the relative strength of linkages and the density of association networks. The application of Hall and Pain in the EU PLOYNET project research is also a method commonly used by domestic scholars in China (Luo et al., 2011; Liu et al., 2016). Although this method has been influential, recent studies have found that urban systems with unbalanced functional linkages and high network density will receive similar scores to urban systems with balanced functional linkages and low network density. It is therefore believed that the network density method would adversely affect the measurement of Functional Polycentricity (Burger & Meijers, 2012).

Therefore, based on the traditional rank-size distribution method, Burger and Meijers (2012) used static statistical data to measure the degree of Morphological Polycentricity, and used real functional linkage data to measure the degree of Functional Polycentricity. The improved method has strong operability, makes up for the defects of the network density method, and can simultaneously measure Morphological Polycentricity and Functional Polycentricity. This paper argues that the innovation of Burger's method, in addition to adding functional contact data to measure polycentricity, also proposes to divide city centrality into internal centrality and external centrality. The specific calculation formula is as follows:

$$Cci = Nc - Cce - Lc \tag{1}$$

Among them, "Cci" is the "Internal Centrality" of the city, which is measured by the inflow intensity of other cities within the urban agglomeration, reflecting the feature of Functional Polycentricity; "Cce" is the "External Centrality" of the city, which is measured by the inflow intensity of other cities outside the urban agglomeration, reflecting the characteristics of Functional Polycentricity; "Lc" is the local importance of the city, measured by the internal flow of the city; "Nc" is the absolute importance of the city, that is, "Nodality", presented together by the city's local importance, internal centrality, and external centrality, reflecting the characteristics of Morphological Polycentric.

Based on the above calculation of centrality and nodality, Burger's method uses logistic regression to analyze the scale and ranking of urban centrality and nodality and estimates the degree of polycentricity by the slope of the regression line. The formula is as follows:

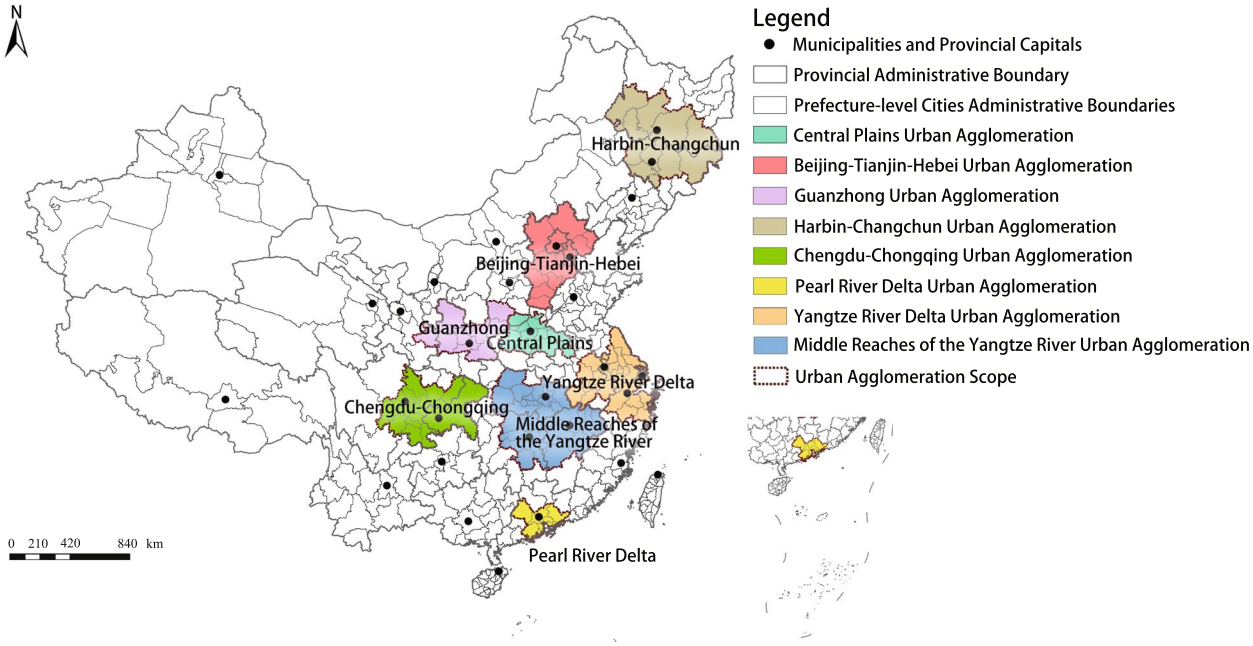

Fig. 2 Spatial distribution of 8 urban agglomerations. Source: Author

$$LN(Size) = \alpha + \beta * LN(Rank - 1/2) \quad (2)$$

Among them, "Size" is the scale of the central city, and "Rank" is the ranking of the scale of that. The purpose of "(Rank-1/2)" is to avoid strong bias in small samples and reduce the ranking bias to a major order. Studies have shown that the β result obtained by the shift of 1/2 is optimal (Gabaix & Ibragimov, 2011). The flatter the regression line, the closer the slope β value is to 0, and the higher the degree of polycentricity.

Although Burger's method divides urban centrality into internal centrality and external centrality, it emphasizes that the polycentricity of current urban agglomerations should reflect the importance of cities with internal centrality, ignoring that external centrality also reflects the status of cities. This paper improves on Burger's method by emphasizing the impact of external linkages on the polycentricity of urban agglomerations. The improved calculation formula is as follows:

$$Cc = Nc - Lc \quad (3)$$

$$Cc = Cci + Cce \quad (4)$$

Among them, "Cc" is the relative importance of the center which represents Functional Polycentricity, including the inner centrality "Cci" and the external centrality "Cce" of the city. In Burger's research, "Cci" and "Cce" are the commuter links between cities as the flow, and "Lc" is the number of local employees in the city. Due to the large scale of urban agglomerations in China, there are fewer high-frequency commutes between cities, but relatively large low-frequency intercity trips. Intercity travel includes travel behaviors for different purposes such as commuting and recreation, and also reflects the functional connection between cities. Scholars around the world have carried out corresponding research (Limtanakool et al., 2009; Niu et al., 2018). Therefore, this paper will use Baidu migration data as the functional connection between cities, and measure the city's local centrality by the size of the city's permanent population. As the resident population data and Baidu migration data cannot be directly superimposed, this study will distinguish and standardize. Finally, the calculation result of "Cc" is calculated by the *formula* (2) to calculate the degree of Morphological Polycentricity and the degree of Functional Polycentricity that take into account internal and external connections.

3 Research scope and data

3.1 Research scope

This paper selects the Beijing-Tianjin-Hebei, Yangtze River Delta, Pearl River Delta, middle reaches of the Yangtze River, Chengdu-Chongqing, Central Plains, Guanzhong and Harbin-Changchun urban agglomerations as the research objects (Fig. 2). Since the definition of the scope of urban agglomerations in China is quite different, the urban agglomerations that have been

Table 1 Basic information of 8 urban agglomerations

Urban Agglomerations	Number of Cities	Main Cities	Area (km^2)	Permanent Residents (million)	GDP (hundred million)	Primacy Ratio	Location	Average Distance between Cities (km)
Beijing-Tianjin-Hebei	13	Beijing, Tianjin	220,248	11,061	80,632	1.39	Northeast	262.17
Yangtze River Delta	26	Shanghai, Nanjing, Hangzhou, Hefei	217,380	15,270	165,194	2.26	Southeast	236.76
Pearl River Delta	9	Guangzhou, Shenzhen	54,647	6151	75,710	1.15	Southeast	100.30
Middle reaches of the Yangtze River	31	Wuhan, Changsha, Nanchang	356,777	12,942	120,602	1.38	South Central	292.60
Chengdu-Chongqing	16	Chengdu, Chongqing	240,120	9960	58,273	1.92	Southwest	191.78
Central Plains	14	Zhengzhou, Luoyang	103,471	6855	35,449	1.13	North Central	158.67
Guanzhong	11	Xi'an	162,599	4390	23,797	1.79	North West	226.63
Harbin-Changchun	11	Harbin, Changchun	346,570	4630	25,344	1.28	Northeast	315.18

Source: Author

approved by the *National Development and Reform Commission (NDRC)* are selected as the research objects.[2] There are obvious differences in the size, location, economy, transportation, and other developments of the above eight urban agglomerations (Table 1), which can reflect the overall characteristics of the development of urban agglomerations in China.

3.2 Research data

The Baidu migration data used in this study focuses on short-term intercity travel between cities across China. This data is based on the positioning service provided by Baidu Maps for apps and websites to obtain the location information of each user. Short-term population intercity travel is identified by identifying the location information of each mobile phone user within a year. Specifically, the city with the most night stays and more than 6 months is the user's resident city; the city where each user stays in a non-resident city for more than 4 h is the travel destination city. This data can supplement the traditional census and population flow data and has significant theoretical and practical significance (Liu et al., 2015; Lai & Pan, 2019).

This article collects the short-term intercity travel between mainland China, Hong Kong, Macau, and Taiwan within 10 days from April 10 to April 20, 2019. The mainland area includes 4 centrally-administered municipalities and 353 prefecture-level administrative units, and the Taiwan area includes 18 city and county units. A total of 223,077,006 travel connections were generated between 377 cities within 10 days (Fig. 3).

4 The polycentricity of the 8 urban agglomerations considering internal and external connections

4.1 Functional Polycentricity comparison of internal and external linkage measurement

To calculate the polycentricity of China's eight urban agglomerations that take into account both internal and external connections, first compare the differences in Functional Polycentricity between internal and external connections. Using the improved rank-size distribution method, internal and external connections were used to measure the Functional Polycentricity of the eight urban agglomerations (Table 2).

Both Hall (2006) & Burger (2012) confirmed that the internal connections of major European urban areas are more polycentric than the external connections. This study found that China's Beijing-Tianjin-Hebei, Yangtze River Delta, Pearl River Delta, middle reaches of the Yangtze River, and Chengdu-Chongqing urban agglomerations have the same characteristics, while the Central Plains, Guanzhong, and Harbin-Changchun urban agglomerations have opposite characteristics. This is related to the development characteristics of urban agglomerations, as reflected in:

[2] Investment projects approved by the National Development and Reform Commission of China will issue investment plans to implement specific project construction, so the urban agglomeration planning approved by the National Development and Reform Commission is more meaningful for implementation.

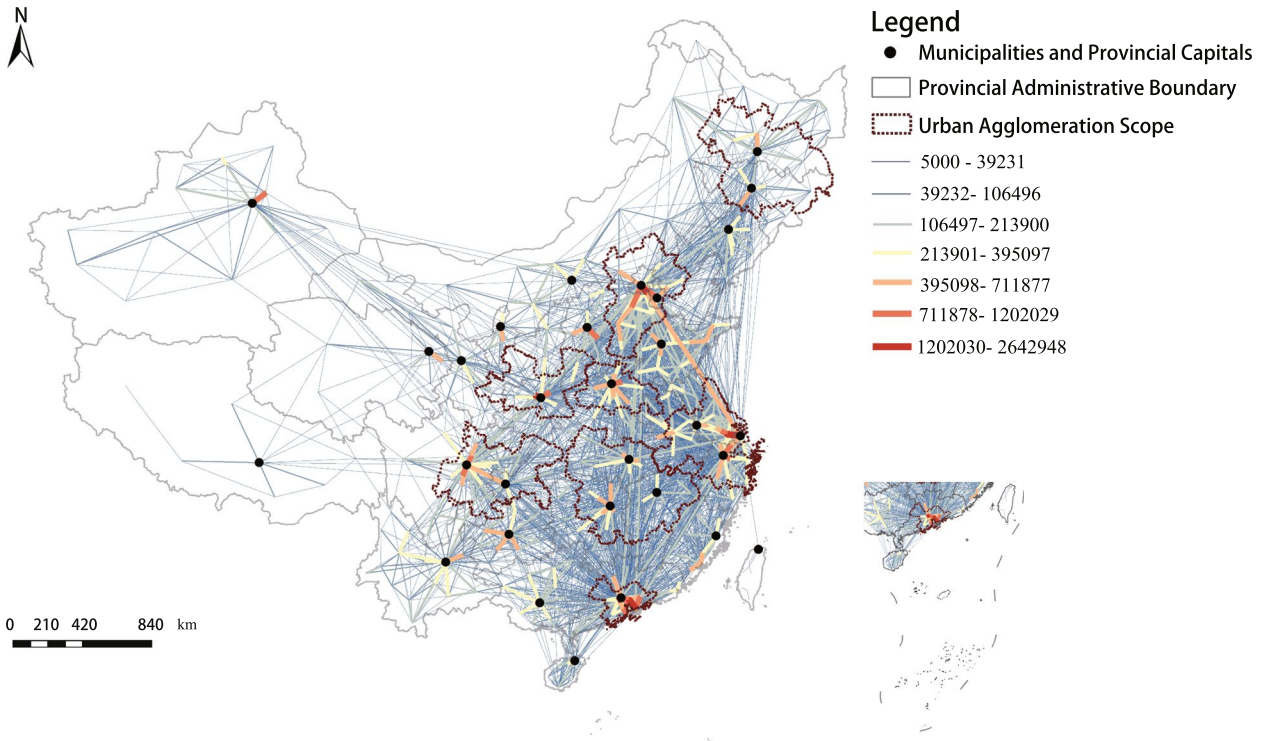

Fig. 3 Intercity trip linkages among cities in China (showing more than 5000 intercity trip linkages). Source: Author

Table 2 Functional polycentricity considering internal and external connections

Urban Agglomerations	Internal	External	(Internal–External) Difference
Beijing-Tianjin-Hebei	-0.7829	-0.8283	0.0454
Yangtze River Delta	-0.7625	-0.7995	0.0370
Pearl River Delta	-0.6792	-0.7659	0.0867
Middle reaches of the Yangtze River	-0.7191	-0.7271	0.008
Chengdu-Chongqing	-0.6872	-0.7817	0.0945
Central Plains	-0.9412	-0.7818	-0.1594
Guanzhong	-1.196	-1.0633	-0.1327
Harbin-Changchun	-0.8152	-0.7786	-0.0366
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Average	-0.8229	-0.8159	--
Median	-0.7727	-0.7818	--
Variance	0.1614	0.0973	--

Source: Author

1. Urban agglomerations with more polycentric internal linkages than external linkages are mainly located in the eastern coastal areas or areas with rapid economic development in the south of China, while the external linkages of relatively backward economically developed regions such as central China, northwest, and northeast China are more polycentric. The intensity of internal and external connections is related to the degree of regional economic development. The stronger the vitality of regional economic development, the higher the degree of regional economic integration, and the closer the functional links between regional cities. At present, China's regional development is not balanced yet. The gap in regional economic development in the east, central, and west has not narrowed. At the same time, a gap between North and South in regional economic development has emerged. The internal linkages of Beijing-Tianjin-Hebei, the Yangtze River Delta, the Pearl River Delta, the middle reaches of the Yangtze River, and the Chengdu-Chongqing urban agglomeration are more polycentric than the external linkages.
2. The difference between internal linkages and external linkages is also related to the central cities in urban agglomerations. Since central cities play the role of internal cores and external gateways in the development of urban agglomerations, the degree of development of central cities also profoundly affects the polycentricity of urban agglomerations. China's central cities such as Beijing, Shanghai, Shenzhen, Guangzhou, Chongqing, Chengdu, and Wuhan are economically developed, occupy an important position in the urban system, and have a strong influence

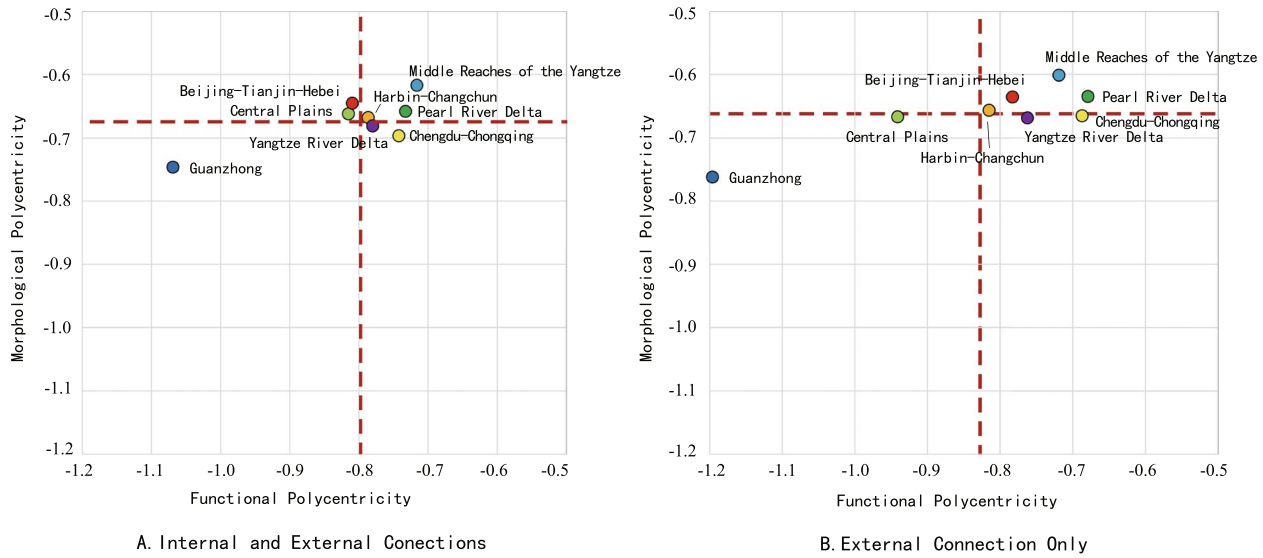

Fig. 4 Morphological Polycentricity and Functional Polycentricity of 8 urban agglomerations in China. Source: Author

on both the inside and outside of the urban agglomeration; their internal and external connections present similar Functional Polycentricity. The external influence of China's Xi'an and Zhengzhou is relatively weak and flat, so the external connection is more polycentric.

4.2 Morphological Polycentricity and Functional Polycentricity considering both internal and external connections

The above research shows that there are differences in the polycentricity of Chinese urban agglomeration's internal and external linkage measurement. This paper takes both internal and external connections into account and measures the Morphological Polycentricity and Functional Polycentricity of different urban agglomerations. At the same time, the degree of polycentricity of the above-mentioned urban agglomerations is measured only based on internal connections for comparison. To measure the degree of morphological or functional polycentricity among these urban agglomerations, based on the average value of Morphological Polycentricity and Functional Polycentricity, four quadrants were divided to determine the types of urban agglomerations (Liu et al., 2016) (Fig. 4, Table 3).

(1) Upper right quadrant

Regardless of both internal and external connections or only internal connections, the middle reaches of the Yangtze River, the Pearl River Delta, and the Harbin-Changchun urban agglomeration in China are polycentric in form and function. Although the above-mentioned urban agglomerations are consistent in their polycentricity, they are substantially different:

On the one hand, China's Pearl River Delta urban agglomeration has typical polycentric features, which have been widely discussed (He et al., 2021; Zhang et al., 2021). The Pearl River Delta urban agglomeration has the smallest range (Table 1), the highest urban density and population density, small distances between cities, convenient transportation links, and the highest degree of economic development integration. It is a typical polycentric urban agglomeration.

On the other hand, the middle reaches of the Yangtze River and the Harbin-Changchun urban agglomeration in China have a relatively large scope compared to other urban agglomerations (Table 1), spanning multiple provinces, and the average distance between cities is relatively large, which inhibits long-distance functional connections and forms a relatively loose spatial structure. However, a relatively independent urban system with close functional connections has been formed around the provincial capital cities, showing polycentricity in morphology and function as a whole.

(2) Upper left quadrant

The Morphological Polycentricity of this type of urban agglomeration in China is higher than the average level, and the Functional Polycentric level is lower than the average level. The functional connection between urban agglomerations is relatively weak, and the polycentricity of urban agglomerations is greatly affected by urban form.

Table 3 Morphological Polycentricity and Functional Polycentricity of urban agglomerations

Urban Agglomerations Beijing-Tianjin-Hebei	Internal and External Connections			Internal Connections		
	Morphological Polycentricity	Functional Polycentricity	(Morphological-Functional) Difference	Morphological Polycentricity	Functional Polycentricity	(Morphological-Functional) Difference
Yangtze River Delta	-0.6454	-0.8096	0.1642	-0.6356	-0.7829	0.1473
Pearl River Delta	-0.6812	-0.7802	0.099	-0.6688	-0.7625	0.0937
Middle reaches of the Yangtze River	-0.6583	-0.7326	0.0743	-0.6349	-0.6792	0.0443
Chengdu-Chongqing	-0.6171	-0.7164	0.0993	-0.6013	-0.7191	0.1178
Central Plains	-0.6965	-0.7424	0.0459	-0.6655	-0.6872	0.0217
Guanzhong	-0.6622	-0.8152	0.153	-0.667	-0.9412	0.2742
Harbin-Changchun	-0.7462	-1.0688	0.3226	-0.7618	-1.196	0.4342
Urban Agglomerations	-0.6681	-0.7865	0.1184	-0.6566	-0.8152	0.1586
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Average	-0.6719	-0.8065	0.1346	-0.6614	-0.8229	0.1615
Median	-0.6652	-0.7834	0.1089	-0.6611	-0.7727	0.1326
Variance	0.0357	0.1047	0.0797	0.0436	0.1614	0.1260

Source: Author

China's Beijing-Tianjin-Hebei and Central Plains urban agglomerations have become such urban agglomerations, taking into account internal and external connections. Some studies believe that the above reasons are due to the mismatch between the urban agglomerations designated by the government and the economically integrated urban agglomerations (Liu et al., 2016). The policy formulation of the Beijing-Tianjin-Hebei and Central Plains urban agglomerations reflects China's national strategic needs. The development goal of the urban agglomerations is to form a regional integration pattern to drive national development and participate in global competition. At present, the flow of elements between cities in the Beijing-Tianjin-Hebei and Central Plains urban agglomerations is relatively weak, and the central cities play a leading role in regional development, and the degree of regional integration is relatively low. The population size between cities is similar, which is conducive to presenting a polycentric pattern.

With only internal connections, the Beijing-Tianjin-Hebei and Central Plains urban agglomerations shifted from the upper left quadrant to the upper right quadrant and lower left quadrant respectively. The enhanced Functional Polycentricity of the Beijing-Tianjin-Hebei urban agglomeration shows that the internal connections of the urban agglomeration are relatively balanced and have flat characteristics; while the external connections of the urban agglomeration are mainly concentrated in Beijing, with obvious polarization characteristics. The Morphological Polycentricity of the Central Plains urban agglomeration is reduced, indicating that the internal connections of the urban agglomeration are more concentrated in Zhengzhou, and the monocentric pattern is obvious, while the external influence of the urban agglomeration is weaker, and the external connections are more flat.

(3) Lower right quadrant

In this quadrant, the Functional Polycentricity of the urban agglomeration is higher than the average level, and the Morphological Polycentricity is lower than the average level. This paper finds that two urban agglomerations belong to this category, namely the Yangtze River Delta urban agglomeration located in the economically developed southeast coastal area of China and the Chengdu-Chongqing urban agglomeration in the southwest mountainous area of China.

Taking into account both internal and external connections, the main reason for the Morphological Monocentric of China's Yangtze River Delta and Chengdu-Chongqing urban agglomerations is that they have two municipalities directly under the central government, Shanghai and Chongqing, respectively, and their populations have a high degree of primacy. In contrast, the Functional Polycentricity is higher than the Morphological Polycentricity, indicating that other small and medium-sized cities in the urban agglomeration of China are well developed, the regional economic vitality is strong, the functional links between cities are close, and the urban hierarchy has the characteristics of flattening. Especially in recent years, the construction of infrastructure such as high-speed railways in China has further lowered the threshold for travel connections between cities and enhanced the internal and external connections of urban agglomerations. Since the Reform and Opening-up policy of China in 1978, the Yangtze River Delta urban agglomeration

has formed a regional economic integration in which large cities such as Shanghai, Nanjing, and Hangzhou form complementary industries with surrounding small and medium-sized cities. With the transfer of industries in the east to the Chengdu-Chongqing urban agglomeration in recent years, the Chengdu-Chongqing urban agglomeration has also learned from the development model of the Yangtze River Delta urban agglomeration, so the degree of polycentricity of the two urban agglomerations is similar.

(4) Lower left quadrant

This kind of urban agglomeration is located in the underdeveloped Guanzhong urban agglomeration in Northwest China, and the level of Functional Polycentricity and Morphological Polycentricity is relatively low. The study of this paper finds that such urban agglomerations include the Guanzhong urban agglomeration with both internal and external connections and the Central Plains urban agglomeration with only internal connections.

The characteristic of this type is that the regional development mainly depends on China's provincial capital city, which brings together the main development elements of the region. The degree of development of central cities will affect the external linkages of urban agglomerations. This study has found that the external linkages of such underdeveloped urban agglomerations have flattening characteristics. However, once the provincial capital cities take the lead in rising, external connections will also show more polarized characteristics, and the future will still show a monocentric pattern.

There are also some urban agglomerations in similar situations in China, mainly located in the economically underdeveloped provinces in the central and western regions. Provincial capital cities have more administrative rights, stronger coordination and control over the region, and can attract more resources, such as large-scale national investment or the transfer of industries in the east. However this will weaken the development of other small and medium-sized cities in the region and further reduce the polycentric pattern of the region.

The comparison of the above calculation and classification shows that, under the condition of considering internal and external connections, the eight urban agglomerations in China show different characteristics of changes in the degree of Morphological Polycentricity and Functional Polycentricity. This difference in the degree of change reflects the inherent differences in the urban systems of each urban agglomeration.

5 Conclusion and discussion

5.1 Conclusion

Based on the national intercity travel data of Baidu Migration, this paper coordinates the internal and external connections of the urban agglomerations, measures the degree of Morphological Polycentricity and the degree of Functional Polycentricity of the main eight urban agglomerations in China, and compares the differences in the calculation results of internal and external connections. The study found:

1. There are differences in the Functional Polycentricity presented by the internal and external connections of China's urban agglomerations, which are related to the economic development of urban agglomerations and their central cities. The stronger the vitality of regional economic development, the higher the degree of regional economic integration, and the closer the functional links between regional cities. The internal linkages of the urban agglomerations in the eastern coastal of China or southern economically developed regions of China are more polycentric than the external linkages, and China's external linkages of the central, northwest, and northeast regions with relatively backward economic development are more polycentric.
2. Comparing the calculations with internal and external linkages and only internal linkages, the corresponding Morphological Polycentricity and Functional Polycentricity of the eight urban agglomerations are not consistent, indicating that external linkages have had a significant impact. China's Beijing-Tianjin-Hebei and Central Plain's urban agglomerations have the most obvious changes in polycentricity, and the types of polycentricity have changed significantly; the polycentricity of other China's urban agglomerations has changed significantly, but the types of polycentricity have not changed.
3. The internal and external connections of urban agglomerations are important functional connections of urban agglomerations, reflecting the external connections of cities in different dimensions. The study of urban agglomerations should not ignore internal or external linkages, and overall consideration can better fully reflect the polycentric characteristics of urban agglomerations.
4. The development of small and medium-sized cities determines the quality of the polycentric pattern. The core areas of most urban agglomerations in China are still in the stage of "Spatial Polarization", and the development factors are flowing from small and medium-sized cities in urban agglomerations to large cities, and the development of small and medium-sized cities are facing difficulties. Taking the Yangtze River Delta urban agglomeration with the highest degree of polycentricity as an example, cities such as Shanghai, Suzhou, Wuxi, Changzhou, and Ningbo have reached a high degree of Functional Polycentricity,

which is related to the development model of industrial complementarity formed between many small and medium-sized cities in the region and Shanghai. "Promoting the coordinated development of large, medium, and small cities and small towns" is conducive to the realization of a polycentric pattern. However, the development of small and medium-sized cities is not only a matter of space, but also involves the national urbanization strategy and the specific conditions of economic development in various places, which need to be considered as a whole. In addition, the modern infrastructure system is the skeleton supporting Functional Polycentricity. Traditionally, the complete transportation facility system and communication facilities such as aviation, high-speed railways, and highways have greatly enhanced the flow of spatial elements such as people, goods, information, and capital between cities, and promoted various functional connections between cities. In the information age, 5G technology promotes the interconnection of all things in the world. The types and forms of functional connections between cities will undergo profound changes, and the polycentric structure will better meet the needs of future network development.

5.2 Discussion

1. Functional and morphological polycentric differences of 8 urban agglomerations in China

In this paper, the average value of Morphological Polycentricity and Functional Polycentricity is used to classify polycentric types of China's urban agglomerations. The results show that there are significant differences in the Morphological Polycentricity and Functional Polycentricity of the eight urban agglomerations. The polycentricity measurement results that consider internal and external connections show that China's Beijing-Tianjin-Hebei, Central Plains, Harbin-Changchun, and Yangtze River Delta urban agglomerations are located near the mean line, with relatively small gaps. However, the measurement results of only internal connections show that the gap between the above-mentioned urban agglomerations has increased significantly. It may be caused by the following reasons: one is to increase the impact of external links on the measurement results, and the other is that the method of mean classification does not clearly distinguish the difference. In the future, various methods can be tried to classify the polycentric types of urban agglomerations.

2. Intercity travel is a common functional link between cities

Although relative studies worldwide often use commuting linkages to measure the degree of polycentricity of urban regions, considering the scale of urban agglomerations in China and the difficulty of obtaining commuting data, it is more suitable for China's national conditions to use intercity travel as the functional linkage of urban agglomerations. In addition to commuting connections, intercity travel also includes travel behaviors with different purposes such as recreation, and has the characteristics of comprehensive functional connections. What is more, functional linkage data are diverse. People flow, material flow, information flow, and capital flow are different types of connections, which comprehensively reflect the functional connections between cities (Hall & Pain, 2006). For different types of connections, the measurement results will have significant differences, which reflects the differences of different types of functional connections. The intercity travel selected in this paper is a common intercity functional connection, but other types of functional connections also need to be considered. Future research needs to comprehensively consider different types of functional connections, take into account both internal and external connections, and comprehensively measure the degree of polycentricity of urban agglomerations, which will be of more reference value.

3. Short-term travel data reflect overall travel characteristics

The above has clarified the significance of intercity travel linkages for this study. Due to the difficulty in obtaining data, this study uses the 10-day Baidu migration data in April 2019. This is equivalent to short-term intercity travel data, reflecting residents' daily intercity travel behavior. This kind of daily intercity travel can only reflect the overall travel characteristics of national residents in a time section. However, the daily travel of residents has a certain regularity and randomness, which contains rich individual decision-making and the influence of various factors of the built environment. This study does not delve into the regular characteristics behind residents' daily intercity travel but only reflects the polycentric spatial structure characteristics of short-term intercity travel as a whole.

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Code availability
Not applicable.

Authors' contributions
WANG Yao and NIU Xinyi contribute to the study conception and design. Material preparation, data collection and analysis are performed by WANG Yao. The first draft of the manuscript is written by WANG Yao and all authors comment on previous versions of the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
The data that support the findings of this study are available from Baidu Huiyan but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. Data are however available from the authors upon reasonable request and with permission of Baidu.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
All authors approved the final manuscript and the submission to this journal.

Competing interests
The authors have no financial or proprietary interests in any material discussed in this article.

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