Does polycentric spatial structure narrow the urban-rural income gap? – Evidence from six urban clusters in China

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A R T I C L E   I N F O

A B S T R A C T

As urbanization and economic development continue to accelerate, social equity issues are becoming increasingly prominent and the urban–rural income gap is an important manifestation of this. This study uses the data of urban clusters from 2010 to 2019 and focuses on the relationship between the polycentric spatial structure of urban clusters and the urban–rural income gap. The findings show that the development of urban cluster polycentricity can reduce the urban–rural income gap, and the higher the degree of polycentricity in morphology, the smaller the gap. However, the relationship between polycentric spatial structure and the urban–rural income gap is "U" shaped, indicating the need for rational planning of urban polycentric development patterns rather than simple expansion. In addition, the polycentric spatial structure of urban clusters can reduce regional disparities by promoting factor mobility and industrial structure optimization. However, this depends on the level of industrial development and infrastructure. This study highlights the importance of a balanced approach to urban development that takes into account regional disparities and issues of social equity.

1. Introduction

Does an appropriate urbanization development model achieve a win-win situation for regional economic growth and coordinated development? Does the polycentric spatial structure reduce the income gap between regions? So far, there is no consensus on these issues in the theoretical literature. The conclusion depends on factors such as the distribution of investment, human capital, the integration process, degree of market development, and government intervention (Liu, 2011; Zhang, Mohsin, Rasheed, Chang, & Taghizadeh-Hesary, 2021). Existing studies provide considerable evidence of the causes of regional disparities in China, but they have also neglected to consider spatial development in their assessments. Along with rapid economic growth, there is likely to be change in the spatial distribution pattern of economic activities resulting from factor mobility. This change has important implications for regional economic growth and income disparities (Desmet & Henderson, 2015). The studies by Meijers and Sandberg (2006) and Malý (2016) suggest that the relationship between regional polycentric development patterns and regional income disparities is ambiguous. In the Chinese context, however, Zhang and Yi (2012) and Liu, Li, and Qin (2017) suggest a positive correlation between the spatial structure of regional polycentrism and economic growth. These studies suggest that polycentric spatial structure may reduce the regional income gap.

We investigate the relationship between the polycentric spatial structure and urban–rural income disparity in Chinese urban

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clusters using the year-end city population, the number of collaborating journals ("ESCI," "SSCI" and "SCI") on the Web of Science as the basic data on polycentric spatial structures. We also elaborate on how the polycentric development of urban clusters promotes the reduction of regional income disparity in terms of industrial development and infrastructure. Our empirical analysis uses data from six urban clusters in China for the period 2003–2019. Our results show that the spatial structure of urban cluster polycentricity can reduce the urban–rural income gap. Specifically, the higher the degree of urban cluster morphological polycentricity, the smaller the urban–rural income gap. Furthermore, there is a "U"-shaped relationship between the spatial structure of urban cluster polycentricity and the urban–rural income gap. These results suggest a threshold value for polycentricity in its effect of reducing the income gap, and, rather than expanding cities we should plan their reasonable polycentric development. In addition, the polycentric spatial structure can reduce regional disparities by promoting factor flows and industrial structure optimization. Nevertheless, the realization of these mechanisms is constrained by industrial development and levels of infrastructure.

There is extensive research exploring the relationship between polycentric spatial structure and regional economic growth and global value chain upgrading and focused on factor agglomeration externalities and their generation mechanisms from a micro perspective (Johansson & Quigley, 2004; Kong, Shen, Sun, & Shao, 2021; Peng, Wang, Jiang, & Kong, 2023; Phelps & Ozawa, 2003; Sassen, 2007). For example, Meijers and Burger (2010) and Zhang, Sun, and Li (2017) find that the polycentricity of urban spatial structures contributes to higher labor productivity and economic efficiency. Brezzi and Veneri (2015) extend their study to the national level and reached similar conclusions. Studies on polycentric spatial structure and global value chain upgrading found a specific U-shaped relationship between polycentric spatial structure and the climbing status of global value chain division of labor (Chen & Liu, 2020; Chen, Qiu, Liu, & Li, 2019). Meng, Wang, and Koopman (2013) and Beverelli, Stolzenburg, Koopman, and Neumueller (2019) indirectly verify the important role of domestic value chain division and resource integration. This finding is based on the role of the interaction between domestic and global value chains in promoting the upgrading of global value chains in Chinese manufacturing with Chinese city networks acting as the spatial carrier.

The relationship between polycentric spatial structures and regional income disparity remains understudied. This is surprising since narrowing the regional income gap appears to be an important consequence of regional economic growth. This relationship is unclear according to a few studies, such as Meijers and Sandberg (2006) and Malý (2016), who investigate the relationship between polycentric spatial structure and regional income gaps. Unlike this study, these focused on urban or national spatial scales. There are specific reasons for our focus on urban clusters. In the context of globalization, international and regional competition has increasingly manifested as urban competition, especially in urban clusters with mega-cities as the core (Kong, Peng, Ni, Jiang, & Wang, 2021; Peng et al., 2023). World Bank data shows that 60% of global economic output is concentrated in city clusters in port and bay areas. For example, bay area economies, for example, New York Bay, San Francisco Bay and Tokyo Bay, have become important growth poles driving global economic development.

Given the above arguments, we fill the existing research gap by examining urban clusters in China and the relationship between the polycentric spatial structure of urban clusters and the urban–rural income gap. We address three questions. First, does the polycentric spatial structure of urban clusters affect the income gap? Second, how does the polycentric spatial structure of urban clusters affect the income gap after considering differences in geographic location, city size, and urban clusters? Third, what are the effects of industrial development and infrastructure construction in urban clusters on the relationship between the polycentric spatial structure and the income gap?

Our study contributes to the literature in three ways. First, we fill a gap in research on the relationship between the spatial structure of polycentric urban clusters and the urban–rural income gap in China. We provide a new perspective and methodology for understanding the relationship between spatial structure and socioeconomic issues within urban clusters. The study finds that the polycentric development of urban clusters helps to narrow the urban–rural income gap. Furthermore, there is a "U" shaped relationship between the degree of polycentricity and the urban–rural income gap, which provides an important reference for urban planning and economic development.

Second, our study proposes new ideas and mechanisms relating to the impact of urban cluster polycentric spatial structures on the urban–rural income gap. The results show that the role in reducing regional disparities played by the spatial structure of the urban clusters' polycenter includes factor flow and promoting industrial structure optimization; however, it is also constrained by industrial development and infrastructure construction. This finding broadens the understanding of the mechanism of spatial structure within urban clusters in influencing development, but also has practical policy implications.

Finally, we use the urban population at the end of the year and the number of "ESCI," "SSCI" and "SCI" journals in the official website of Web of Science as methodological indicators. The number of cooperating journals is used as an index to measure the degree of polycentricity of urban clusters in terms of "morphological polycentricity" and "functional polycentricity." These two indices not only consider the diversity of spatial structures of urban clusters, but also provide references for other related studies. In addition, we introduce grouping variables, such as city size and geographic location, to the research framework. This allows us to more accurately analyze the relationship between spatial structure and the urban–rural income gap within urban clusters.

2. Hypothesis development

The process of narrowing the urban–rural income gap is a complex and continuous process influenced by a city's spatial organization. The main driver of this process is the spatial agglomeration effect. The theory on static agglomeration economies suggests that the spatial structure of a single center resulting from factor agglomeration leads to a widening of the income gap within a region. By contrast, dynamic agglomeration theory suggests that when an agglomeration exceeds a certain size threshold, the negative externalities of agglomeration will dominate, with a negative impact on economic growth.

As a region grows economically, the dispersion and distribution of economic activities tends to reduce regional disparities (Williamson, 1965). Initially, agglomeration is necessary within a region because of the scarcity of factor resources (Kong, Li, Ni, & Peng, 2022; Wong, Li, Zhang, Kong, & Cai, 2021). However, in the early stages of development, spatial agglomeration of factors and the spatial structure of a single center will inevitably widen the income gap within the region. In the later stage of economic development, overconcentration and overcrowding will introduce extensive negative externalities. With sufficient factor mobility, factors are gradually redistributed within the region, creating a polycentric spatial structure and reducing the regional income gap (Hansen, 1990; Henderson, 2003; Johansson & Quigley, 2004).

Studies have shown that proximity between cities can be effective in sharing agglomeration economies (Phelps & Ozawa, 2003). However, once cities become too large, there may be congestion effects. A polycentric spatial structure facilitates economic growth because congestion effects tend to be confined within a single city. Polycentric city networks also allow cities to share agglomeration economies and, without losing those economies, completely replace the spatial structure of giant monocentric cities (Johansson & Quigley, 2004). Based on these observations, we propose Hypothesis 1:

Hypothesis 1. A polycentric spatial structure of urban clusters can reduce the urban–rural income gap, and a polycentric spatial structure is more effective than a monocentric structure in reducing the urban–rural income gap.

Narrowing the income gap between urban and rural areas requires the free flow of factors between cities and coordinated industrial development. Polycentric development can facilitate the formation of a functional network of cities with an orderly division of labor and strong linkages, which greatly facilitates the movement of people, goods, and information between cities (Glaeser, Ponzetto, & Zou, 2016; Kong, Li, Jiang, Sun, & Peng, 2022; Wu & Liu, 2008). However, the realization of such mechanisms is only possible when the level of infrastructure is sufficiently high to support inter-city factor mobility.

A monocentric structure tends to concentrate highly skilled labor and firms in a region's central city, further widening the inter-regional income gap. In contrast, polycentric structures encourage a more even distribution of factors within regions, narrowing regional income gaps. Therefore, well-developed infrastructure is critical to support the network of cities generated by polycentric development. Such infrastructure not only increases the choice of locations for high-quality factors, but also results in a more even distribution of factors.

In terms of coordinated industrial development, the polycentric spatial structure of urban clusters can avoid inefficient resource allocation resulting from overconcentration of resources and promote coupling and coordination of manufacturing and productive services through industrial and spatial correlation. This creates a reasonable urban hierarchy in which different cities can specialize in different industries, a win-win situation rather than a zero-sum game. A polycentric spatial structure can effectively promote the transfer of industries from advanced to less-advanced regions (Duranton & Puga, 2004), drive the development of small and medium-sized cities, and ultimately narrow the regional gap. Based on these ideas, we propose Hypothesis 2.

Hypothesis 2. The polycentric spatial structure of urban clusters can reduce regional disparities by facilitating factor flows and promoting industrial structure optimization, but the realization of these mechanisms is constrained by industrial development and infrastructure levels.

3. Models, variables, and data

3.1. Variable selection and description

3.1.1. Explained variable

In this study, we combine population weights and urban–rural income disparities and use the Thiel index as an explained variable to measure the per capita disparity in income between urban and rural residents in China. In the equation below, $i = 1$, 2 denotes urban and rural areas, t denotes the year, p represents total income, and Z represents the total population. The formula for the Thiel index is as follows:

$$Theil_{it} = \sum_{i=1}^{2} \left(\frac{p_{it}}{p_t}\right) ln \left(\frac{p_{it}/p_t}{Z_{it}/Z_t}\right) \tag{1}$$

3.1.2. Explanatory variables

We measure the polycentric spatial structure index of Chinese urban clusters in terms of their morphological and functional polycentricity, referring to Meijers and Burger (2010); Meijers, Burger, and Hoogerbrugge (2016); Peng et al. (2023).

First, regarding the morphological polycentric spatial structure (Mor_poly_{it}), we adopt city year-end populations as the base index. We grouped and sorted the visualized data and regressed these using the subgroup-year method to obtain each urban clusters' Mor_poly_{it} index as follows.

$$lnPeo_{it} = c - Mor\_poly_{it} lnRank_{it} \tag{2}$$

In Model (2), Peo_{it} is the end-year population of city, c is a constant term, $Rank_{it}$ is the ranking of the year-end population of city i in year t in the urban cluster in which i is located. We regress Model (2) on cities with $Rank_{it} = 2$, 3, 4 to obtain the Mor_poly_{it} index of the urban clusters, and take the mean value of Mor_poly_{it} with reference to Meijers and Burger (2010) and Peng et al. (2023).

Second, regarding the functional polycentric spatial structure ($Func\_poly_{it}$), for the baseline data we draw on Li and Phelps (2017)

and for the number of collaborating journals per city we refer to the official Web of Science website for "ESCI," "SSCI," "SCI," and other journals. We measure the *Func_poly_it* index as follows.

$$lnRelation_{it} = c - Func\_poly_{it}lnRank_{it} \tag{3}$$

$$Relation_{it} = \sum_{j}^{n} Paper_{ijt}, i \neq j \tag{4}$$

In Models (3) and (4), *Relation_it* is the sum of the degree of functional linkage of city *i* within the city cluster in year *t*, *Rank_it* is the ranking of the degree of functional linkage of city *i* in the city cluster in year *t*. *Paper_ijt* is the number of journal papers co-authored by city *i* and city *j* as reflected in the Web of Science core database in year *t*.

3.1.3. Moderating variables

Based on the theoretical analysis in Section 2.2, we introduce the degree of industrial agglomeration (*Ind_agg*), the urban industrial division of labor (*Ind_div*), informatization (*Informatization*), and urban accessibility (*Accessibillity*) as moderating variables to test research Hypothesis 2. These four moderating variables affect economic activity and development in urban areas and can help reduce the urban–rural income gap by generating jobs and increasing wages. The calculation of these four moderating variables is shown in Table A1.

3.1.4. Control variables

Our control variables are the internal market potential (*Market_potential*), level of external opening (*Openness*), government intervention (*Gov_intervention*), level of transportation infrastructure (*Transportation*), and level of urbanization (*Urbanization*) (referring to Kong, Peng, et al., 2021; Peng et al., 2023). These factors all have a noteworthy impact on economic development and the urban–rural income gap (Jiang, Li, & Si, 2022).

Internal market potential (*Market_potential*) is a measure of the potential for economic activity within a given market. Markets with high potential tend to attract firms and industries, leading to an increase in economic activity and employment opportunities, which can, in turn, reduce the urban–rural income gap through increasing the jobs available for workers in urban areas.

The level of external opening (*Openness*) measures the extent to which a market is open to foreign trade and investment. A more open market tends to attract more foreign investment, which can lead to economic growth and job creation; more jobs for workers in urban areas can help reduce the urban–rural income gap.

Government intervention (*Gov_intervention*) measures the degree to which the government intervenes in the economy, such as through regulations, subsidies, or taxes. Government intervention affects economic growth and development (Zhang, 2023), and, as such, has an impact on the rural–urban income gap.

The level of transportation infrastructure (*Transportation*) measures the quality and accessibility of transportation infrastructure within a market. Good transportation infrastructure can make it easier for businesses and industries to operate and for workers to commute. This can help close the urban–rural income gap by providing more jobs for workers in urban areas.

The level of urbanization (*Urbanization*) measures the degree of urbanization in an area. Higher levels of urbanization may lead to more jobs and higher wages in urban areas, which can exacerbate the urban–rural income gap. All of these control variables are important because they can influence the economic development of urban areas, which, in turn, affects the urban–rural income gap. Including these control variables in the analysis allows us to better understand the factors contributing to the gap and develop more effective policies and strategies to address the problem. The calculation of these five control variables is shown in Table A1.

3.2. Sample and data processing

We take the data for six urban clusters from 2010 to 2019 as the study sample. Currently, the Chinese government has laid out 19 national-level city clusters. Due to the different paces of their economic development, there is considerable variation in the positioning of these city clusters. Among them, the Beijing-Tianjin-Hebei, Yangtze River Delta, Pearl River Delta, and Chengdu-Chongqing clusters, and the clusters along the middle reaches of the Yangtze River are relatively mature and are in the "optimization and upgrading range." The Shandong Peninsula, Central Plains, Guanzhong Plain, Guangdong, Fujian, Zhejiang, and Beibu Gulf clusters have taken shape and are categorized as needing to be "developed and expanded." The city clusters of Ha-Chang, South Central Liaoning, Central Yunnan, and the North Slope of Tianshan have not yet taken shape and are still under "cultivation and development." Considering the actual construction of these city clusters and data availability, we finally selected as the study sample six city clusters—the Yangtze River Delta, Pearl River Delta, Chengdu-Chongqing, Middle Yangtze River, Central Plains, and Beibu Gulf clusters—with a total of 118 cities.

The original data for measuring urban–rural income disparity, the polycentric spatial structure index, levels of industrial development and infrastructure, and all control variables were obtained from the *China Urban Statistical Yearbook,* the *China Regional Economic Statistical Yearbook*, the website of the National Bureau of Statistics, and the Web of Science. This study mainly carried out the following aspects in terms of data screening and processing (referring to Kong, Shen, et al., 2021; Peng et al., 2023). First, we use linear interpolation to fill in the gaps for the variables with missing data of less than 20%. Second, for the indicators with a missing rate higher than 20%, we adopt the replacement variable method. Third, we carried out the 1% and 99% quantile tail reduction for continuous-type variables.

3.3. Econometric models

In this study we construct a fixed-effects model (see Models (1) and (2)) to examine the Hypothesis 1.

$$Theil_{it} = \xi_0 + \xi_1 Mor\_poly_{it} + \xi_2 Controls_{it} + \lambda_i + \gamma_t + \varepsilon_{it} \tag{5}$$

$$Theil_{it} = \varphi_0 + \varphi_1 Func\_poly_{it} + \varphi_2 Controls_{it} + \lambda_i + \gamma_t + \varepsilon_{it} \tag{6}$$

In Models (5) and (6), the explained variable, $Theil_{it}$, represents the urban–rural income gap in city i in year t. The explanatory variables include Mor_poly_{it} and $Func\_poly_{it}$, denoting the morphological and functional polycentric spatial structure indexes, respectively; $Controls_{it}$ represents the set of control variables.

The level of industrial development among cities within a single urban cluster and the varying infrastructure development among different urban clusters may affect the polycentric spatial structure and income gap. Therefore, based on Models (5) and (6), the interaction term between industrial development, infrastructure is introduced; see Models (7) and (8).

$$Theil_{it} = \xi_0 + \xi_1 Mor\_poly_{it} \times Industry_{it} + \xi_2 Controls_{it} + \lambda_i + \gamma_t + \varepsilon_{it} \tag{7}$$

$$Theil_{it} = \varphi_0 + \varphi_1 Func\_poly_{it} \times Infrastructure_{it} + \varphi_2 Controls_{it} + \lambda_i + \gamma_t + \varepsilon_{it}, \tag{8}$$

where $Industry_{it}$ denotes the level of industrial development of urban clusters, and the industrial division of labor (Ind_agg) and industrial agglomeration (Ind_div) are used as proxy variables, $Infrastructure_{it}$ denotes the level of infrastructure of urban clusters, and the level of information technology ($Informatization$) and urban accessibility ($Accessibility$) are used as proxy variables; the other variables are the same as in Models (5) and (6).

4. Results and discussion

4.1. Baseline regression results

To examine the polycentric spatial structure on the income gap, we conduct a benchmark regression analysis with year and region fixed effects. In Table 1, the goodness-of-fit is high, indicating a good fit of the model. As set out in Table 1, the Mor_poly is significantly positive at the 1% level; in contrast, the coefficient of $Func\_poly$ is insignificant. This result indicates that as a spatial structure, morphological polycentricity of urban clusters has a significant adverse effect on the income gap, while functional polycentricity does not. This is initial verification of Hypothesis 1.

This finding may be because morphological polycentricity describes the region's spatial structure in terms of the distribution of the population or the different classes of towns in the region, emphasizing the absolute centrality of each central city in the region (Veneri & Burgalassi, 2012). The morphological polycentric spatial structure avoids inefficient resource allocation due to excessive concentration of resources; the labor force is also effectively allocated, which is conducive to reducing the income gap (Liu, Li, & Chen, 2017).

Table 1
Results of the baseline regression.

Variables	(1)	(2)	(3)	(4)
	Theil	Theil	Theil	Theil
Mor_poly	−0.1185***	−0.1063***		
	(0.0253)	(0.0206)		
Func_poly			−0.0014	−0.0004
			(0.0048)	(0.0049)
Market_potential		−0.0072**		−0.0084**
		(0.0026)		(0.0029)
Openness		−0.1822***		−0.1813***
		(0.0474)		(0.0415)
Gov_intervention		−0.0251		−0.0184
		(0.0184)		(0.0170)
Transportation		0.0006**		0.0006**
		(0.0002)		(0.0002)
Urbanization		−0.0147***		−0.0208***
		(0.0032)		(0.0043)
Accessibility		−0.0055***		−0.0064***
		(0.0013)		(0.0012)
Constant	0.1483***	0.2649***	0.0750***	0.2177***
	(0.0162)	(0.0446)	(0.0084)	(0.0414)
Year FE	YES	YES	YES	YES
Region FE	YES	YES	YES	YES
N	1100	1100	1100	1100
adj. R^2	0.918	0.922	0.913	0.919

Note: Robust standard errors are reported in parentheses, and *, **, and *** represent the 10%, 5%, and 1% significance levels.

Functional polycentricity emphasizes the need for each central city to be interconnected with smaller neighboring cities to play its role as a central city (Veneri & Burgalassi, 2012). With the network economy and the improvement of transportation infrastructure, regional interconnection is not only dependent on geographical location; the interdependence of the central and surrounding smaller cities is weakened, and the geographical scope of social and economic activities expands. Therefore, urban clusters achieving functional polycentricity limits the income gap.

4.2. Robustness tests

4.2.1. Explanatory variables lagged

There may be a lag in the impact of urban cluster polycentric spatial structure on the income gap and it will not necessarily manifest in the current period. Meanwhile, to test the robustness of the empirical results, we refer to the study of Chen, Lin, and Lin (2014) and conduct regression analysis on the explanatory variable, the urban–rural income gap, using a one-period lag of the core explanatory variable. As the results in Table 2 show, after controlling for year and region fixed effects, the coefficients of *Mor_poly* lagged one period are significantly negative at the 1% level, and the coefficients of *Func_poly* lagged one period are insignificant, indicating that the impact of urban clusters' polycentric spatial structure on the income gap is persistent. The results of the regression using the explanatory variables with a one-period lag are generally consistent with the benchmark results, thus confirming that the regression results are robust.

4.2.2. Replacement of explanatory variable measures

We verify the robustness of the results by replacing the measures of the explanatory variables. Referring to Jiang (2013), we use the logarithm of the ration of urban to rural per capita income (*Ratio*) to measure the income gap. The results are shown in Table 3. When the regression is conducted with *Ratio* as the explanatory variable, the coefficient of *Mor_poly* is −0.3909, which is significant at the 1% level; the coefficient of *Func_poly* is not significant. In Table 1, the coefficient of *Mor_poly* from the regression with *Theil* as the explanatory variable is −0.1063, which is significant at the 1% level; the coefficient of *Func_poly* is also insignificant. This result verifies the negative relationship between the income gap and the morphological polycentricity of urban clusters and the irrelevance of their functional polycentricity. This indicates that replacing the measures of the explanatory variables does not affect the regression results, thus verifying the relevant baseline results. In addition, the regression results for other model variables are consistent with Table 1 and will not be repeated here. In summary, the robustness of the results in this study is confirmed.

4.2.3. Instrumental variable method test

Measurement errors and omitted variables may raise endogeneity concerns. This study uses panel data, which, to some extent, overcomes the problem of omitted variables (individual heterogeneity). As much as is possible, we also control for other factors that may affect the urban–rural income gap. Variables affecting the urban–rural income gap may nevertheless have been omitted. In addition, there may be other sources of endogeneity, for example, errors in the process of measuring the polycentric spatial structure of urban clusters and the urban–rural income gap. We specifically address these issues of potential endogeneity (from omitted variables and measurement errors) using the instrumental variables approach and two-stage least squares (2SLS) regression.

According to the New Economic Geography theory of increasing returns to scale and the "iceberg cost" hypothesis, the existence of regional "transportation costs" allows products with higher transportation costs to have a local-production advantage in geographic locations other than the central region. This advantage leads to the formation of several cities within the region. The average elevation (*Ahigh*) is chosen as the instrumental variable of the polycentricity index. In addition, following Li and Liu (2012), the lagged period of the functional polycentricity index of urban clusters is used as its instrumental variable. The instrumental variables were selected to satisfy the conditions of relevance and exclusivity.

The results are presented in Table 4; the odd columns are the estimated results of the first-stage regression, and the even columns are the estimated results of the second-stage regression. Columns (1)–(4) are the results using the mean elevation (Ahigh) as an

Table 2
Robustness test results: explanatory variables lags.

Variables	(1)	(2)	(3)	(4)
	Theil	Theil	Theil	Theil
Mor_poly_after1	−0.0910***	−0.0805***		
	(0.0218)	(0.0178)		
Func_poly_after1			−0.0007	−0.0021
			(0.0050)	(0.0049)
Constant	0.1278***	0.2303***	0.0710***	0.1980***
	(0.0139)	(0.0374)	(0.0089)	(0.0347)
Controls	NO	YES	NO	YES
Year FE	YES	YES	YES	YES
Region FE	YES	YES	YES	YES
N	990	990	990	990
adj. R^2	0.921	0.925	0.918	0.923

Note: Robust standard errors are reported in parentheses, and *, **, and *** represent the 10%, 5%, and 1% significance levels.

Table 3
Robustness test results: replacement of explanatory variable measures.

Variables	(1)	(2)	(3)	(4)
	Ratio	Ratio	Ratio	Ratio
Mor_poly	−0.4213***	−0.3909***		
	(0.1024)	(0.1063)		
Func_poly			0.0004	0.0035
			(0.0222)	(0.0228)
Constant	1.0789***	1.4244***	0.8089***	1.2417***
	(0.0654)	(0.1383)	(0.0394)	(0.1340)
Controls	NO	YES	NO	YES
Year FE	YES	YES	YES	YES
Region FE	YES	YES	YES	YES
N	1100	1100	1100	1100
adj. R^2	0.910	0.913	0.907	0.910

Note: Robust standard errors are reported in parentheses, and *, **, and *** represent the 10%, 5%, and 1% significance levels.

instrumental variable for the polycentricity index of urban form. Columns (5)–(8) are the test results using the one-period lag of urban clusters' functional polycentricity index as the instrumental variable. In this study, we assess whether the instrumental variables are unidentifiable and whether they are weak instrumental variables, using the the Kleibergen-Paap rk LM statistic and Kleibergen-Paap rk Wald F statistic, respectively.

As can be seen in Table 4, the Kleibergen-Paap rk LM test rejects the null hypothesis of under-identification of instrumental variables at the 1% level. Further, the Kleibergen-Paap rk Wald F statistic is greater than the critical value at the 15% level of the Stock-Yogo test and greater than the empirical value of the relevant instrumental variable at the one-stage level, as proposed by Staiger, Stock, & Watson (1997). Thus, the assumption that the instrumental variable is weakly identified is rejected. Further, the regression results for the key explanatory variables are generally consistent with the estimates in Table 1. This validates the conclusion that the morphological polycentric spatial structure of urban clusters has a significant negative effect on the urban–rural income gap, while the effect of the functional polycentric spatial structure is not significant. This is sufficient to prove that the results above are robust and there is no statistically relevant endogeneity problem.

4.3. Heterogeneity analysis

4.3.1. Geographic location of urban clusters

Due to their different geographical locations, each region in China is endowed with different resources, resulting in disparities among regions in terms of economic and social development. This regional disparity has an impact on the spatial structure of cities. Therefore, this study divides the sample into three categories according to the geographical location of the urban clusters: the eastern,

Table 4
Endogeneity test results: instrumental variable method.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	First	Second	First	Second	First	Second	First	Second
	Mor_poly	Theil	Mor_poly	Theil	Func_poly	Theil	Func_poly	Theil
Ahigh	−0.0001***		−0.0001***					
	(0.0000)		(0.0000)					
Func_poly_after1					0.1351***		0.1332***	
					(0.0379)		(0.0379)	
Mor_poly		−0.4253***		−0.2066***				
		(0.0440)		(0.0458)				
Func_poly						−0.0051		−0.0159
						(0.0191)		(0.0196)
Constant	0.6690***	0.3748***	2.2021***	0.7173***	1.4597***	0.1161***	1.4051***	0.2548***
	(0.0095)	(0.0287)	(0.0710)	(0.1022)	(0.0659)	(0.0327)	(0.2485)	(0.0469)
Controls	NO	NO	YES	YES	NO	NO	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES
Region FE	YES	YES	YES	YES	YES	YES	YES	YES
Kleibergen-Paap rk LM statistic	71.012	71.012	45.521	45.521	11.424	11.424	11.273	11.273
	[0.0000]	[0.0000]	[0.0000]	[0.0000]	[0.0007]	[0.0007]	[0.0008]	[0.0008]
Kleibergen-Paap rk Wald F statistic	127.193	127.193	41.700	41.700	12.726	12.726	12.336	12.336
	{8.96}	{8.96}	{8.96}	{8.96}	{8.96}	{8.96}	{8.96}	{8.96}
Observations	1100	1100	1100	1100	990	990	990	990
R-squared		−1.522		0.464		0.928		0.930

Note: Robust standard errors are reported in parentheses; *, **, and *** represent the 10%, 5%, and 1% significance levels; the values in [] are the *p*-values of the corresponding statistics; and the critical values at the 15% level of the Stock-Yogo test are in {}.

central, and western regions are distinguished to examine the impact of the polycentric spatial structure of urban clusters on income disparity in different regions.

From Table 5, relative to the eastern and central regions, the morphological polycentric spatial structure in the western region significantly promotes the urban–rural income gap, while the functional polycentric spatial structure significantly suppresses this gap. Due to its inferior infrastructure, the central city's economic growth in the western region tends to have less driving effect in the periphery, exhibiting lower innovation agglomeration, and extremely slow talent flow. Therefore, the absolute centrality of each central city in the region as a result of the increased polycentricity of urban clusters aggravates the economic gap. This is detrimental to the economic development of the peripheral cities and causes the income gap to widen. Moreover, the functional polycentricity of urban clusters emphasizes the connection between cities. This precisely makes up for the lagging economic development in the western region due to the scattered cities and backward transportation conditions. The increase in the degree of functional polycentricity of urban clusters has led to a rise in the mobility of talent, which has resulted in the economic development of different regions being balanced within the radius of the central city and, as a result, the urban–rural income gap has decreased.

4.3.2. Urban cluster echelon

The sample is divided into two categories of city clusters according to their development positions: first-echelon city clusters that need to "optimize and enhance their scope," and second-echelon city clusters that need to "develop and grow." The first-tier city clusters include the Yangtze River Delta, Pearl River Delta, Chengdu-Chongqing and Yangtze River midstream city clusters; the second-tier city clusters include the Central Plains and Beibu Gulf city clusters.

The results in Table 6 show the effect of *Mor_poly* on the urban–rural income gap is significantly negative in the first-tier urban clusters. In the second-tier urban cluster, the *Mor_poly* has no significant effect on the urban–rural income gap. The first-tier urban clusters mainly include cities in coastal and developed areas that have concentrated talent and geographical advantages and more complete infrastructure. The polycentric form of urban clusters increases the flow of factors and releases resource congestion in central cities, thereby reducing the income gap.

In addition, in the second-tier urban clusters, the impact of *Func_poly* on the income gap is significantly negative. In the first-tier urban cluster, the *Func_poly* has no significant effect on the urban–rural income gap. The Zhongyuan urban cluster, a second-tier cluster has the largest urban groups, the densest population, the fastest industrialization, a high level of urbanization, and prominent transportation-related location advantage in the 500 km radius that includes Beijing, Wuhan, Jinan, and Xi'an. The Beibu Gulf city cluster is backed by the southwest, is adjacent to Guangdong, Hong Kong and Macao, faces Southeast Asia, and is an essential hub of the Maritime Silk Road. Second-tier urban clusters thus have a more positive impact on the income gap due to their rich resources and important geographic locations that allow the advantages of functional polycentricity to be brought into play.

4.3.3. Geographic location of cities

We carry out heterogeneity analysis from the perspective of coastal and non-coastal cities to examine, see Table 7. Columns (1)–(4) are the results for the coastal city sample and Columns (5)–(8) for the non-coastal city sample. As can be seen in Table 7, *Mor_poly* is significantly negative for both coastal and non-coastal cities. The *Func_poly* is also negative in coastal cities but is not significant in non-coastal cities. Comparing the regression results for the two subsamples, we find that the absolute value of *Mor_poly* is larger for coastal cities than for non-coastal cities, indicating that the negative effect of coastal urban polycentricity on the income gap is larger than that of non-coastal cities.

The reason may be that coastal cities are highly open to the outside world and are economic and densely populated regions. Effective policy support and many innovative talents allow the development advantages of the central area to radiate to the surrounding areas effectively and rapidly. The income gap is thus reduced. In coastal cities, urban cluster functional polycentricity also has a significant negative effect on the income gap; that is, the higher the degree of functional polycentricity, the smaller the income gap; while in non-coastal cities the effect of urban functional polycentricity on the income gap is not significant. The reason may be that

Table 5
Heterogeneity results: East, Central and West region.

Variables	East region		Central region		West region	
	(1)	(2)	(3)	(4)	(5)	(6)
	Theil	Theil	Theil	Theil	Theil	Theil
Mor_poly	−0.1217		−0.0352		0.2217***	
	(0.0701)		(0.0445)		(0.0682)	
Func_poly		0.0037		−0.0087		−0.0290***
		(0.0042)		(0.0118)		(0.0059)
Constant	0.2253***	0.1332***	0.1661*	0.1603**	0.0871	0.2244***
	(0.0551)	(0.0203)	(0.0742)	(0.0662)	(0.0653)	(0.0644)
Controls	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
Region FE	YES	YES	YES	YES	YES	YES
N	300	300	580	580	220	220
adj. R^2	0.907	0.903	0.879	0.879	0.949	0.955

Note: Robust standard errors are reported in parentheses, and *, **, and *** represent the 10%, 5%, and 1% significance levels.

Table 6
Heterogeneity results: first and second tier urban clusters.

Variables	First tier urban clusters				Second tier urban clusters			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Theil	Theil	Theil	Theil	Theil	Theil	Theil	Theil
Mor_poly	−0.1683***	−0.1396***			−0.0588	−0.0406		
	(0.0198)	(0.0198)			(0.0677)	(0.0759)		
Func_poly			0.0066	0.0056			−0.0166**	−0.0192***
			(0.0063)	(0.0070)			(0.0060)	(0.0057)
Constant	0.1662***	0.2751***	0.0517***	0.2066***	0.1337**	0.2690**	0.1196***	0.2602***
	(0.0121)	(0.0404)	(0.0115)	(0.0420)	(0.0479)	(0.0887)	(0.0099)	(0.0467)
Controls	NO	YES	NO	YES	NO	YES	NO	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES
Region FE	YES	YES	YES	YES	YES	YES	YES	YES
N	760	760	760	760	340	340	340	340
adj. R^2	0.897	0.903	0.886	0.896	0.939	0.944	0.940	0.946

Note: Robust standard errors are reported in parentheses, and *, **, and *** represent the 10%, 5%, and 1% significance levels.

Table 7
Heterogeneity results: coastal and non-coastal cities.

Variables	Coastal cities				Non-coastal cities			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Theil	Theil	Theil	Theil	Theil	Theil	Theil	Theil
Mor_poly	−0.3672***	−0.3185***			−0.0891***	−0.0868***		
	(0.0634)	(0.0528)			(0.0214)	(0.0190)		
Func_poly			−0.0211**	−0.0163*			−0.0002	0.0007
			(0.0084)	(0.0076)			(0.0046)	(0.0051)
Constant	0.3140***	0.4398***	0.0860***	0.2614***	0.1336***	0.2244***	0.0788***	0.1912***
	(0.0460)	(0.0472)	(0.0153)	(0.0408)	(0.0132)	(0.0605)	(0.0080)	(0.0539)
Controls	NO	YES	NO	YES	NO	YES	NO	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES
Region FE	YES	YES	YES	YES	YES	YES	YES	YES
N	210	210	210	210	890	890	890	890
adj. R^2	0.957	0.964	0.946	0.955	0.899	0.903	0.896	0.900

Note: Robust standard errors are reported in parentheses, and *, **, and *** represent the 10%, 5%, and 1% significance levels.

in coastal cities the central and surrounding areas are more closely connected and the high level of infrastructure development allows the advantages of functional polycentricity to emerge and be realized. Inter-regional development can thus be balanced and the urban–rural income gap reduced.

4.3.4. City level

Provincial capital cities have better infrastructure and policy support than non-capital cities, so the impact of their spatial structure will differ. This study divides the sample into provincial capital and non-capital city subsamples, as set out in Table 8. With and without

Table 8
Heterogeneity results: provincial capitals and non-capital cities.

Variables	Provincial capitals cities				Non-capital cities			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Theil	Theil	Theil	Theil	Theil	Theil	Theil	Theil
Mor_poly	−0.1848***	−0.1371***			−0.1099***	−0.0981***		
	(0.0302)	(0.0267)			(0.0248)	(0.0214)		
Func_poly			0.0167*	0.0027			−0.0028	−0.0014
			(0.0085)	(0.0061)			(0.0049)	(0.0049)
Constant	0.1572***	0.4684***	0.0147	0.3513**	0.1463***	0.2371***	0.0806***	0.1938***
	(0.0183)	(0.1379)	(0.0155)	(0.1515)	(0.0160)	(0.0431)	(0.0086)	(0.0393)
Controls	NO	YES	NO	YES	NO	YES	NO	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES
Region FE	YES	YES	YES	YES	YES	YES	YES	YES
N	110	110	110	110	990	990	990	990
adj. R^2	0.889	0.918	0.867	0.905	0.914	0.919	0.910	0.915

Note: Robust standard errors are reported in parentheses, and *, **, and *** represent the 10%, 5%, and 1% significance levels.

control variables, *Mor_poly* is significantly negative in these two subsamples. The absolute values of the coefficients of the spatial structure indices of urban-cluster morphological polycentricity are higher for provincial capital cities than for non-capital cities; the higher morphological polycentricity in the provincial capital cities makes it easier to reduce the urban–rural gap than it is for non-capital clusters. The reason may be that the population, economy, science and education, culture, and other resources in a province concentrate in the provincial capital under the influence of factors such as resource factor flow and policy preferences, which results in a strong tendency toward center polarization. The polycentric spatial structures have contributed to the sharing of resources within regions, a clear regional division of labor, and an accelerated process of regional integration, narrowing the income gap (Liu, Li, & Chen, 2017).

4.3.5. City size

This study employs heterogeneity analysis by city size. We use the size of the urban population to classify the sample, as shown in Table 9. Overall, the effect of the polycentric urban spatial structure on the income gap is significantly negative for large, medium, and small cities. The comparison of the regression results reveals that the absolute value of the *Mor_poly* coefficient is significantly larger for large cities than for medium and small cities. This indicates that the negative effect of morphological polycentricity on the income gap is greatest in large cities and relatively weaker in medium and small cities. Large cities have a higher degree of infrastructure modernization and have the advantage of economies of scale in population aggregation. As a result, they can effectively attract industrial transfer from developed cities within the region. This gradient transfer between cities within the region can effectively promote employment growth in the lagging regions and raise the income level in the lagging regions, thus narrowing the gap (Liu, Li, & Qin, 2017).

5. Expanded analysis

5.1. Discussion of nonlinear effects

Previous studies have found that the morphological polycentric spatial structure has a negative relationship with the income gap, while the functional polycentric spatial structure has an insignificant relationship. This study examines the potential mechanism for the impact of polycentric urban spatial structure on the urban–rural gap. It examines the nonlinear impact of the polycentric spatial structure of urban clusters by adding the quadratic terms of the explained variables for regression; the results are shown in Table 10; *Mor_poly2* is the quadratic term of morphological polycentricity of urban clusters, and *Func_poly2* is the quadratic term of functional polycentricity of urban clusters. From Table 11, the primary term of urban cluster polycentricity is negative at the 1% level, and the secondary term is positive at the 1% level, indicating that the relationship between urban cluster polycentricity and the urban–rural income gap is negative and then positive in a "U" shape. After adding the control variables, the direction of the coefficients of the primary and secondary terms of the polycentric spatial structure of the urban clusters remains unchanged at the 10% significance level, further confirming the "U" shape of the relationship between urban cluster polycentricity and the urban–rural income gap. Therefore, it can be concluded that the income gap can be reduced during the early stages of urban cluster polycentricity. However, with the continuous development of polycentricity, the income gap will be widened after a threshold value is exceeded.

5.2. Moderating effect of industry development

The results of the nonlinear test indicate that the polycentric spatial structure of an urban cluster has a negative and then positive "U" shaped relationship with the urban–rural income gap. The rationality of industrial structure has an important influence on the relationship between urban clusters and the urban–rural income gap. Therefore, this study further analyzes the mechanism from the perspective of industrial structure and uses the industrial division of labor and industrial agglomeration as moderating variables to

Table 9
Heterogeneity results: different city sizes.

Variables	Large cities		Medium cities		Small cities	
	(2)	(4)	(6)	(8)	(10)	(12)
	Theil	Theil	Theil	Theil	Theil	Theil
Mor_poly	−0.1458***		−0.0748***		−0.0801**	
	(0.0204)		(0.0230)		(0.0295)	
Func_poly		−0.0005		−0.0010		−0.0036
		(0.0064)		(0.0036)		(0.0055)
Constant	0.3648***	0.2916***	0.0815	0.0471	0.2685***	0.2370***
	(0.0712)	(0.0586)	(0.0675)	(0.0630)	(0.0395)	(0.0312)
Controls	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
Region FE	YES	YES	YES	YES	YES	YES
N	273	273	423	423	398	398
adj. R^2	0.947	0.938	0.929	0.927	0.880	0.878

Note: Robust standard errors are reported in parentheses, and *, **, and *** represent the 10%, 5%, and 1% significance levels.

Table 10

Results of non-linear effect test.

Variables	(1)	(2)	(3)	(4)
	Theil	Theil	Theil	Theil
Mor_poly	−1.2443***	−0.5613*		
	(0.2486)	(0.2704)		
Func_poly			−0.2112	−0.0404
			(0.1982)	(0.0760)
Mor_poly2	1.0293***	0.4317*		
	(0.2146)	(0.2218)		
Func_poly2			0.0648	0.0129
			(0.0508)	(0.0196)
Constant	0.4361***	0.7452***	0.2415	0.5884***
	(0.0822)	(0.0613)	(0.1919)	(0.1002)
Controls	NO	YES	NO	YES
Year FE	NO	NO	NO	NO
Region FE	YES	YES	YES	YES
N	1100	1100	1100	1100
adj. R^2	0.741	0.892	0.753	0.891

Note: Robust standard errors are reported in parentheses, and *, **, and *** represent the 10%, 5%, and 1% significance levels.

Table 11

Results of the moderating effect of industry development level.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Theil	Theil	Theil	Theil	Theil	Theil	Theil	Theil
Mor_poly	0.3242***	0.0949**	−0.1515***	−0.0577***				
	(0.0760)	(0.0374)	(0.0111)	(0.0134)				
Func_poly					−0.2978***	−0.1274***	0.0275	0.0257**
					(0.0839)	(0.0160)	(0.0263)	(0.0104)
Ind_agg	0.1754***	0.0711***			−0.4073***	−0.1589***		
	(0.0470)	(0.0208)			(0.1163)	(0.0193)		
Ind_div			−0.0176***	−0.0041***			0.0123***	0.0077***
			(0.0009)	(0.0009)			(0.0035)	(0.0016)
Mor_poly_Ind_agg	−0.2949***	−0.1003***						
	(0.0743)	(0.0278)						
Mor_poly_Ind_div			0.0291***	0.0076***				
			(0.0013)	(0.0014)				
Func_poly_Ind_agg					0.2225***	0.0947***		
					(0.0681)	(0.0121)		
Func_poly_Ind_div							−0.0070***	−0.0040***
							(0.0020)	(0.0009)
Constant	−0.1208**	0.1777***	0.1655***	0.3155***	0.6155***	0.4370***	0.0240	0.2070***
	(0.0487)	(0.0343)	(0.0085)	(0.0282)	(0.1430)	(0.0335)	(0.0471)	(0.0325)
Controls	NO	YES	NO	YES	NO	YES	NO	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES
Region FE	NO	NO	NO	NO	NO	NO	NO	NO
N	1100	1100	1100	1100	1100	1100	1100	1100
adj. R^2	0.183	0.630	0.213	0.635	0.221	0.637	0.198	0.639

Note: Robust standard errors are reported in parentheses, and *, **, and *** represent the 10%, 5%, and 1% significance levels.

investigate the influence of the industrial division of labor and industrial agglomeration on the relationship between the polycentric spatial structure of urban clusters and the urban–rural income gap. In Table 11, the explanatory variables in Columns (1)–(4) are *Mor_poly*, the moderating variable in Columns (1) and (2) is industrial agglomeration (*Ind*), and the moderating variable in Columns (3) and (4) is industrial division of labor (*Ind*). Similarly, the explanatory variables in Columns (5)–(8) are *Func_poly*.

In Table 11, *Mor_poly_Ind* is significantly negative, indicating that industrial agglomeration negatively modifies the relationship between the polycentric spatial structure of urban clusters and the income gap. Further analysis, as set out in Columns (1) and (2) of Table 11, shows that *Mor_poly* is significantly positive. At this point, the marginal effect of morphological polycentricity on the urban–rural gap is precisely the product of the coefficient of *Mor_poly_Ind* and the value of *Ind* plus the coefficient of *Mor_poly*. Combined with the significantly negative *Mor_poly* coefficient in the benchmark regression, it can precisely indicate that the negative effect of urban cluster polycentricity on the urban–rural gap is likely to be brought about by the moderating effect of industrial agglomeration. This means that the higher the level of industrial agglomeration, the greater the negative effect of urban cluster polycentricity on the income gap, and the smaller the income gap. In relation to the moderating effect of the industrial division of labor, the coefficient of *Mor_poly_Indiv* is positive, indicating that the industrial division of labor has a positive moderating effect on the relationship between the morphologic polycentricity of urban clusters and the urban–rural gap. The higher the level of industrial

division, the less the negative effect of urban cluster morphological polycentricity on the urban–rural gap.

Columns (5) and (6) of Table 11 show that *Func_poly_Ind* is significantly positive, indicating that industrial agglomeration has a positive moderating effect on the relationship between the functional polycentric spatial structure of urban clusters and the income gap. Also, since *Func_poly* is significantly negative here and negative but not significant in the baseline regression, the negative effect of *Func_poly* on the income gap may be offset by the positive moderating effect of the level of industrial agglomeration. Similarly, it can be concluded that the industrial division of labor has a negative moderating effect on the relationship between the functional polycentricity of urban clusters and the urban–rural income gap. This negative moderating effect is likely to offset the positive effect of *Func_poly* on the income gap. The above results verify Hypothesis 2, in part: the polycentric spatial structure of urban clusters can reduce regional disparities by promoting factor mobility and industrial structure optimization, but the realization of these mechanisms is constrained by the level of industrial development.

5.3. Moderating effect of infrastructure level

In addition to the industrial structure, infrastructure affects the relationship between urban cluster polycentricity and the income gap. We thus further analyze this relationship in terms of urban clusters' level of infrastructure and examine the effects of informatization (*Inf*) and urban accessibility (*Acc*) as moderating variables. In Table 12, Columns (1)–(4) set out the results where the explanatory variable is *Mor_poly*, where the moderating variable in Columns (1) and (2) is the level of informatization (*Inf*), and the moderating variable in Columns (3) and (4) is urban accessibility (*Acc*). Similarly, Columns (5) and (8) examine the results where the core explanatory variable is *Func_poly*.

In Table 12, *Mor_poly_Inf* and *Mor_poly_Acc* are both significantly negative, indicating that information technology and urban accessibility have a negative moderating effect on the relationship between the polycentric spatial structure of urban clusters and the urban–rural income gap. Because *Mor_poly* is significantly positive, the negative moderating effect of informatization and urban accessibility makes an important contribution to the negative effect on the urban–rural income gap of urban cluster polycentricity. By contrast, the results in Columns (5)–(8) show that *Func_poly_Acc* is significantly positive, indicating that urban accessibility has a positive moderating effect on the relationship between the functional polycentricity of urban clusters and income disparity. Also, since the coefficient of *Func_poly* is significantly negative, a positive moderating effect of urban accessibility may offset the negative effect of *Func_poly* on the income gap. Thus far, Hypothesis 2 of this study has been verified.

6. Conclusions and recommendations

Urbanization is an important driver in China's current expansion of domestic demand and sustainable economic development. Urban clusters, a major carrier of China's urbanization, have become an important platform to ensure the quality of China's economic growth. After the reform and opening up, China's economy has developed rapidly, and the income level of urban and rural residents has increased. However, with the rapid growth of total economic volume and economic efficiency, social inequality has become a more prominent problem. The widening urban–rural income gap is one of the important manifestations (Jiang et al., 2022). Therefore, it is vital to consider the impact of polycentric spatial agglomeration in urban clusters on the urban–rural income gap. We use selected urban clusters from 2003 to 2019 as a research sample to examine the impact of urban cluster polycentricity on the urban–rural income gap. We analyze heterogeneity in terms of geographic location, administrative hierarchy, size, degree of marketization, and urban cluster type.

In addition, this study constructs a quadratic term for the spatial structure of urban cluster polycentricity to further examine the nonlinear effects of urban cluster polycentricity. Finally, this study sets moderating variables related to two factors—industrial development and infrastructure level of urban clusters—to investigate the mechanism by which the urban cluster polycentricity influences the income gap.

The conclusions of this study are the following. First, the results of the benchmark regression show that urban cluster morphological polycentricity has a significant negative effect on the urban–rural income gap—the higher the degree of morphological polycentricity, the smaller the urban–rural income gap. In contrast, the impact of urban cluster functional polycentricity on the urban–rural income gap is insignificant. Second, the robustness tests show that these findings are robust and valid using the instrumental variables method and replacing the method by which variables are measured. Third, geographic location, administrative rank, size, and type of urban clusters all affect the impact of urban cluster polycentricity on the income gap. Fourth, the relationship is "U" shaped, beginning with a negative inhibitory effect and later promotion. Moreover, industrial agglomeration, level of informatization, and urban accessibility have a negative moderating effect on the relationship between the polycentric spatial structure of urban clusters and the income gap, while the industrial division of labor and the urban–rural income gap have a positive moderating effect. Industrial agglomeration and urban accessibility have a positive moderating effect on the relationship between the functional polycentricity of urban clusters and income disparity; the industrial division of labor has a negative moderating effect.

The following insights are drawn from the findings of this study. First, the government should play a macro-control function and formulate relevant policies to consolidate the dominant position of core cities. Taking national strategic needs as the guide, the government should deepen the understanding of scientific issues in the formation and development of urban clusters, including by taking into account in-depth research on the spatial agglomeration spillover effects of urban clusters and identifying scientific solutions to the problem of resource and environmental carrying capacity of high-density agglomerations in urban clusters. There should be increased innovation in the management of developing urban clusters, and the establishment of public finance systems for urban clusters should be studied. Further, reasonable technical protocols should be formulated to prepare urban cluster plans and the criteria

Table 12

Results of moderating effect of infrastructure level.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Theil	Theil	Theil	Theil	Theil	Theil	Theil	Theil
Mor_poly	0.0447***	0.0263**	0.0768***	0.0167**				
	(0.0050)	(0.0091)	(0.0063)	(0.0070)				
Func_poly					−0.0334***	−0.0208***	−0.0759***	−0.0285***
					(0.0089)	(0.0037)	(0.0106)	(0.0031)
Informatization	0.3783**	0.1425			−0.9970**	−0.2363		
	(0.1175)	(0.0906)			(0.3479)	(0.2505)		
Accessibility			0.0015***	0.0004***			−0.0015***	−0.0006***
			(0.0002)	(0.0000)			(0.0002)	(0.0001)
Mor_poly_Informatization	−1.1717***	−0.3260**						
	(0.2137)	(0.1241)						
Mor_poly_Accessibility			−0.0025***	−0.0009***				
			(0.0004)	(0.0001)				
Func_poly_Informatization					0.3522*	0.1065		
					(0.1755)	(0.1311)		
Func_poly_Accessibility							0.0008***	0.0003***
							(0.0001)	(0.0001)
Constant	0.0532***	0.1115***	0.0254***	0.2152***	0.1406***	0.1830***	0.2073***	0.2581***
	(0.0029)	(0.0184)	(0.0040)	(0.0170)	(0.0154)	(0.0244)	(0.0185)	(0.0158)
Controls	NO	YES	NO	YES	NO	YES	NO	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES
Region FE	NO	NO	NO	NO	NO	NO	NO	NO
N	1100	1100	1100	1100	1100	1100	1100	1100
adj. R^2	0.314	0.616	0.184	0.627	0.311	0.619	0.198	0.630

Note: Robust standard errors are reported in parentheses, and *, **, and *** represent the 10%, 5%, and 1% significance levels.

for defining the spatial scope of urban clusters.

Second, regional infrastructure and industrial structures should be further developed. The proportion of investment in infrastructure within urban clusters should be increased, transportation costs reduced, the input-output linkage of demand linkage strengthened, and urban clusters' development efficiency and quality promoted. In addition, the government should strengthen the diversified and specialized division of labor and collaboration within city clusters and among different cities and build an industrial division of labor pattern with a reasonable division of functions and complementary advantages among different cities. The government should promote the integration of industrial development and layout, infrastructure construction, urban-rural construction, and urban–rural integration among cities in urban clusters. It should ensure that the urban–rural income gap is reduced and that urban clusters become economic communities and communities of interests and destiny for mutual benefit, generating a win-win outcome for all cities.

Third, policymakers should leverage the comparative advantages of the backward regions. These are usually relatively labor-rich and should focus on the comparative advantage they hold in respect of labor-intensive products to generate benefits from the market. Further, the advantageous resources of the central cities can promote the industrialization of the backward regions through industrial transfer. The development of labor-intensive industries and the improvement of income levels will significantly enhance the capital accumulation ability of the backward regions. The capital supply in the region will become more and more abundant, gradually improving conditions for developing capital-intensive industries (Zhang & Kong, 2022). When capital-intensive industries establish comparative and competitive advantages, the division of labor between developed and backward regions changes from an inter-industry to an intra-industry division, the income gap between regions tends to narrow, and balanced development is possible between cities and villages.

Data availability

Data will be made available on request.

Acknowledgements

Appendix A. Definition, calculations, and descriptive statistics of variables

Table A1
Definitions of moderating and control variables.

Variables	Definition	Calculation method and process
Moderating variables		
Ind_agg_{it}	Industrial Agglomeration	$Ind_{it} = \frac{Industry_{2it}}{GDP_{it}} / \frac{Industry_{2t}}{GDP_t}$; where $\frac{Industry_{2it}}{GDP_{it}}$ denotes the share of secondary industry output in GDP for city i in year t, $\frac{Industry_{2t}}{GDP_t}$ denotes the share of secondary industry output in GDP for the country in year t.
Ind_div_{it}	Urban Industrial Division of Labor	$Indiv_{it} = \sum_{j=1}^{n} Indiv_{ijt}$, $Indiv_{ijt} = \sum_{k=1}^{6} \left(\frac{Employee_{ikt}}{Employee_{it}} - \frac{Employee_{jkt}}{Employee_{jt}} \right)$; where $Employee_{ikt}$, $Employee_{jkt}$ denote the number of employees in industry k in year t in city i and city j, $Employee_{it}$, $Employee_{jt}$ denote the number of employees in all industries in city i and city j in year t, respectively.
$Informatization_{it}$	Informatization	Total telecom business of prefecture-level cities (RMB million)/Total national telecom business (RMB million)
$Accessibillity_{it}$	Urban Accessibility	Inverse of city-weighted average travel time, referring to Shi and Zhou (2013)
Control variables		
$Market\_potential_{it}$	Internal Market Potential	ln (total retail sales of social consumer goods (million yuan)/distance within the municipal district); where $Distance_i = \frac{2}{3} \times \left(\frac{S_i}{\pi} \right)^2$, and S_i denotes the land area of the administrative area of the municipal district of city i.
$Openness_{it}$	Level of External Opening	Actual amount of foreign capital used (USD million)/regional GDP (RMB million)
$Gov\_intervention_{it}$	Government Intervention	Government fiscal expenditure (million yuan)/regional GDP (million yuan)
$Transportation_{it}$	Level of Transportation Infrastructure	City district year-end actual urban road area (square meters)/year-end total population (10,000 people)
$Urbanization_{it}$	Level of Urbanization	Total year-end population of municipal districts (10,000)/Total year-end population of the city (10,000)

Table A2
Descriptive statistics of the main variables.

Variable	Definition	Obs	Mean	Std. Dev.	Min	Max
Theil	Urban-rural income gap	1100	0.073	0.035	0.005	0.263
Mor poly	Morphological Polycentricity Index	1180	0.645	0.108	0.519	0.928
Func poly	Functional Polycentricity Index	1180	1.766	0.169	1.516	2.351
Market_potential	Internal Market Potential	1180	13.150	0.859	10.164	14.908
Openness	Level of External Opening	1180	0.023	0.018	0.001	0.103
Gov_intervention	Government Intervention	1180	0.162	0.050	0.059	0.313
Transportation	Level of Transportation Infrastructure	1180	5.030	5.568	0.339	36.958
Urbanization	Level of Urbanization	1180	0.364	0.246	0.050	1.000
Accessibility	Urban Accessibility	1180	3.572	0.708	1.526	5.103

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