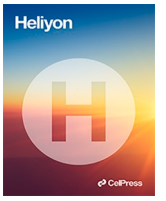
Heliyon 10 (2024) e37742

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon



Research article

Exploring the temporal-spatial characteristics and determinants of high-quality development of city clusters in China

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ARTICLE INFO

Keywords:
HQD of city clusters
Kernel density estimation
Elliptical standard deviation
Moran index
Geodetector
GWR
Influencing factors

ABSTRACT

The complexity, severity, and uncertainty of the international situation have prompted the development of city clusters to focus more on resilience and the building of infrastructures and safeguards. Chinese-style modernization proposes a new realization path for the high-quality development (HQD) of city clusters, based on which an evaluation system for HQD indicators of city clusters is constructed. We also measured the HQD levels of 19 city clusters from 2011 to 2021 and analyzed their spatial differentiation characteristics, agglomeration evolution characteristics, and influencing factors by using kernel density, standard deviation ellipse, Moran's index, geographic detector, and geographically weighted regression. The study revealed that (1) the overall level of HQD of China's city clusters shows a trend of continuous growth, and there is obvious polarization in the high quality of city clusters in different regions. (2) The spatial distribution of HQD in city clusters decreased in the "East, Center and West" direction, but the spatial patterns of "Southeast highlighting" and "Northwest rising" became more obvious. (3) The HQD of city clusters shows obvious spatial agglomeration characteristics and overall presents a spatial pattern of "hot in the east and cold in the west", with the scope of the cold spot area gradually shrinking, and the hot spot area tends to spread outward, with mature city clusters at the core. (4) The influencing factors of HQD in Chinese city clusters are diverse, with financial levels, digital economics, human capital and green innovations having decreasing influence on HQD in city clusters but showing an obvious two-factor enhancement trend, with financial levels being able to effectively stimulate the driving potential of other factors. Financial levels can effectively stimulate the driving potential of other factors. (5) The coefficients of the driving factors affecting the HQD of city clusters vary significantly spatially, with human capital, financial levels and green innovations showing a north–south hierarchical banded distribution of "high in the south and low in the north", and digital economy shows an east-west hierarchical belt distribution of "high west and low east". Based on the above conclusions, the realization path of accelerating the HQD of China's city clusters is proposed by optimizing the functional division of labor of the city clusters, giving full play to the comparative advantages of the hinterland city clusters, and relying on the high level of the city clusters for opening up.

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https://doi.org/10.1016/j.heliyon.2024.e37742
Received 4 February 2024; Received in revised form 5 August 2024; Accepted 9 September 2024
Available online 12 September 2024

1. Introduction

At present, the world economy has been hard hit by the double impact of reverse globalization and the new coronavirus epidemic. With the unprecedented changes in the past century, how the Chinese economy can make a new start amidst these changes has become the focus of development in the new period. High-quality development (HQD) harmonizes efficient economic growth, socially inclusive development, and ecological sustainability and integrates economic, social, and environmental benefits [1,2]. There is an urgent need to shift the driving force of China's economic growth from "factor input" to "innovation-driven", the economic structure from "imbalance" to "balanced" development, and the mode of economic growth from focusing on "scale and speed" to "quality and efficiency" [3]. City clusters have become an important engine of economic development by promoting the free flow of factors and realizing economies of scale, knowledge spillovers, and technological progress, leading to incremental returns to scale [4]. As the core growth poles of China's economy, city clusters have become the main spatial carriers for China's participation in international competition and the construction of the "Belt and Road". The development experience of world-class city clusters shows that city clusters, through the improvement of the coordination mechanism of resources and factors in the region, promote the continuous change of the regional economy in terms of structure, efficiency, power, etc., which has a significant role in optimizing the pattern of regional development and driving the whole economy HQD, and at the same time, it also enables the people in the whole region to enjoy the greater well-being brought by development [5].

However, even in developed economies, the construction and development of city clusters still face many challenges. (1) Overdevelopment of city clusters. In the case of the London metropolitan area, which is part of the city clusters in the south-central part of the United Kingdom, for example, the expansion of London's economic influence, particularly the increase in its financial and tax advantages, has brought about a series of social problems, such as a significant increase in the cost of living, including housing costs and various types of urban services. Commuting distances from other towns to London currently possibly exceed 100 km, and with water supplies for London households being piped in from other areas, such long commuting distances will have a domino effect that not only puts considerable pressure on the city's transportation network but also increases the price of real estate in these areas [6,7], a problem that is common in the process of building world-class city clusters for China. (2) Contraction of the development of city clusters. For example, some city clusters in northwestern European countries such as Germany and France have already experienced contraction in their development, which may also hinder the economic development of the region as a whole. Simmie (2002) [8] found that due to structural economic problems, the gradual loss of population inflow to many cities whose mainstay industries are steel, machinery, automotive, textile, or mining, coupled with the increasing trend of aging in the European region, it is likely that there will be more shrinking cities and regions in Europe in the future. (3) Uncontrollable development of city clusters. As a result of uncontrollable factors such as the COVID-19 global pandemic, the Russian-Ukrainian conflict, and the Israeli-Palestinian conflict, large city clusters across the globe may be forced to become more "self-sufficient", investing in their large markets to keep them running. In this context, air, water, housing supply, energy costs and supply chains are likely to be at the forefront of governments' considerations in the construction of city clusters [9,10].

Based on this, the basic connotation of Chinese-style modernization provides realistic and feasible solutions for the HQD of city clusters, fully reflects the current unbalanced and insufficiently specific national conditions, and constructs a new path for the HQD of city clusters from five dimensions, namely, population size, common prosperity, material and spiritual coordination, symbiosis between human beings and nature, and peaceful development. Then, based on this connotation, how can a set of comprehensive, multilevel, and wide-area high-quality evaluation index systems be set for city clusters? What kind of spatial differentiation and cluster characteristics does the HQD of Chinese city clusters exhibit? What are the key factors affecting the HQD of city clusters? Clarifying these issues can provide a reference for the current dilemmas and challenges encountered in the construction of city clusters and at the same time is of great practical significance for the advancement of the modernization process.

This paper takes 19 city clusters in China as research objects, constructs an evaluation system of HQD indicators for Chinese city clusters based on the basic connotation of Chinese-style modernization, and explores the spatial differentiation evolution characteristics of the HQD of city clusters as well as agglomeration trends by using kernel density estimation, standard deviation ellipse, spatial Markov model, Moran index, etc. Furthermore, a geographic detector and geographic weighted further, geographic probes and geographically weighted regression are used to reveal the driving mechanism and explore the effects and interactions of the driving factors.

The rest of the paper is organized as follows: Part II is a review of related literature; Part III introduces the indicator evaluation system and research methodology; Part IV analyzes the spatial differentiation characteristics and cluster characteristics; Part V analyzes the influencing factors of HQD in city clusters; and Part VI summarizes the findings of the study and proposes policy recommendations and an outlook.

2. Literature review

2.1. The definition of HQD in city clusters

Lang (2005) [11], in "*Beyond Megalopolis: Exploring America's New 'Megapolitan' Geography*", proposed the concept of "Megapolitan". Since then, the spatial form of city clusters has gradually matured, and many scholars have researched the concept of city clusters on the basis of this concept to continuously enrich the theory of city clusters. Regarding the definition of HQD, most scholars have not singled out the concept of "HQD", focusing only on the concept of "quality of development". In their study of the quality of development, Tan et al. (2014) [12] analyze the difference between "sudden" and "harmonious" economic growth from the perspective

of the quality of economic growth and clarify the difference between the two, arguing that the quality of economic development needs to emphasize coordinated, stable and healthy growth and should focus not only on the increase in economic quantity but also on the harmonious development of the economy, the environment and people. Barro (2002) [13] argued that the quality of economic growth is closely related to quantity and that two aspects are taken into account when measuring the quality of economic development: economic dimensions, such as productivity and the utilization rate, and human factors, such as the country's political system, religion, and crime rate. Lau & Choong (2014) [14] considered the quality of economic growth and considered the impact of carbon emissions on the economy and the environment. Roy & Goll (2014) [15] combined factors such as human resources and social civilization on this basis and considered the mechanism of their role in the quality of economic growth. Schumpeter (2021) [16] argues that economic growth is the overall manifestation of the development of material production in society, which mainly includes an increase in the number of products as well as the effects brought about by an increase in the volume of products, and emphasizes that the study of how to promote rapid economic growth should be viewed in the context of the entire production process and should not focus only on the results. Knowles (2022) [17] sees the connotation of the quality of economic development and suggests that economic development is not simply a matter of total economic growth but also includes fiscal balance, social harmony, ecological excellence, and the improvement of national quality. Mlachila (2017) [18] argued that the amount of public expenditure on poverty, the level of institutional quality, the state of financial development, and the degree of foreign direct investment are external factors that affect the quality of economic growth. Li & Phelps (2019) [19] argue that upgrading the quality of the labor force can increase the efficiency of labor in order to further promote economic growth. In summary, the relevant literature suggests that high-quality development involves not only economic growth, but also focuses on the social and environmental effects brought about in the process of economic growth. These include high-quality economic growth, harmonious social development, green development of ecological environment and high-level development of opening up to the outside world. Combined with the basic connotation of Chinese-style modernization and the research content of this paper, this paper argues that the definition of high-quality urban development can be summarized as follows: it is the development that gives full play to the advantages of the enormous size of the population, the development of regional co-ordination and wealth-sharing, the development of the economy and grammar that go hand in hand, the development of the ecological environment in a sustainable manner, and the development of opening up to the outside world at a high level, and it is also the development that embodies the new development concepts of innovation, coordination, openness, greenness, and sharing.

2.2. Factors affecting the level of HQD in city clusters and methods of measurement

In their research on the influencing factors of the HQD of city clusters, scholars believe that fixed asset investment, industrial structure, the level of opening-up, scientific and technological innovation, human capital and so on will affect the HQD of city clusters. He et al. (2019) [20] constructed a multidimensional input–output framework for HQD in Yangtze River Delta city clusters based on the theoretical framework of the "New Development Philosophy" by adding the economic dimension and analyzed its dynamic evolution using the spatial Markov chain to analyzing its dynamic evolution. Xu & Jiao (2021) [21] explain China's economic growth in terms of labor, capital, and total factor productivity by estimating the Cobb–Douglas production function using China's official data. La & Marsiglio (2010) [22] used the entropy weight method to measure the weights of indicators and to analyze the main factors affecting economic growth. Fang et al. (2021) [23] studied the factors affecting the development quality of city clusters by using a geographically weighted regression model of fixed asset investment, industrial structure, the level of opening-up, the level of urbanization, transportation and communication, and the level of governmental expenditures and concluded that the level of fixed asset investment, the level of fiscal expenditure, and the level of transportation and communication have a significant impact on the development of Beijing-Tianjin-Hebei city clusters. By constructing an econometric model, Chen et al. (2023) [24] concluded that science and technology innovation, human capital and foreign investment have a positive effect on the HQD of Central Plains city clusters, in which the effect of science and technology innovation and human capital is significant. Li et al. (2022) [25] explored the factors affecting the HQD of city clusters in the Pearl River Delta and the Yellow River Basin in terms of economic, social and ecological factors and used gray correlation analysis and the AHP-DEMATEL method to conduct quantitative research. The results show that innovation ability, talent resources, education resources and openness level are the key factors affecting the HQD of city clusters. Starting from the five development concepts of "innovation, coordination, greenness, openness and sharing", Liu (2023) [26] selected the indicators of environment, finance, opening-up, technology, and income as the explanatory variables and utilized the GMM model to explore the influence of each indicator on the HQD level of city clusters along the Yellow River.

The above literature provides a preliminary analysis of the theoretical connotations, influencing factors and evaluation methods of the HQD of city clusters, which provides ideas for drawing on and logical references for this paper, but there are still the following enhancements. Firstly, there is no uniform standard for the construction of evaluation indices of HQD at the city clusters. Secondly, the spatial characteristics and influencing factors of the HQD of Chinese city clusters in the new era are not yet clear. Given this, this paper constructs a multidimensional system for measuring the HQD of city clusters based on the basic connotation of Chinese-style modernization, combines panel data on 19 city clusters in China from 2011 to 2021, quantitatively portrays the HQD of each city clusters and analyzes its spatial differentiation characteristics as well as the influencing mechanism to provide a practical basis and decision-making reference for exploring new dynamics and new paths of future development based on city clusters. The main contributions of this paper are as follows: Firstly, based on the basic connotation and five characteristics of Chinese-style modernization, this paper analyses the theoretical connotations of the HQD of city clusters, that is, the HQD of city clusters is the development of fully releasing the talent dividend, the development of regional coordination and sharing of the commonwealth, the development of coordinating the economy with culture, ecology-driven sustainable development, and the development of opening up to the outside world at a high level. First, it improves the theory of HQD and incorporates regional coordination, high-level opening-up, and talent

dividend release into the theoretical framework of HQD from the perspective of Chinese-style modernization. Secondly, it enriches the theoretical practice of Chinese-style modernization, which has been put forward for only one year, mostly from qualitative analysis to study its theoretical connotations and less practical application research. This paper innovatively proposes a theoretical path for how city clusters can realize China's modernization with respect to HQD from the perspective of city clusters. Second, the spatial and temporal characteristics and influencing factors of the HQD of Chinese city clusters are analyzed, which provides a realistic basis for further research by policymakers and urban planners. City clusters are spatial forms that appear in the advanced stage of urbanization, and spatial spillover effects inside and outside city clusters have a greater impact on HQD. This paper uses kernel density estimation, standard deviation ellipse, and Moran's index to investigate the spatial differentiation evolution characteristics of the HQD of city clusters, as well as the trend of agglomeration. The HQD of city clusters shows obvious spatial agglomeration characteristics, and the overall spatial pattern of "hot in the east and cold in the west" is presented. Moreover, the driving mechanism of the HQD of city clusters is revealed by using geographic detectors and geographically weighted regression methods, and the level of finance, the digital economy, human capital, and green innovation can influence the level of the HQD of city clusters. These findings provide decision-making references for the development strategy of city clusters.

3. Evaluation system of indicators and research methods for HQD in Chinese city clusters

3.1. Construction of an indicator evaluation system for the HQD level of Chinese city clusters

Based on the basic connotation of Chinese-style modernization, this paper takes five characteristics as the first-level indicators and combines relevant research and data availability to select 40 representative indicators to construct an evaluation system of indicators

Table 1
Evaluation system of indicators of the HQD level of China's city clusters.

Level 1 indicators	Level 2 indicators	Indicator description	Attributes
Huge Population	Education Benefits	Number of university students per 10,000 population	+
		Teacher–student ratio in primary and secondary schools	+
		Expenditure on education per capita	+
	Medical Care Levels	Number of doctors per 1000 people	+
		Number of beds in hospitals and health centers per 1000 people	+
	Social Security	Per capita social security and employment expenditure	+
		Number of health social insurance and social welfare employees per 10,000 people	+
	Traditional Infrastructure	Road area per capita	+
		Public Transportation Vehicle Ownership per 10,000 People	+
	New Infrastructure	Number of internet broadband access users per 10,000 people	+
Coordinated Regional Development	Urbanization level	Urbanization rate of resident population	+
	Urban–rural income	Per capita disposable income of urban residents	+
		Per capita disposable income of rural residents	+
	Urban–rural gap	Ratio of urban and rural incomes	–
	Income Distribution	Gross wages/GDP	+
	Regional Gap	Gini coefficient based on night light data	–
	Employment level	Urban survey unemployment rate	–
Material and Cultural-ethical Advancement	Economic Development	GDP per capita	+
		Brightness of lights at night	+
	Industrial Structure	Index of advanced industrial structure	+
		Industrial structure rationalization index	–
	Economic Vitality	Total sales of social retail goods/GDP	+
	Cultural Industries	Number of persons employed in culture, sports and recreation per 10,000 persons	+
	Cultural Products	Number of public library collections per capita	+
	Quality of Innovation	Urban Innovation Index	+
	Research Input	Science Expenditure per Capita	+
Ecological Sustainability	Urban Greening	Green space per capita	+
		Green coverage rate of built-up areas	+
	Pollution Reduction	Electricity consumption per unit of GDP	–
		Industrial Value Added/Sulfur Dioxide Emission	+
	Air Quality	Annual average concentration of PM2.5	–
		Proportion of days when urban air quality meets secondary standards	+
	Effectiveness	Centralized sewage treatment rate	+
		Harmless treatment rate of domestic garbage	+
	Green Technology	Number of green patent applications per 10,000 people	+
Opening-up	Foreign Investment	Number of foreign-invested enterprises	+
	Utilized Foreign Capital	Actual Utilization of Foreign Investment/GDP	+
	Foreign Trade	Total Import and Export/GDP	+
	Social Openness	International Tourism Income/GDP	+
	Government Effectiveness	Public Service Expenditure/GDP	+

of the HQD level of China's city clusters, and the specific indicators and descriptions are shown in Table 1. This indicator encompasses all aspects of HQD in China's city clusters. Specifically, firstly, Huge Population not only reflects the quality of the population through education, welfare, health care, and social security but also includes traditional and new infrastructure as basic indicators to improve the quality of the population. Secondly, at the level of Coordinated Regional Development, in order to reflect such connotations, such as narrowing the gap between urban and rural areas and regional development and expanding the proportion of income of middle groups, should be considered. The Gini coefficient is calculated based on traditional indicators, concerning the use of nighttime lighting data as a proxy for per capita income, to measure regional income disparities and to reflect the fairness of income distribution. Thirdly, Material and Cultural-ethical Advancement dimensions, drawing on the practices of Hendernson et al. (2012) [27] and Wu & Wang (2019) [28], the annual average light brightness of each city is used to measure the level of economic development. The industrial structure is measured using the index of advanced industrial structure, the industrial structure rationalization index is used to measure the industrial structure, and scientific and technological innovation, as an inexhaustible driving force for the realization of modernization, is measured in this paper using China's urban and industrial innovation index. Fourthly, in the Ecological Sustainability dimension, this paper selects indicators for greening, energy savings, emission reduction and governance, while green technology is characterized by the number of green patent applications by 10,000 people. The PM2.5 data in this dimension are from the Atmospheric Composition Analysis Group of Washington University in St. Louis, and the green patent-related data are from the China Research Data Service Platform (CNRDS). Fifthly, the opening-up dimension, which fully considers the four dimensions of foreign investment, actual use of foreign capital, foreign trade and social openness, also includes government effectiveness indicators, reflecting the efficiency and convenience of government governance in the process of modernization. The data of the above indicators are mainly obtained from the CNRDS database, the Wind database, the National Intellectual Property Rights database and the statistical yearbook of each city.

3.2. Research methodology and sample selection

3.2.1. CRITIC-entropy weight method

The entropy weight method is a method used to determine the weight of indicators through the size of the information utility value of each indicator; the CRITIC method measures the objective weight of indicators based on the comparative strength and conflict of evaluation indicators. To prevent the weights of the indicators determined through the entropy weighting method and CRITIC method from deviating relatively greatly, it is necessary to find the optimal combination of weights to calculate the comprehensive score of the HQD level of city clusters.

(1) Entropy weight method

The first step is data preprocessing. There are n evaluation years, each with m evaluation indicators, constituting the initial matrix $X=(x_{ij})_{n\times m}$. In order to eliminate the difference in scale, the data of positive and negative indicators are standardized:

The formula for normalizing positive indicators is:

$$z_{ij} = \left[x_{ij} - min(x_j)\right] \Big/ \left[max(x_j) - min(x_j)\right] \quad (i=1,2,\ldots,n; j=1,2,\ldots,m) \tag{1}$$

The formula for normalizing the inverse indicator is:

$$z_{ij} = \left[max(x_j) - x_{ij}\right] \Big/ \left[max(x_j) - min(x_j)\right] \quad (i=1,2,\ldots,n; j=1,2,\ldots,m) \tag{2}$$

Where i represents the city, j represents the indicator, x_{ij} denotes the original value of the jth indicator of city i, and z_{ij} denotes the value of the jth indicator of city i after standardization.

In the second step, the information entropy of the jth indicator is calculated:

$$e_j = -\frac{1}{\ln n}\sum_{i=1}^{n} p_{ij}\ln\left(p_{ij}\right), p_{ij} = \frac{z_{ij}}{\sum_{i=1}^{n} z_{ij}} \tag{3}$$

In the third step, the entropy weight of the indicator is calculated:

$$w_{1j} = \frac{1-e_j}{\sum_{j=1}^{m} 1-e_j} \tag{4}$$

(2) CRITIC method

In the first step, the amount of information contained in the jth indicator is calculated:

$$C_j = \sigma_j \Big/ \sum_{i=1}^{n}\left(1-|r_{ij}|\right) \tag{5}$$

Where σ_j represents the standard deviation of the jth indicator, which characterizes the variability of the indicator; r_{ij} represents the

correlation coefficient between the indicators; $\sum_{i=1}^{n}(1-|r_{ij}|)$ characterizes the degree of conflict between the jth indicator and the other indicators; and C_j represents the amount of information contained in the jth indicator.

In the second step, the objective weight of the jth indicator is calculated:

$$w_{2j} = C_j \Big/ \sum_{j=1}^{m} C_j \tag{6}$$

(3) CRITIC-entropy weighting method

In the first step, the portfolio weights are calculated. In this paper, it is assumed that the two weight calculation methods have the same importance, so that $\beta = 0.5$.

$$w_j = \beta w_{1j} + (1-\beta) w_{2j} \tag{7}$$

In the second step, a composite score for the level of HQD of the city clusters is calculated:

$$S_{ij} = w_j \times z_{ij} \tag{8}$$

3.2.2. Geodetector

Geodetector is a tool for detecting spatial variability characteristics and is used to explain the driving role of factors influencing a particular geographic element (Yang et al., 2023) [29]. Geodetection portrays the extent to which an independent variable X explains a dependent variable Y by means of a q-value, and the formula for geodetection is as follows:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2} = 1 - \frac{SSW}{SST} \tag{9}$$

$$SSW = \sum_{h=1}^{L} N_h \sigma_h^2 \quad SST = N\sigma^2 \tag{10}$$

Where h is the high-quality development level of the city clusters or the stratification of the influencing factor X. N and Nh are the numbers of units of the Chinese city clusters and the stratum h, respectively. σ^2 and σ_h^2 is the variance of the high-quality development level of the Chinese city clusters and the stratum h, respectively.SSW is the sum of the variances within each stratum, and SST is the total variance of the high-quality development level of the Chinese city clusters. q takes the value in the range of [0,1], and if stratification h is generated by the influencing factor X, the value of q represents the degree of explanation of the influencing factor for the high-quality development level of the city clusters.

Moreover, the interaction detection in the geodetector model is based on the assessment of the explanatory power q(X1) and q(X2) of different factors for the high-quality development of city clusters, and measures the comparative explanatory power q(X1 ∩ X2) of the factors' high-quality development of city clusters after the interaction, in order to identify the driving ability of the two-factor interaction. According to the relative position of the two-factor explanatory power in the two single factors, the types of interaction can be classified as follows: interaction, nonlinear attenuation, single-factor nonlinear attenuation, two-factor enhancement, independence and nonlinear enhancement.

3.2.3. Geographically weighted regression

Geographically weighted regression model (GWR) is a regression analysis method that incorporates spatiotemporal information on the basis of ordinary linear regression to study spatiotemporal specificity. The formula of the GWR model is shown below:

$$y_i = \beta_0(u_i, v_i, t_i) + \sum_{k=1}^{p} \beta_k(u_i, v_i, t_i) x_{ik} + \varepsilon_i \tag{11}$$

Where y_i represents the high-quality development level of the city clusters at sample point i; (u_i, v_i, t_i) represents the spatiotemporal coordinates of the ith sample point; $\beta_0(u_i, v_i, t_i)$ represents the regression constant of the point, that is, the constant term in the spatiotemporal geographically-weighted regression. $\beta_k(u_i, v_i, t_i)$ represents the k regression parameter of the point i; x_{ik} represents the first eigenvariable of the i sample point i; and ε_i represents the error term of the sample point i.

The GWR model is estimated via Eq. (12):

$$\widehat{\beta}(u_i, v_i) = \left[X^T W^T W X\right]^{-1} X^T W^T W Y \tag{12}$$

Among them, the elements of the spatial weight matrix W are calculated with three factors determined by spatial bandwidth, kernel function, and distance formulae, which are constructed based on adaptive bandwidth, Gaussian kernel function, etc., and determined by guidelines, drawing on the approach of Huang et al. (2010) in this paper.

3.2.4. Moran index I

The Moran index I is a measure used to assess the degree of spatial autocorrelation in spatial data. The formula for its calculation is as follows:

$$S^2 = \frac{\sum_{j=1}^{n} w_{ij}(x_i - \overline{x})^2}{n} \tag{13}$$

$$I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i - \overline{x})(x_j - \overline{x})}{S^2 \sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}} \tag{14}$$

In Eq. (13), S^2 is the sample variance, w_{ij} is the element of the spatial weight matrix. This paper uses a nested matrix, i.e., the combination of the geographic inverse distance weight matrix and the economic weight matrix. The expression form is $W(\varphi) = (1-\varphi)W^G + \varphi W^E$, W^G and W^E are the geographic inverse distance matrix and the economic weight matrix, and the specific calculation formula is borrowed from Yu (2009) [30] and Parent & LeSage (2008) [31]. If the Moran index I is significantly greater than 0, it indicates the existence of spatial positive autocorrelation in the sample data; if it is less than 0, it indicates the existence of negative autocorrelation; and if the index is close to 0, it indicates that spatial correlation cannot be supported.

3.2.5. Sample selection

In this paper, 19 city clusters in China are studied (see Fig. 1), which can be divided into optimization and enhancement city clusters (Beijing-Tianjin-Hebei, Yangtze River Delta, Pearl River Delta, Chengdu-Chongqing and Middle Yangtze), growing city clusters (Shandong Peninsula, Yueminzhe Coastal, Central Plains, Kuan-chung Plains, Beibu Gulf) and nurturing developmental city

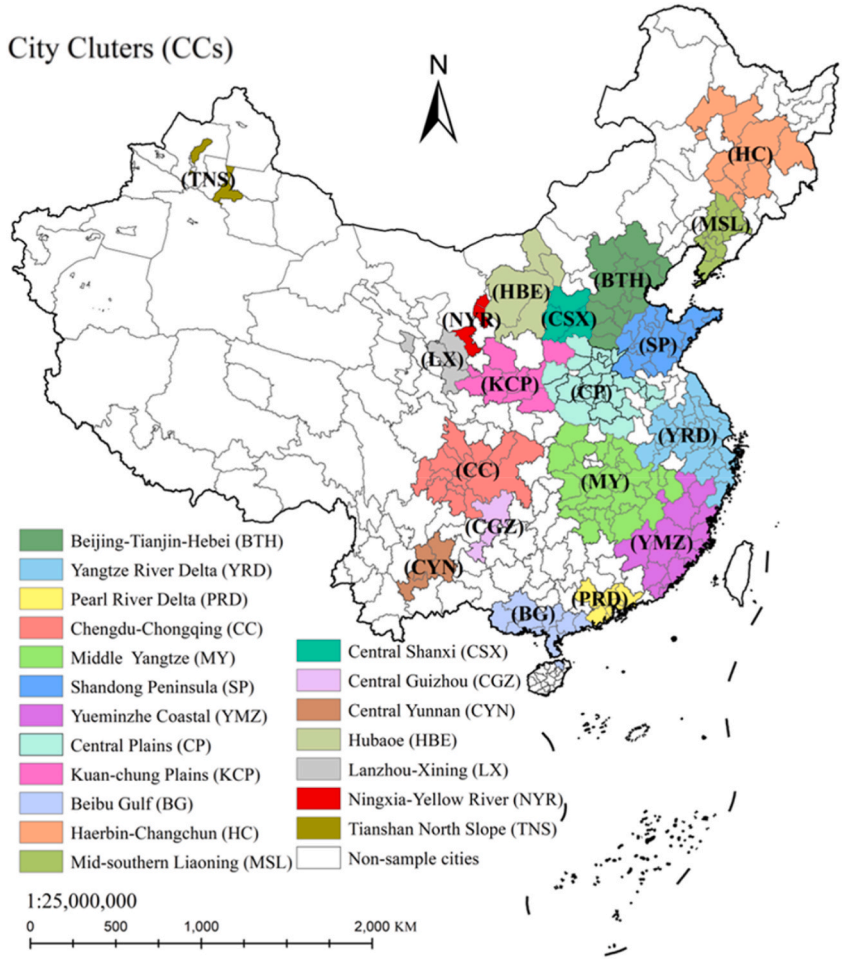

Fig. 1. China's city clustering division.

clusters (Haerbin-Changchun, Mid-southern Liaoning, Central Shanxi, Central Guizhou, Central Yunnan, Hubaoe, Lanzhou-Xining, Ningxia-Yeallow River, Tianshan North Slope). Due to the large amount of missing data in the city clusters of Central Yunnan, Central Guizhou, and the Tianshan North Slope, this paper studies 212 prefecture-level cities, and the missing data for some of the cities are supplemented by interpolation. The text classifies individual cities that are included in both clusters into clusters that are closer to the central city or more economically connected based on their distance to the central city and the degree of economic connection.

4. Spatial differentiation and cluster characteristics of HQD in Chinese city clusters

4.1. Spatial differentiation characteristics of HQD in city clusters

4.1.1. Weakening of the spatial pattern of the "East-Central-West" gradient

Fig. 2 shows the overall level of HQD and the characteristics of each dimension of China's city clusters from 2011 to 2021. Overall, the HQD of city clusters shows a steady increase during the sample period, from 0.211 in 2011 to 0.290 in 2021, with an average rate of change of 3.40 %, which shows two phases of steady improvement and rapid development. (1) In the steady improvement stage (2011–2017), the HQD of the city clusters increased from 0.211 in 2011 to 0.250 in 2017, with an average change rate of 2.63 %. This is mainly because of the constraints of the "growthism" of China's economy at this stage, the greater emphasis on structural adjustment and transformation, and the increased investment in infrastructure, especially high-speed railways, which has improved the accessibility of the internal and external links of city clusters. On the other hand, support for high-tech industries has strengthened, and the digitally enabled e-commerce economy has developed rapidly; for example, in 2017, online retail sales grew 20 percentage points higher than the total social sales of retail goods, which has become the main driving force for market consumption. (2) Rapid development stage (2017–2021). The HQD in the city clusters increased from 0.250 in 2017 to 0.290 in 2021, with an average change rate of 3.20 %. During the 13th Five-Year Plan period, China's economy accelerated its transformation from speed and scale to quality and efficiency, and coordinated regional development and environmentally sustainable development provided new impetus and space for high-quality development, with the effect of coordinated development contributing to the acceleration of high-quality development. In this phase, the new development pattern and HQD require that science, technology and innovation play a strong supportive role, innovation clusters based on city clusters are gradually becoming the new engine of regional development, and the Global Innovation Index 2023 shows that China's global top 100 technology clusters exceed that of the US for the first time.

This paper divides the HQD levels of city clusters in 2011 and 2021 according to the natural breakpoints of the urban modernization level in 2016, with split points of 0.2211, 0.2619, 0.3119, and 0.3786 (see Fig. 3), and divides city clusters with different levels of development into four types: early growth, growth mid-growth, late growth and mature stage. From the spatial distribution of China's city clusters in 2011, 2016 and 2021 in Fig. 3, the following characteristics can be found. (1) The HQD levels of city clusters, in general, show an obvious gradient pattern of "East, Central and West". Taking 2021 as an example, the city clusters in the maturity stage are mainly the Yangtze River Delta, Pearl River Delta, and Beijing-Tianjin-Hebei city clusters, which are consistent with the division of city clusters and play the role of growth poles in the process of regional HQD. The late-growth-stage city clusters are mostly clustered around the mature-stage city clusters and close to the eastern coastal areas, such as the Shandong Peninsula, Mid-southern Liaoning, and the Yueminzhe Coastal, so that they can take over the technological spillover and industrial transfer from the mature city clusters through the advantage of geographic proximity. The city clusters in the mid-growth stage are mainly Middle Yangtze, Haerbin-Changchun, Hubaoe, Chengdu-Chongqing, and Central Yunnan, which are wrapped by early-growth and late-growth city clusters and have greater development potential. Early growth and early city clusters are mostly located in the central and western regions,

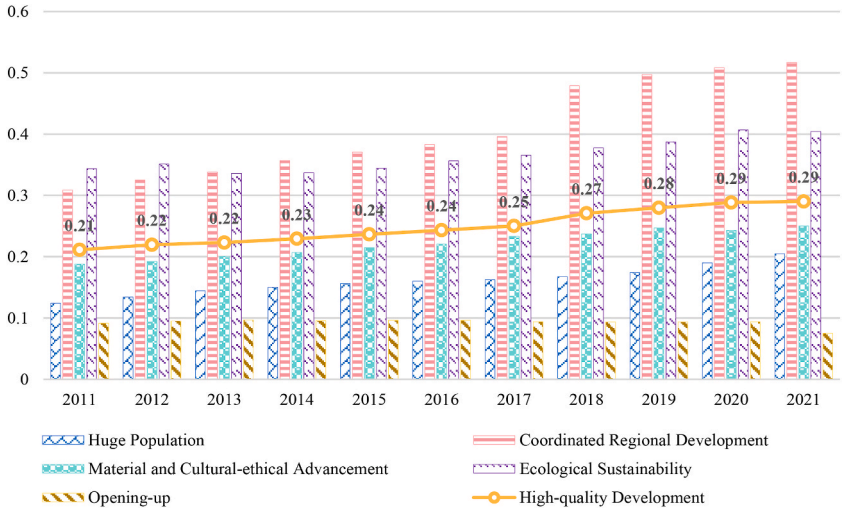

Fig. 2. HQD level and modernization level of Chinese city clusters by dimension, 2011–2021.

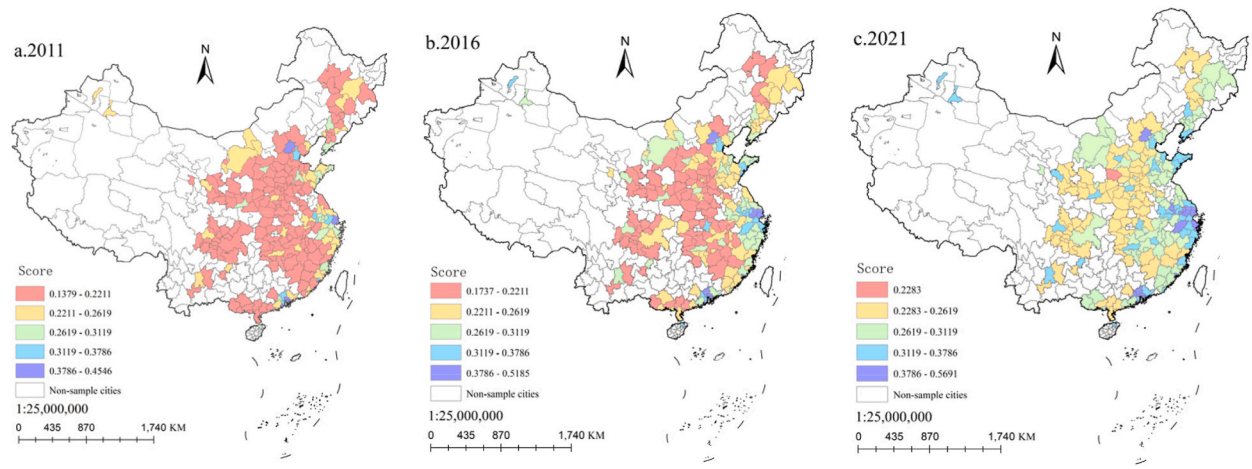

Fig. 3. Spatial distribution pattern of China's city clusters in terms of HQD level, 2011, 2016 and 2021.

with a relatively weak foundation for modernization. (2) The gradient pattern of "East-Central-West" is weakening year by year. With the promotion of strategies such as the rise of central China, the new round of western development and the revitalization of the old industrial bases in northeastern China, the spatial distribution of HQD of city clusters shows a shift from the remarkable "cross-ranking" pattern in 2011 (dominated by city clusters in the early and early stages of growth, with sporadic distribution of city clusters in the late stages of growth and maturity) to the "multi-ranking and cross-graded" pattern (dominated by city clusters in the early and mid-stage of growth, with intersections of city clusters in the late stage of growth and maturity) in 2021, with a gradual narrowing of the gap between the city clusters. (3) The spatial pattern of "southeast prominence" and "northwest rise" gradually formed. Fig. 3(a-c) shows that the modernization levels of the Yangtze River Delta, the Yueminzhe Coastal, and some cities in the Middle Yangtze River are greater than those of the Northeast, North China, and Central China city clusters as a whole, firstly, because the Northeast and North China city clusters are facing greater pressure from economic restructuring and environmental governance. Secondly, the central areas, such as the Central Shanxi and Central Plains city clusters, which are limited by resource endowment, outstanding industrial isomorphism, and opening-up, need to be further improved. Hubaoe, as a new growth pole of the Northwest city clusters, has fully utilized its advantage of being connected to Russia in the north and the North China Plain in the south.

4.1.2. Analysis of kernel density estimation

In order to show the overall level, distribution evolution, extensibility, and polarization trend of HQD of city clusters in China more graphically and intuitively, this paper uses the three-dimensional dynamic kernel density of city clusters' HQD to plot Fig. 3. First, from the distribution position of the kernel density curve, Fig. 4(a)–(d) shows that the HQD kernel density curve of city clusters shows an overall rightward shifting trend during 2011–2021, which is in line with the previous characterization that the level of HQD of city

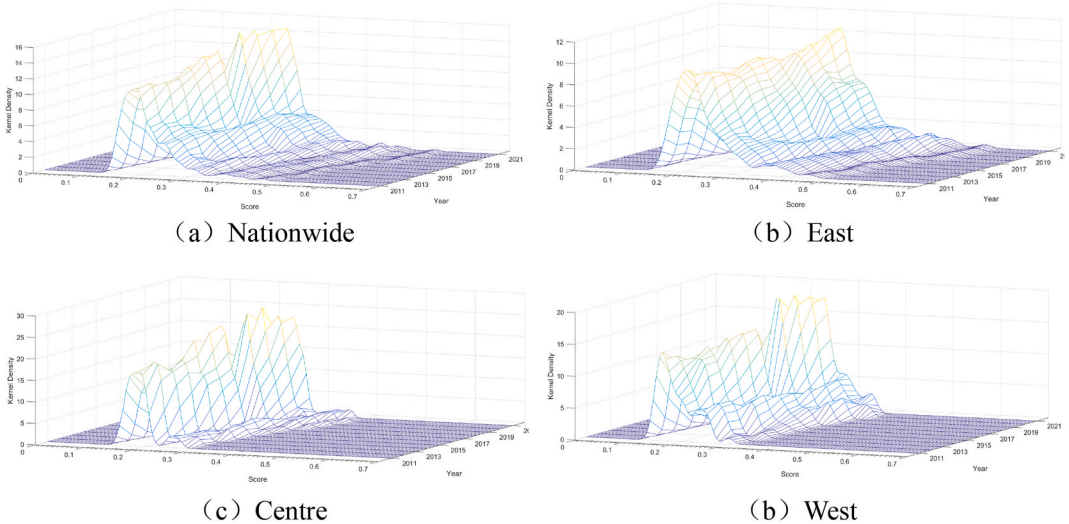

Fig. 4. Distribution of kernel density at the HQD level for national and regional city clusters, 2011–2021.

clusters has been increasing. The eastern city clusters have the most obvious shift to the right. Secondly, from the viewpoint of the distribution pattern of the main peak, the national kernel density curve in 2011–2021 shows a gradual increase in the height of the main peak and a narrowing width, which implies that the absolute gap in the level of HQD of the city clusters is gradually narrowing, and the degree of dispersion is decreasing. The relatively wide bandwidth of the eastern city clusters is because the Beijing-Tianjin-Hebei, Yangtze River Delta and Pearl River Delta city clusters are in a leading and exemplary position in the process of modernization advancement, and their modernization levels are ahead of their time, exacerbating the modernization differences between the city clusters of the eastern region. Although the bandwidth of the central city clusters is the narrowest, city clusters and metropolitan areas such as the Central Shanxi, Middle Yangtze, and Kuan-Chung Plains emanate from multiple points, which continuously spawn the cluster and fusion of factors such as labor, capital, and data; the linkages between the city clusters and metropolitan areas are strengthened in terms of population, capital, industries, innovations, consumption, and investments; and the inter-regional gap in HQD among city clusters is gradually narrowing. Again, from the viewpoint of the extensiveness of distribution, the national city clusters HQD shows an obvious right trailing phenomenon, and specific to the region, it can be found that the kernel density curves of the eastern and western city clusters have a serious right trailing, which indicates that there are obvious "leaders" in the HQD of these two regional city clusters, such as the Beijing-Tianjin-Hebei, Yangtze River Delta, Pearl River Delta city clusters, and Chengdu-Chongqing, which lead the regional HQD. Finally, regarding the number of wave peaks, the HQD kernel density curves of the national, eastern and central city clusters show a single-peak trend, indicating a clear polarization phenomenon, while those of the western region change from a double peak to multiple-peak, showing a multi-polarization trend. At the same time, the main peak is located on the right side of the side peaks, which indicates that HQD advancement in the western city clusters has certain bottlenecks and needs to be accelerated to compensate for the short boards.

4.1.3. Characterization of the evolution of the center of gravity and standard deviation ellipse

In order to accurately grasp the spatial distribution pattern of the HQD level in Chinese city clusters, this paper utilizes the standard deviation ellipse technique and adopts the SDE method to measure the standard deviation ellipse parameter of the HQD level of Chinese city clusters in 2011, 2016 and 2021, and the results are shown in Fig. 5. In terms of the center of gravity of distribution, the center of gravity of the HQD of China's city clusters shows a clear trend of "southward and westward" movement during the period of 2011–2021, specifically in Maanshan and Xinyang in Anhui Province, which belong to the Middle Yangtze city clusters. In terms of the distribution range, the ellipse area gradually narrowed from 2011 to 2016, and the ellipse area fluctuated and expanded after 2016, indicating that the level of HQD of city clusters showed a trend of agglomeration followed by diffusion because the 19 city clusters have

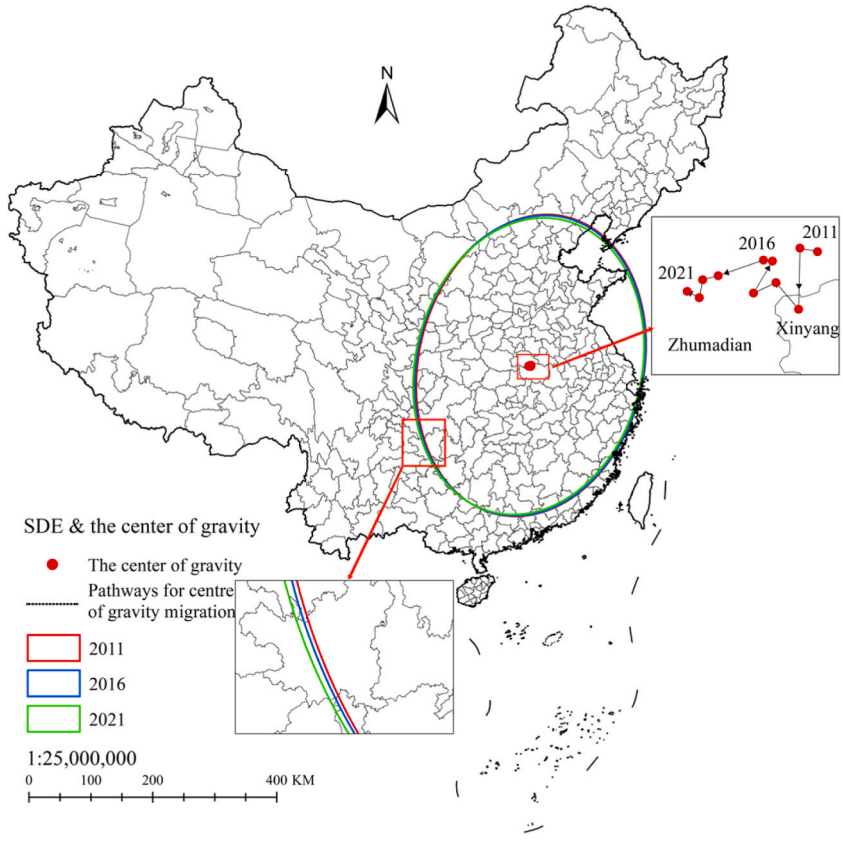

Fig. 5. HQD standard deviation ellipse and its center of gravity migration for China's city clusters, 2011–2021.

gradually become new growth poles to support regional development, especially as the upper, middle, and lower reaches of the Yangtze River Economic Belt together constitute the east–west axis of China's development, which has prompted the standard deviation ellipse to gradually move to the southwest. In terms of the spatial distribution, the azimuth angle of the standard deviation ellipse of the spatial distribution of HQD in city clusters during 2011–2021 and the changes in the long and segmental semi-axes are limited, with the long semi-axis always larger than the short semi-axis, the short semi-axis slightly increasing and the long semi-axis slightly shortening, while the expansion and contraction amplitude of the short axis is stronger than that of the long axis, presenting a circularization trend. This indicates that the concentration of HQD in Chinese city clusters has slightly weakened, and the pulling effect of the east–west direction on the HQD of city clusters has gradually weakened. The azimuth angle gradually increases, with the clockwise rotation angle increasing from 13.12° in 2011 to 13.85° in 2021, indicating an increase in the modernization level of the city clusters in the southwest and northeast directions.

4.2. Characteristics of the spatial agglomeration evolution of HQD levels in city clusters

4.2.1. Spatial agglomeration characteristics of the HQD of city clusters

In order to study more deeply the spatial cluster state of the HQD level of China's city clusters in 2011–2021, this paper first examines whether there is spatial correlation in the HQD level of each city cluster through the global Moran index. Table 2 shows that all the Moran indices of HQD levels of Chinese city clusters in the sample period are positive, and all of them pass the significance test. This shows that there is a significant positive spatial correlation in the HQD of Chinese city clusters, and according to the trend of the change in Moran's I value, the global Moran's I index fluctuates within the interval of 0.538–0.582 from 2011 to 2021, and the HQD of city clusters in the spatial cluster degree is relatively stable.

Based on the global autocorrelation analysis, this paper portrays the spatial patterns of the evolution of hotspot and coldspot areas by the hotspot analysis method, and the results are shown in Fig. 6. Among the hotspot areas, the hotspot areas of the HQD level of the city clusters are mainly distributed in and around the Pearl River Delta and Yangtze River Delta city clusters, in which the hotspot significance of some cities within Guangdong, Fujian, Zhejiang, and the Middle Yangtze gradually increases and eventually becomes a significant area. The possible reason is that the Pearl River Delta and Yangtze River Delta city clusters have a faster rate of HQD, during which industrial transfer, technology diffusion, and knowledge spillover have led to the rapid development of neighboring city clusters, which have gradually become hotspots. From the perspective of cold spot areas, the cold spot areas of Chinese city clusters with HQD levels are mainly located in the city clusters of the Kuan-Chung Plains, Central Shanxi, Chengdu-Chongqing, Central Guizhou, etc. The number of city clusters in the cold spot areas gradually decreased, and the significance level of the cold spot areas clearly decreased during the sample period. The probable reason is that under the promotion of the rise of central China and the development of western China, the HQD of these city clusters accelerated, showing a significant catching-up trend. Overall, the HQD of China's city clusters shows a spatial pattern of "hot in the east and cold in the west", with the scope of cold spots gradually shrinking, and hot spots showing a tendency to spread outward, with mature city clusters at the core.

4.2.2. Characterizing the spatial evolution of the HQD of city clusters

To deeply analyze the spatial evolution characteristics of the HQD of Chinese city clusters, this paper constructs a traditional Markov transfer probability matrix and a spatial Markov transfer probability matrix incorporating spatial lag factors. The HQD level of city clusters is discretized into four states, namely, low, lower, higher, and high, which are denoted by k = 1, 2, 3, and 4, respectively. At the same time, the transfer of HQD level from low to high values is an upward transfer, and vice versa. The traditional Markov transfer probability matrix of HQD of Chinese city clusters in 2011–2021 is shown in Table 3, and the results of Table 3 can be summarized as follows: (1) The probability value of the diagonal is greater than the probability value of non-diagonal, which indicates that the transfer of the HQD state of city clusters is stable and more likely to maintain the current status quo. (2) The HQD of China's city clusters has an obvious "club convergence" phenomenon, in which the two types of states, high and higher, have the highest probability of maintaining the state of year t in year t+1, which is 79.83 % and 98.35 %, respectively. (3) The probability of "leapfrog transfer" of the HQD status types of city clusters in neighboring years is zero, and all status types will not transfer across grades in neighboring years.

Table 2
Global Moran's index for the HQD of city clusters in China, 2011–2021.

Year	Moran's I	Z Value	P Value
2011	0.547	19.348	0.000
2012	0.539	19.052	0.000
2013	0.582	20.622	0.000
2014	0.555	19.635	0.000
2015	0.559	19.751	0.000
2016	0.561	19.859	0.000
2017	0.558	19.745	0.000
2018	0.546	19.368	0.000
2019	0.552	19.583	0.000
2020	0.548	19.442	0.000
2021	0.538	19.087	0.000

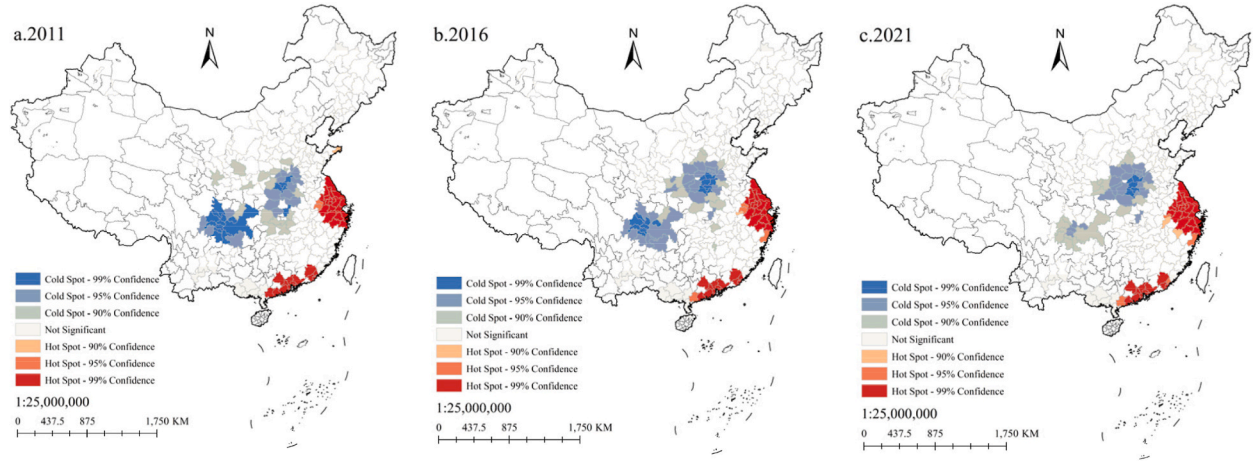

Fig. 6. Analysis of cold hotspots at the HQD level, 2011, 2016 and 2021.

Table 3
Traditional Markov transfer probability matrices.

t\t+1	n	1	2	3	4
1	52	0.7551	0.2449	0	0
2	53	0.0298	0.6778	0.2925	0
3	44	0	0.0270	0.7983	0.1746
4	41	0	0	0.0165	0.9835

Because the HQD of city clusters has an obvious positive spatial correlation, the high-quality transfer path of city clusters in the future will be affected by the development of neighboring city clusters. This paper adds spatial lag conditions to the traditional Mrakov transfer probability matrix and constructs the spatial Markov probability transfer matrix, as shown in Table 4. Based on the results of the calculations, we draw the following conclusions: (1) The spatial factor plays an important role in the process of the state transfer of the HQD of city clusters. Compared with the traditional Markov probability transfer matrix, after adding the spatial lag condition, the state transfer probability of the next year of the HQD of city clusters in different neighboring contexts changes significantly. (2) The HQD of city clusters has obvious synergy with regional HQD, i.e., the type of development state maintains great consistency with the neighborhood. For example, when the development state of the neighborhood is low ($k = 1$), the number of city clusters in the low state in years t and t+1 is significantly greater than that of other states; when the development state of the neighborhood is high ($k = 4$), the number of city clusters in the higher and high states in years t and t+1 is the greatest. (3) Neighborhood HQD status has a greater impact on the transfer path of high-quality city clusters. In general, the probability of a downward shift in the development status of a city clusters in year t+1 increases when it is adjacent to a city clusters whose HQD is low, while the probability of an upward shift in the development status of a city clusters is greater when the neighbor's development status is high. For example, in a neighborhood with an HQD status of 1 for the city clusters, $P_{21|1}(0.0909) > P_{21}(0.0298)$, $P_{32|1}(0.0541) > P_{32}(0.0270)$, while in a neighborhood with a

Table 4
Spatial Markov transfer probability matrix.

Lag	t\t+1	n	1	2	3	4
1	1	28	0.8726	0.1274	0	0
	2	17	0.0909	0.7662	0.1429	0
	3	4	0	0.0541	0.6216	0.3243
	4	2	0	0	0.0588	0.9412
2	1	18	0.5503	0.4497	0	0
	2	20	0.0326	0.7645	0.2029	0
	3	9	0	0.0494	0.7901	0.1605
	4	9	0	0	0.0517	0.9483
3	1	2	0.7391	0.2609	0	0
	2	8	0	0.5169	0.4831	0
	3	13	0	0.0217	0.8652	0.1130
	4	15	0	0	0.0165	0.9835
4	1	4	0.4545	0.5455	0	0
	2	8	0.0250	0.6250	0.3500	0
	3	18	0	0.0150	0.7368	0.2481
	4	15	0	0	0.0069	0.9931

HQD status of 4 for the city clusters, $P_{23|4}(0.3500) > P_{23}(0.2925)$, $P_{34|4}(0.2481) > P_{34}(0.1746)$. (4) The spatial Markov transfer probability matrix also shows an obvious "club convergence" phenomenon in the spatial dimension; i.e., affected by the development status of the neighborhood, the probability of upward transfer of the HQD status of the city clusters is greater than the probability of downward transfer, and the higher the HQD status of the neighborhood is, the greater the probability of upward transfer of the HQD status of the city clusters. The higher the neighboring HQD status is, the greater the probability of upward transfer of the HQD status of city clusters, indicating that the HQD of city clusters in China shows an upward trend (see Table 4).

5. Detection of the driving factors of HQD in Chinese city clusters

In order to deeply analyze the intrinsic mechanism and influencing factors of economic HQD, this paper adopts the geodetector model. The model does not require strict conditional assumptions, can effectively overcome the problem of multivariate covariance, and analyses the interactions between the intrinsic influencing factors and their interactions by measuring spatial heterogeneity [32]. The model combines the GIS spatial overlay technique and set theory with a clear physical meaning that accurately identifies the relationships among multiple factors [33]. In terms of variable selection, the literature shows [4] that human capital, financial level, green innovation, and the digital economy are the four most widely adopted and representative variables in the study of the HQD of the economy and that they can summarize the main aspects of the HQD of city clusters to a high degree and in a comprehensive way; at the same time, combined with the analysis of the mechanism of the influence of the HQD of the economy in the previous paper, this paper finally selects the above four variables as the core influencing factors. Moreover, combined with the previous analysis of the influence mechanism of high-quality economic development, this paper selects the above four variables as the core influence factors. Human capital is measured by the productivity of labor in society as a whole. financial levels are quantified by the percentage of bank deposits and loan balances. Green innovations are proxied by the percentage of green inventions in the total number of patents filed in the region in a given year. and digital economics is measured by digital attention.

4.3. Factor detection analysis of HQD in China's city clusters

In this paper, the natural discontinuity method is applied to classify the four variables in 2011–2021 at 5 levels to maximize the differences between the groups, to realize the transformation of data attributes and to import the classification results into the geodetector to obtain the factor detection results, as shown in Table 5. From the results of the factor detection analysis in Table 5, all four factors at the national level passed the 1% significance test, and all of them were the key factors affecting the level of HQD in city clusters. Among them, the magnitude of the q value indicates the extent to which the dependent variable, the level of HQD of city clusters, is influenced by the independent variables (factors), and among these four factors, financial level (X2) has the highest q value of 0.320, followed by digital economics (X4) with a q value of 0.153, which explains 32.0 % and 15.3 % of the HQD of city clusters, respectively. This shows that both financial levels and digital economics can effectively improve the HQD of city clusters. On the one hand, the financial industry realizes benefit sharing and cost sharing within city clusters by exploring the construction of the "city clusters integration fund". On the other hand, digital economics closely integrates and intertwines traditional industrial and economic business with cutting-edge digital technology, which provides an inherent driving force for the construction of modernized economic systems of city clusters. The explanatory power of human capital (X1) and green innovation (X3) for HQD in city clusters is less than 10 %. Emphasis on improving the labor productivity of the whole society and focusing only on the proportion of green invention applications may squeeze the play of other factors in city clusters and weaken the driving effect of these factors on HQD in city clusters.

Specifically, there are dynamic and heterogeneous effects of each factor on HQD in city clusters (see Table 5): (1) Temporal heterogeneity: HQD in city clusters is a long-term accumulation process. Human capital, financial levels, green innovations, and digital economics declined in 2011–2015 and 2016–2021 compared to 2011–2021, suggesting that city clusters' HQD requires the operation of all aspects over a longer period in order to exert its influence. In particular, human capital did not have a significant effect on HQD in city clusters during the period 2011–2015, suggesting that human capital has accumulated over a long period. (2) In terms of regional heterogeneity, city clusters in the central and western regions have greater development potential. All four factors passed the 5 % significance test. The financial levels and digital economics of the eastern city clusters have a greater impact on the HQD of the city clusters than on that of the whole country. This is in line with the reality that the eastern city clusters have a greater degree of financial development and digital empowerment, while human capital and green innovations have relatively weaker effects. The impact of the four factors on the HQD of city clusters in the central and western regions is stronger than that of the whole country, indicating that the HQD of city clusters in the central and western regions is in a stage of rapid growth and that green innovation, human capital, and financial levels can have greater multiplier effects. At the same time, the "Belt and Road Initiative" provides opportunities for cities in

Table 5
Factor detection analysis of the HQD levels of Chinese city clusters, 2011–2021.

Impact Factor	National	Eastern	Central	Western	2011–2015	2016–2021
Human capital (X1)	0.078***	0.039**	0.299***	0.095**	0.028	0.024*
Financial levels (X2)	0.320***	0.338***	0.360***	0.372***	0.302***	0.266***
Green innovations(X3)	0.039***	0.038***	0.136***	0.141***	0.027**	0.039***
Digital economics(X4)	0.153***	0.179***	0.233***	0.212***	0.137***	0.041***

Note: Values in the table are q-statistic values, ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

the central and western regions to expand their consumption demand.

4.4. Interaction detection of HQD levels in Chinese city clusters

The above analysis revealed that the influence of individual factors on HQD in city clusters is limited; therefore, geodetectors were used to conduct an interaction analysis to identify the effects of interactions between different factors on HQD in city clusters, and the results are shown in Fig. 7. The results show that the influence of any two detecting factors after the interaction is greater than the influence level of a single factor, which fully indicates that the HQD of city clusters is the result of a variety of factors, and it is more necessary to be supported by a good composite city clusters development strategy. Overall, compared with the single-factor detection results, the explanatory ability of the four detecting factors on the HQD of city clusters after the two-by-two interaction is significantly enhanced, exceeding the influence of the single factor and showing a two-factor enhancement trend, which suggests that the interaction of multiple factors promotes the development of city clusters in terms of HQD. Among them, the interaction value of financial levels with other detection factors is higher than 0.30, which effectively stimulates other factors to release their potential, confirming that finance is the bloodline of economic HQD, providing financial support for scientific and technological research and development, industrial chain shaping, green and low-carbon development, as well as reforms in key areas of people's livelihoods in city clusters and providing sufficient financial security for other factors and sharing certain risks. It is worth noting that the two-by-two interaction power of the detection factors of the central and western city clusters is much higher than that of the whole country and the eastern region. The first is the interaction power of financial levels and other factors because, against the background of the accelerated rise of central China, the new round of great development in western China and the accelerated construction of Chengdu-Chongqing and central and western China have generated large investment demands; in particular, the demand for infrastructure investment continues to increase. In particular, the demand for infrastructure investment continues to increase, and financial resources and various investments have a greater multiplier effect, helping the central and western city clusters to realize the "curved road to overtake the car". In addition, the interaction between digital economics and other detection factors in central and western city clusters also shows a stronger driving force, and digital industrialization and industrial digitization provide an endogenous impetus for the transformation and upgrading of traditional industries in the central and western city clusters. At the same time, digital economics breaks through the constraints of geographic conditions and environmental carrying capacity, greatly improves the efficiency of the flow of factors of production through digital transformation and digital services, and pushes the enterprises of central and western China to participate in the construction of financial and information industries in the east and share opportunities for economic development with the east. Among all the interactions in the central and western city clusters, the interaction power of human capital and financial levels is the highest, at 0.701 and 0.606, respectively, indicating that human capital accumulation is still an important driving force for HQD in the central and western city clusters and that attracting population clusters to improve the quality of talent is still one of the main focuses for alleviating the imbalance and insufficiency of the central and western city clusters.

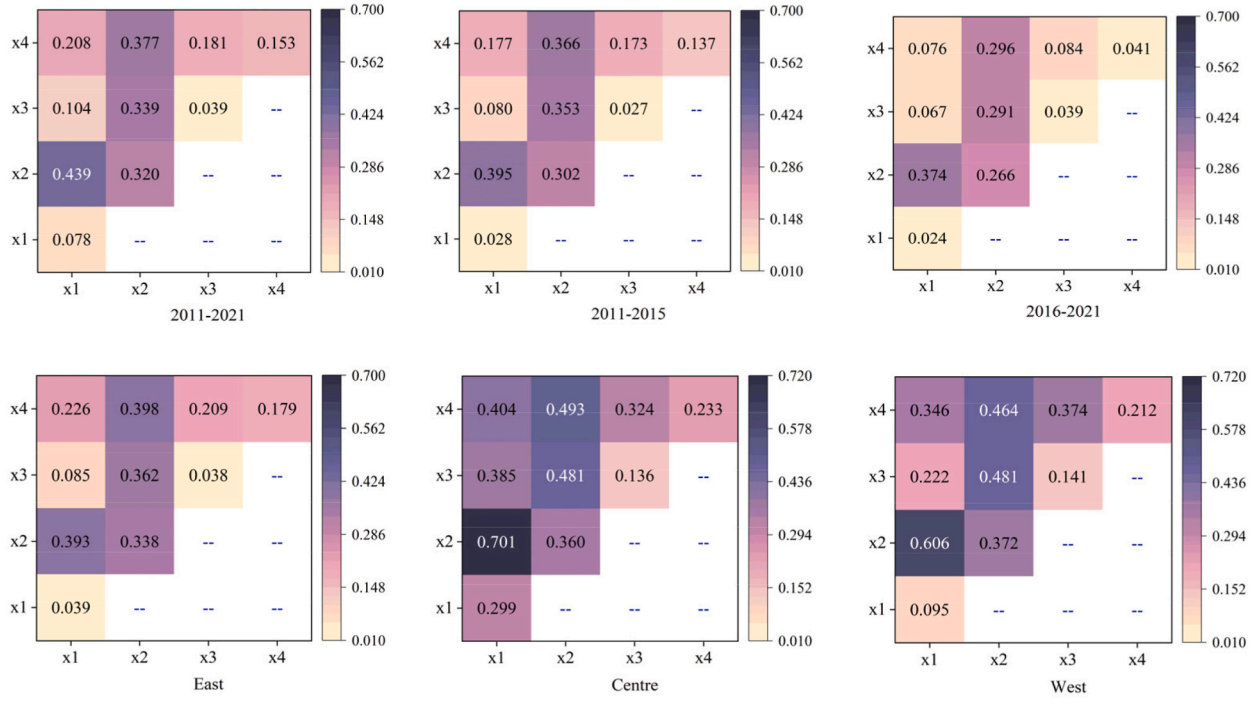

Fig. 7. Interaction analysis of HQD detection factors in city clusters.

4.5. Analysis of the influence of GWR on HQD in city clusters

The GWR model is further introduced to analyze the local variability in the intensity and direction of the effect of each factor on the HQD of city clusters. The cross-sectional data for 2021 are selected minus the corresponding indicator values for 2011 and standardized, the changes in the four detected factors obtained are used as the independent variables of the model, and the changes in the HQD of the city clusters are used as the dependent variables. After testing, the corresponding R2 under the OLS model estimation is 0.616, while the R2 under the GWR model estimation is 0.629, which indicates that the GWR model has more explanatory power, and

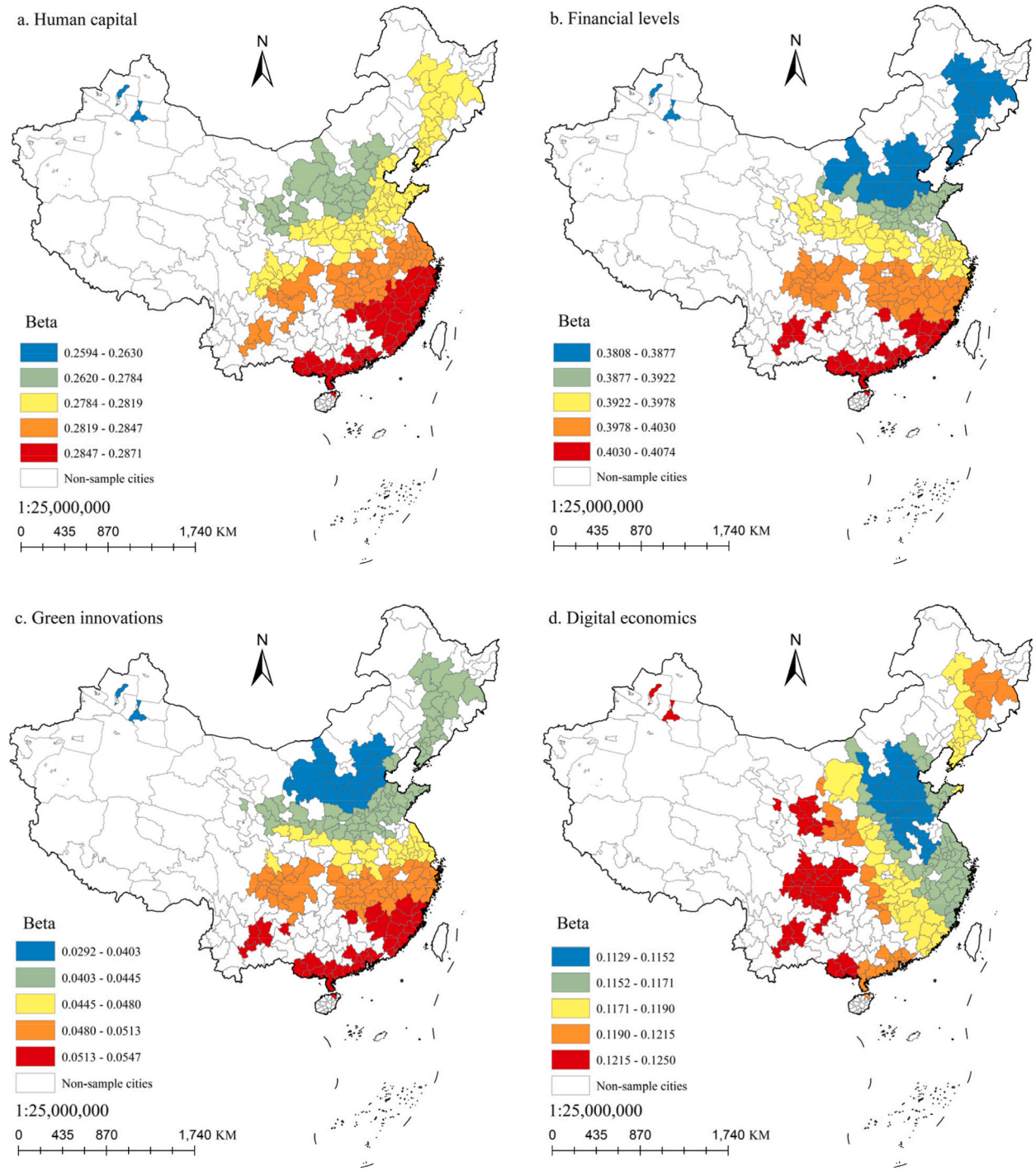

Fig. 8. Spatial distribution of the coordination regression coefficient estimates in the GWR model of HQD in city clusters.

the GWR model is selected for the driving force analysis. As shown in Fig. 8, the coefficients affecting the HQD of city clusters vary significantly spatially and generally show a banded distribution of development. Human capital, financial levels and green innovations show a north–south hierarchical banded distribution, digital economics shows an east–west hierarchical banded distribution, and the impact coefficients of the four factors are positive. According to the absolute value of their impact size, they are financial levels > human capital > digital economics > green innovations in the order of financial levels > human capital > digital economics > green innovations.

Firstly, the improvement of financial levels has a positive role in promoting HQD in city clusters, specifically showing "southwest high northeast low" spatial characteristics. The reason lies in the significant imbalance in the allocation of financial resources between the north and the south; for example, the financing scale of the northern city clusters in 2021 accounted for only 27.9 %, the balance of credit debt was 9.7 trillion yuan, which accounted for 40.2 %, but Beijing contributed close to half of the exclusion of Beijing, which still accounted for 20.5 %. At the same time, the overall weak qualifications of enterprises in the North and the lack of financial centers also contribute to the weak allocation of financial resources in the North. The "financial expeditor" principle increases the HQD gap between city clusters in the South and the North. Secondly, the increase in human capital plays a positive role in promoting the HQD of city clusters and spatially shows the characteristic change of "high in the southeast and low in the northwest", with the regression coefficient fluctuating in the range of 0.2594–0.2871, and the city clusters along the southeast coast are the most dependent on human capital, which is consistent with the spatial distribution of human capital. This is consistent with the spatial distribution of human capital; a higher level of human capital increases the economic efficiency of the labor force, and at the same time, the southeastern coastal city clusters also form the basis of the labor force for the development of high-tech industries. Thirdly, the regression coefficient of green innovations and HQD in city clusters is relatively low but significantly positive, also showing the spatial characteristics of "high in the southeast and low in the northwest". The levels of intellectual property protection, green technology R&D investment and green patent cooperation in the southeastern coastal region are significantly higher than those in the northern city clusters, which improves the energy utilization efficiency of the city clusters through higher total factor productivity. At the same time, from southeast to northwest, the trend of "the strong are always strong and the weak are catching up" is shown. Finally, the positive effect of digital economics on the HQD of city clusters shows a banded distribution in the east and west, and the regression coefficients show a spatial pattern of "high in the west, low in the east, and decreasing from the west to the east". The "East Counts, West Counts" project promotes the rapid advancement of new infrastructure construction in the western region, drives the development of digital economics and industrial investment in the western region, and further narrows the development gap between the east and the west. At the same time, the digital empowerment of the western region has given full play to the advantage of "catching up after the late", and large-scale data acceptance and calculation have provided a more intensive and efficient path for the HQD of city clusters.

5. Conclusions and policy recommendations

5.1. Conclusions

Based on the basic connotation of Chinese-style modernization, this paper establishes an evaluation system of HQD indicators for city clusters consisting of 40 indicators and applies the CRITIC-entropy weighting method to measure the HQD of a total of 212 cities in 19 city clusters in China from 2011 to 2021. Then, the spatiotemporal characteristics of HQD in Chinese city clusters were analyzed by using kernel density estimation, standard deviation ellipse, and Moran's index, and the influencing factors and driving mechanisms of HQD in city clusters were empirically investigated by using geo-detector method and geographically weighted regression. The specific conclusions are as follows:

Firstly, China's city clusters HQD steadily advanced, with two phases of steady improvement and rapid development occurring during the sample period, and the level of city clusters HQD varied widely across dimensions. At the same time, the modernization level of each city clusters shows obvious differentiation characteristics due to different resource endowments, development dynamics and policy support. The results of the kernel density estimation show that the absolute gap in HQD in city clusters is gradually narrowing, and the "leader" effect of the eastern coastal city clusters is more obvious, while the western city clusters have certain shortcomings in the promotion of HQD. Secondly, the gradient pattern of "East-Central-West" in the spatial distribution of HQD in city clusters gradually weakens, and the spatial patterns of "southeast highlighting" and "northwest rising" gradually form. Standard deviation ellipse analysis and analysis of the center of gravity migration characteristics revealed that the role of the Yangtze River Economic Belt's east–west development axis further increased, but the pulling effect of the east–west direction on the city clusters gradually weakened, revealing a new trend of "north–south differentiation". Thirdly, the spatial clustering pattern of HQD in city clusters has gradually strengthened. Specifically, the hotspots are mainly located in the Kuan-chung Plains, Central Shanxi and Chengdu, Chongqing, Central Guizhou and other city clusters, showing an overall spatial pattern of "hot in the east and cold in the west", with the scope of the cold spot areas gradually shrinking and the hotspot areas showing a trend of spreading outward with the mature city clusters as the core. Fourth, the geodetector results show that the driving factors of HQD in Chinese city clusters have diverse characteristics. In terms of the strength of the force of the detecting factor, there is an obvious decreasing trend in financial levels, digital economics, human capital and green innovations; at the same time, the driving effect of the two-by-two interaction of the detecting factor is larger than that of the single-factor force, which shows a two-factor enhancement trend. Financial levels can effectively stimulate the driving potential of other factors. In the central and western city clusters, there is a greater interactive force with other factors, and the interaction between human capital and financial level is the highest, indicating that human capital accumulation and financial investment remain important drivers of HQD in the central and western city clusters. Finally, the geographically weighted regression results show that the coefficients of the driving factors affecting the level of HQD in city clusters

are spatially significantly different, and the impact coefficients of the four driving factors are all positive, showing a banded distribution of development in general. Among them, human capital, financial levels, and green innovations show a north–south banded distribution with "high in the south and low in the north", while digital economics show an east–west banded distribution with "high in the west and low in the east".

5.2. Recommendations

Firstly, regional strategic coordination and interaction should be strengthened to further optimize the functional division of labor among city clusters(Liet al., 2024)[34][]. Mature city clusters such as Beijing-Tianjin-Hebei, the Yangtze River Delta and the Pearl River Delta should take the initiative to undertake the historical mission of taking the lead in realizing Chinese-style modernization and striving to be a model, give full play to the role of radiation driving, and use city clusters in the early and middle stages of their growth as the main support for industrial transfer and trans-regional cooperation. Through various organizational forms and cooperation modes, such as the enclave economy, sharing economy, platform economy and leasing economy, they can realize the sharing of resources and elements, further give full play to regional comparative advantages, and build a modernized economic system with special characteristics. At the same time, growing city clusters should further strengthen exchanges and cooperation with mature city clusters, for example, by transplanting and learning from mature experiences and scientific practices, to consolidate the soft and hard foundations of economic and social operation.

Secondly, the potential advantages of hinterland city clusters should be considered to maximize the comprehensive carrying capacity of city clusters. With the advantages of large development space, abundant resources and relatively low labor costs, city clusters in the central and western parts of the country have greater potential to achieve "curved road overtaking" in light of industrial transfer and digitalization opportunities in the eastern part of the country. First, we should further strengthen the transportation function of the central city of the central and western city clusters, accelerate the layout of internal and external transportation infrastructure, build a comprehensive transportation network of the city clusters, and use transportation as an axis to smooth the full flow of industry, innovation, population and other factors among the cities within the city clusters. The second is to effectively play the radiation-driven role of the central city and to enhance the support and carrying capacity for economic and social development through the expansion of economic boundaries in terms of regional resources and energy, the ecological environment, infrastructure, public services and so on.

Thirdly, seizing the opportunities of the "Belt and Road" strategy should be seized, and the major cities of the city clusters should be relied upon to increase the level of opening-up. First, the status of the eastern coastal city clusters should be consolidated as a pioneer in opening-up. Beijing, Shanghai, Guangzhou, Shenzhen and other mega-mega-cities to take the lead in promoting high-level opening-up to build global cities and world cities and improve the function of global factor allocation. Second, it will accelerate the pace of liberalization in the central and western city clusters. It will improve the construction of inland ports, airside economic demonstration zones and the core area of the "Belt and Road" and will actively replicate the results of institutional innovations in the eastern city clusters. The city clusters rely on the Beijing-Guangzhou, coastal, Longhai-Lanxin and new land and sea corridors to strengthen cross-regional openness and linkages between the East and the West, vigorously cultivate inland globally important processing and manufacturing bases and new growth poles, and promote synergistic openness and cooperation between the East, the West and the North and the South.

5.3. Limitations and future research

Based on the basic connotation of Chinese-style modernization, this paper attempts to construct a set of all-round, wide-area, and multi-level evaluation index systems for HQD in China based on three scales (overall, inter-urban cluster, and intra-urban cluster), four aspects (level measurement, spatiotemporal characteristics, spatial evolution, and driving factors) and five dimensions (Huge Population, Coordinated Regional Development, Material, and Cultural-ethical Advancement, Ecological Sustainability, Opening-up) attempted to construct a set of omnidirectional, wide-area, multi-level evaluation index systems for HQD and conducted a comprehensive, systematic and in-depth analysis of the current situation of the HQD of city clusters in China. The driving factors affecting the HQD of city clusters are human capital, financial level, green innovation, and the digital economy. The economic links between city clusters, resource complementarity, talent flow, and other factors make city clusters in a state of HQD interrelated and interact with each other, while the spatial agglomeration characteristics within city clusters are directly related to factor flow, industrial agglomeration and other factors directly affecting the economic development of city clusters. Therefore, it is highly important to further explore the spatial evolution characteristics and driving factors of the HQD of city clusters for regional cooperative development and city clusters development planning. With the advancement of China's modernization level, on the one hand, China's modernization development path and HQD strategy can provide a reference for other developing countries based on their practices; on the other hand, China's large population also provides large market and development opportunities for the world. Therefore, this study is of practical significance for policy planning related to China's city clusters, the promotion of modernization, and even global economic development.

However, limited by the research conditions and vision, this study also has several shortcomings, which need to be studied more deeply in the future. First, the indicator system needs to be further improved. Although the evaluation index system for the HQD of Chinese city clusters established in this paper is relatively perfect, due to the lack of a unified measurement method, the selection of individual indicators needs to be improved. For example, owing to the difficulty of obtaining data on open development, the caliber of the prefectural cities is not uniform, which makes it difficult to truly reflect the level of open development of city clusters, and in the future, we will supplement the index system by using Python and other tools to obtain more information. Second, the factors affecting

the high-quality development of city clusters need to be further enriched. In this paper, we only analyzes the influence of four factors, namely human capital, financial level, green innovation and digital economy, which makes it difficult to reveal the driving mechanism of high-quality development of city clusters in a comprehensive way, and there are still many other factors to be further researched, such as regional differences, urban-rural development, opening up and cultural development, and so on. Therefore, in-depth exploration of the factors affecting the high-quality development of city clusters will be the focus of future research in order to reflect the driving mechanism of high-quality development of city clusters in a more comprehensive way. Third, there are differences between the city clusters studied in this paper and the criteria for world-class city clusters; discussing only the level of HQD of China's city clusters plays a role in the generality of the study, and there is a greater need to look at the evolution of HQD of city clusters from a global perspective, which will be discussed more comprehensively at the global scale in the future.

Data availability statement

Data associated with study is not deposited into a publicly available repository. Data will be made available on request.

CRediT authorship contribution statement

Zilong Ma: Data curation. **Zhichen Yang:** Writing – review & editing. **Qingwen Li:** Writing – original draft. **Xianqing Tu:** Data curation. **Yichun Xu:** Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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