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Research article

Measurement and spatial correlation analysis of high-quality development Level: A case study of the Yangtze River Delta urban agglomeration in China

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ABSTRACT

Against the backdrop of slowing economic growth and increasing environmental pressure, the Yangtze River Delta city cluster, as one of the largest city clusters in the world, has become more driven in its pursuit of high-quality development. We constructed a system of 24 evaluation indexes and used entropy-weighted TOPSIS to calculate and study the high-quality development index of urban agglomerations in the region. First, the level of high quality development (HQD) of the Yangtze River Delta city cluster generally improved from 2010 to 2021, with 2017 was the best year, while 2010 was the worst year. Second, in the multidimensional evaluation of HQD, Jiangsu excels in innovation and people's livelihood with 0.524 and 0.534, respectively; Shanghai (0.531) excels in coordinated development; Zhejiang excels in green and economic development with 0.557 and 0.484, respectively; and Anhui lags behind in all aspects. Third, the development process of HQD in the Yangtze River Delta region is uneven, and the level of HQD development varies greatly among the city clusters in the province. The measurement results show that Shanghai (0.511) has the highest score, followed by Zhejiang (0.484), Jiangsu (0.440) and Anhui (0.435). Fourth, spatial correlation analysis shows that Shanghai and Jiangsu are mainly distributed in the double-high region, Zhejiang is distributed in the high-low region, while Anhui is concentrated in the low-low region. The results of this study help us understand more deeply the characteristics and challenges of high-quality development in the Yangtze River Delta urban agglomerations and provide a scientific basis for more precise urban development policies.

1. Introduction

As the hub of national economic development, urban agglomerations dominate the regional spatial layout and strategic position, and the high-quality development (HQD) of urban agglomerations influences the overall level of development quality of a country's cities [1]. With China's increasing emphasis on HQD of urban agglomerations, its connotation has been enriched and expanded. HQD refers to the development that meets the growing needs of the people for a better life. HQD is the development that solves the problem of "insufficient and unbalanced development" [2–5]. The successful achievement of high-quality development in urban agglomerations

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necessitates each region to align with its unique circumstances, tailor its approach to local conditions, leverage its strengths and address its weaknesses, ultimately formulating a high-quality development strategy that aligns with the specific context of the region. To achieve this goal, the Outline of the Fourteenth Five-Year Plan for National Economic and Social Development of the People's Republic of China and Vision 2035 propose to promote the integrated development of urban agglomerations, and re-emphasize the construction of 19 major urban agglomerations across the country such as the Yangtze River Delta (YRD) and the Pearl River Delta (PRD), and the improvement of spatial layout of urbanization. As the first region in China to enter and complete HQD, the YRD urban agglomeration has an obvious demonstration effect on other urban agglomerations [6,7]. However, the rapid development of urban agglomerations in the Yangtze River Delta (YRD) region still faces some problems, such as the quality of the overall development of the YRD urban agglomerations needs to be improved, the development gap within the urban agglomerations is large, and the links between the cities are not sufficiently close, etc. Therefore, it is necessary to further explore the path to achieve high-quality development of the Yangtze River Delta city cluster and its optimization scheme.

Current domestic and international research on the level of HQD of urban agglomerations focuses on the relationship between urbanization and HQD, urban agglomeration development, as well as a series of studies on theories and methodological systems. In terms of research objects, existing studies on HQD at national and inter-provincial levels focus more on overall economic growth and macro-regional balance, for example, some researchers focus on the efficiency of HQD of China's overall economy and on the impact of provincial panel data on HQD [8–10]. In contrast, HQD at the city cluster scale focuses more on the synergistic development between cities, spatial correlation, and optimal resource allocation, for example, scholars focus on the study of the impact of the agglomeration of productive service industries on the HQD of city clusters in the Yangtze River Economic Belt [11]. In terms of theory, some researchers point out that the high-quality integrated development of the four provinces in the YRD has become a model for the whole country, and the key to achieving such efficient development lies in advancing economic restructuring, deepening reform and opening up of the Chinese economy, strengthening innovation capacity building, and realizing economic synergy [12–14]. In terms of research methodology, researchers have adopted different research methods to analyze their development characteristics from different dimensions. Among them, the level measurement methods about HQD are mainly categorized into two types: one is to measure HQD by using a single variable; the other is to measure HQD by using comprehensive indicators [15,16].

In summary, existing research on HQD has achieved some results; however, it is primarily focused on qualitative studies, with a limited number of quantitative analyses. Regarding the research scope, most studies examine HQD from a temporal perspective, largely neglecting a comprehensive view that includes both time and spatial dimensions [17–19]. Methodologically, due to varying interpretations of HQD in urban agglomerations among scholars, there is currently no unified evaluation standard within the academic community [20]. While single indicators can offer a partial view of a region's high-quality development, they are insufficient for capturing the overall picture. Lastly, in terms of research subjects, there is a growing trend toward micro-level studies on HQD implementation, but research on the scale of urban agglomerations remains limited [21]. In light of this, the present study focuses on 27 city clusters across four provinces in China's Yangtze River Delta (YRD). To offer a more comprehensive view, our analysis incorporates both temporal and spatial dimensions. We use various indicators related to High-Quality Development (HQD) as explanatory variables, constructing a multidimensional evaluation system that includes five key areas:innovation-driven growth, coordinated development, economic advancement, environmental sustainability, and social well-being. The entropy value method is employed to quantify the HQD levels of these urban agglomerations, while Moran's I is used to examine their spatial correlation in depth. This paper's methodological contributions lie in its multi-dimensional evaluation system, designed to address the limitations of existing single-indicator approaches. In addition, the application of these methods will produce a more nuanced understanding of the HQDs of the YRD urban agglomerations, reveal the differences and connections between cities, and provide a scientific basis for the future YRD HQDs.

The structure of this article is as follows: Part 2 offers an in-depth literature review, focusing on the measurement of HQD in the YRD city clusters, and examines geographical linkages and regional integration. Part 3 outlines the data sources and analytical methodologies employed in this study, as well as the urban context and the five key dimensions of HQD in the YRD's four provinces. Part 4 presents a comprehensive data analysis using the TOPSIS entropy weight method and spatial correlation analysis. In Parts 5 and 6, we address the research questions, summarize our findings,and discuss the study's contributions to both theory and practice. The paper concludes by summarizing key insights and discussing their implications for future research.

2. Methodology

2.1. Methodological flow

With the burgeoning development of inter-city clusters in the YRD, these clusters have seen escalating economic levels and increasing openness, attracting foreign investment annually and holding a central role in China's economic landscape. This study introduces a novel technique for creating an indicator system to measure HQD from the standpoint of key expansion paradigms. Drawing on data from the National Bureau of Statistics of the People's Republic of China, as cited in multiple studies [22–26], our empirical analysis employs a stochastic TOPSIS approach coupled with spatial autocorrelation analysis. We preprocess the data and integrate HQD dimensions into our indicator system, which comprises five key areas: innovation-driven growth, coordinated development, economic advancement, environmental sustainability, and social well-being. The entropy method is applied to determine the weights of each indicator, and the TOPSIS technique is used to assess the congruence between the evaluation values and high-ranking development. Further, through comprehensive evaluation scores and an analysis of HQD dimensions, we assess the HQD in three districts and one region within the YRD. Finally, exploratory spatial data analysis (ESDA) is used to unveil spatial linkages across these urban agglomerations and explore local spatial variations and evolutions [27,28]. The research process is shown in Fig. 1.

2.2. Study areas

This study includes the YRD region of China, as depicted in Fig. 2. Located between longitudes 118°24′ to 122°48′ E and latitudes 29°18′ to 34°26′ N, the YRD is one of China's most economically vibrant areas and serves as a critical test bed for the nation's HQD initiatives. The Yangtze River Delta city cluster includes 27 cities in Shanghai and parts of Jiangsu, Zhejiang and Anhui provinces, according to the Plan for the development of the Yangtze River Delta City Cluster approved by The State Council. The YRD is at the forefront of China's economic, demographic, and technological evolution. Its geographical environment, climate, and cultural heritage further enhance its research value.

Slope analysis indicates that most of the YRD region is characterized by low elevation, flat terrain, minimal elevation changes, and gentle slopes. Cities and industrial zones are primarily situated on plains, influenced mainly by hydrological factors, while agricultural and forestry activities are commonly found in river basins and hilly areas. Overall, the analysis of slope and aspect contributes valuable insights into the region's topography, hydrology, vegetation, and land use patterns. In conclusion, research on the YRD's HQD has both practical and academic implications and can serve as a valuable reference for China's broader developmental trajectory. According to the latest YRD City Cluster Development Plan, this study focuses on Shanghai, Zhejiang, Jiangsu, and Anhui provinces, covering the period from 2010 to 2021.

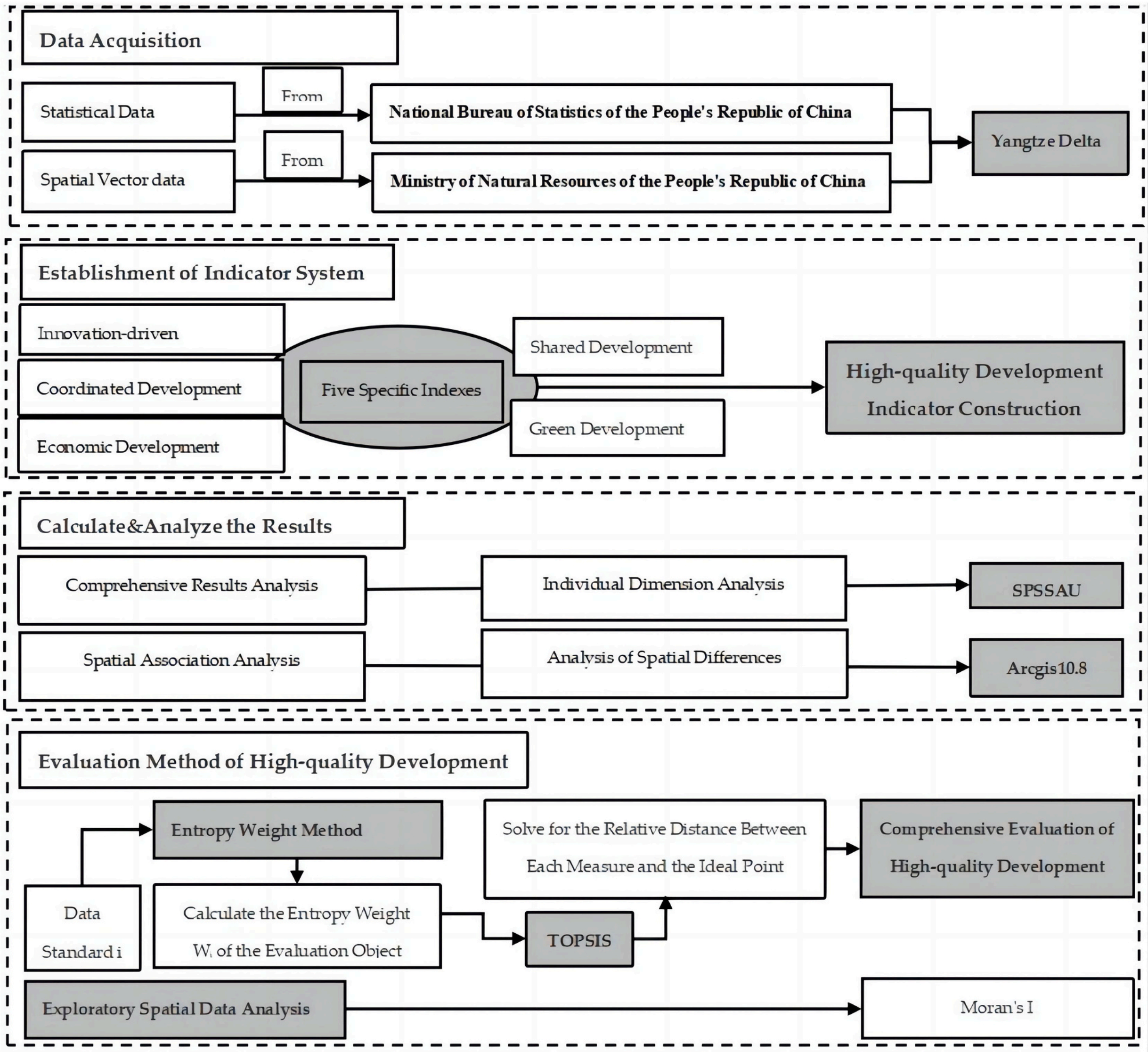

Fig. 1. Methodology flow chart.

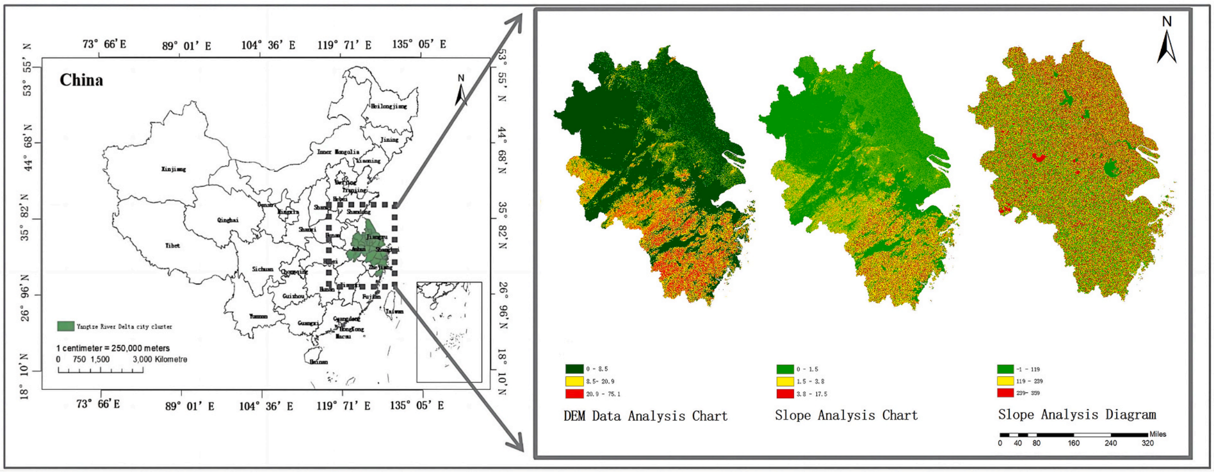

Fig. 2. Study area introduction.

Table 1
Hierarchy of the YRD quality development level indicator system.

Target layer L	First index C	Secondary index R	Unit	Index weight	Index attributes
Innovation-driven	Innovation investment	Research and development expenditure	Ten thousand yuan	0.031	+
		Number of research and development product projects	Number of projects in progress	0.0330	+
	Innovative output	Patent authorization for invention	Number of patent licenses issued	0.0318	+
		Technology market transaction	Ten thousand yuan	0.0194	+
Harmonious development	Regional coordinated development	Per capita disposable income of residents	Yuan	0.0196	+
		Household consumption expenditure	Yuan	0.1113	+
	Coordinated development between urban and rural areas	Urban-rural income gap	Yuan	0.0299	+
		Urban-rural consumption gap	Yuan	0.0304	+
Economic development	National economy	Consumption level of residents	Yuan	0.0315	+
		Gross domestic product	One hundred million yuan	0.0367	+
		Gross national income	One hundred million yuan	0.0338	+
	Open structure	Foreign trade coefficient	One hundred million yuan	0.0239	+
		External investment dependence	Ten thousand yuan	0.0509	+
Green development	Pollution reduction	Control of industrial pollution	Ten thousand yuan	0.1817	+
		The harmless treatment rate of municipal solid waste	%	0.0465	+
	Green environmental protection	Afforestation area	0.01 square kilometers	0.0389	+
		Basic information of nature protection	100 square kilometers	0.0354	+
Improving people's livelihoods	Life well-being	Income dominance	Yuan	0.0332	+
		Social security employment expenditure	One hundred million yuan	0.0357	+
		Urban unemployment ratio	%	0.0199	–
	Public resource	Medical and health conditions	One hundred million yuan	0.0361	+
		Public transport resources	One hundred million yuan	0.0208	+
		Cultural infrastructure	One hundred million yuan	0.0470	+
		Education investment	One hundred million yuan	0.0216	+

2.3. Research design

2.3.1. Index system construction

Since the introduction of the HQD strategy, scholars both domestically and internationally have explored its various facets, exhibiting certain notable trends. In terms of research content, many scholars have devised measurement systems based on differing interpretations of HQD. Some scholars have chosen single indicators such as economy and ecology to study HQD in the YRD region [29–31]. Others have developed evaluation systems that incorporate the five key aspects of innovation, coordination, greenness, openness, and sharing, focusing on the factors influencing HQD. Additional research has extended the evaluation model to include economic performance, innovation efficiency, coordinated growth, environmental sustainability, and social welfare, while examining spatiotemporal variations in development levels and associated factors [32–34]. According to existing literature on urban agglomerations and HQD, HQD aims to fulfill the growing aspirations for a better future, encapsulating new development concepts like innovation, coordination, green growth, and improved quality of life [35–39]. The Analytic Hierarchy Process (AHP) serves as a structured decision-making tool in this domain. It simplifies complex problems by constructing a hierarchical model, followed by comparative evaluation and prioritization to identify the best solution. This involves building an indicator system and standardizing it to derive the weights for each parameter, ultimately producing a comprehensive evaluation that reflects the HQD of the YRD city clusters.

The initial goal level of this study is the "Five Aspects of the YRD's HQD Level L." Below this overarching aim, the first-level indicators consist of various features that impact the goal level. The second-level indicators influence the first-level indicators and serve as their reflections. In constructing this indicator system, the study adhered to principles of identification, standardization, dynamism, accessibility, and functionality. Building on the central tenets of HQD in the YRD city cluster and incorporating findings from related research, a comprehensive indicator framework was formulated to assess the HQD level in the region. The framework includes five objective layers, ten primary indicators, and twenty-four secondary indicators (Table 1) .

(1) Innovation-driven. Innovation serves as the bedrock of economic and social advancement, transitioning growth from merely incremental to efficient. To gauge the efficacy of innovation, it's crucial to consider both the investment cost in technological innovation and its qualitative output. We have thus constructed two sub-index systems under the primary indicator for technological innovation efficacy. These sub-indices aim to evaluate the performance of technological innovation in terms of research expenditure and the number of research product projects. Additionally, we measure innovation output by assessing granted patents and technology market transactions. Through these metrics, we can more comprehensively understand the role of innovation and make data-driven decisions to bolster economic and social growth.

(2) Coordinated development. This dimension encompasses both regional and urban-rural integration. Regional coordination centers on metrics like per capita disposable income and household consumption expenditure. Urban-rural coordination, on the other hand, looks at the income and consumption disparities between urban and rural areas. In this study, we devised two main indicator systems to assess the efficacy of both types of coordination, with each main system containing two sub-index systems.

(3) Economic development. Economic development captures the vitality and structural dynamics of a country's economy. Amid global economic uncertainties and the quest for sustainable growth, maintaining a balanced and stable economy is essential for China. Metrics like consumption levels, Gross Domestic Product (GDP), and Gross National Income (GNI) serve as concrete indicators of economic health. In light of frequent international trade disputes, this study also evaluates economic openness through two sub-indices: the foreign trade development coefficient and the level of external openness in economic and trade activities.

(4) Green development. Aligned with China's Nineteenth Congress's emphasis on transitioning to a green, low-carbon economy, the importance of environmental sustainability in the economic context cannot be overstated. To assess green development, this study employs two main indicators: pollution reduction and environmental protection. The effectiveness of pollution control is gauged by two sub-indices: the level of industrial pollution control and the rate of harmless disposal of municipal solid waste. On the other hand, environmental protection is measured using sub-indicators like green areas and nature conservation. The weights assigned to each index vary, with industrial wastewater treatment receiving the highest weight at 0.174, and the rate of sound municipal waste treatment allocated the lowest weight at 0.015.

(5) Improving people's livelihoods. The ultimate aim of HQD is to satisfy the increasing desires of people for a better life and elevate their happiness index. HQD is marked by robust and high-quality economic performance, a balanced and equitable distribution of benefits across different social strata, and high levels of resident satisfaction. To evaluate people's well-being, this study employs indicators such as disposable income, social security and employment expenditures, and the urban unemployment rate. Additional metrics like medical and health conditions, public transportation resources, cultural infrastructure, and investment in education are included to assess whether public resources are adequately meeting people's basic life necessities. By evaluating these indicators, we gain a nuanced understanding of how effectively HQD is addressing the needs of the populace.

2.3.2. Data sources and processing

The purpose of this study is to examine HQD in four provinces in the YRD region and to use these characteristics as explanatory variables. The statistical data used in this study include multiple indicators in the areas of innovation-driven, coordinated development, economic development, green development and people's livelihood. These data were mainly obtained from the China Statistical Yearbook and provincial statistical yearbooks, and the time range was 2010–2021. At the spatial scale (administrative level), we focus on the provincial administrative units of the YRD city cluster, including Shanghai, Jiangsu, Zhejiang, and Anhui provinces, and further subdivide them into the prefecture-level administrative units of each province for analysis. We used the statistical yearbooks of the YRD region, which include data from the official website of the National Bureau of Statistics of the People's Republic of China, as well as selected data from the China City Statistical Yearbook and the statistical yearbooks of Shanghai, Zhejiang, Jiangsu, and Anhui provinces. It is important to note that the urban unemployment rate is an inverse indicator of the evaluation index. To facilitate the interpretation of the quality development level measures, we transform the inverse indicator into a positive indicator by taking its inverse and standardizing it to mitigate the effect of size differences.

2.4. Evaluation methodology

2.4.1. Entropy weight TOPSIS

The stochastic approach allows us to objectively assess the HQD in the YRD area.The main concept behind this strategy is to use the TOPSIS method to standardize all indicators and rank them in order of quality. By using entropy weighting and the TOPSIS method, we can accurately assess the HQD level of the YRD region, thus reducing over-reliance on indicators and ranking the high-quality level more accurately [40–42]. In this study, the data was processed using SPSSAU software, and the entropy weighting method was employed to examine the HQD level measurement.

The first step is to normalize the indicators. In order to make the model evaluation more fair and accurate, all negative indicators were positively processed, i.e., they were made positive through certain mathematical transformation. The purpose is to let all indicators be considered under the same evaluation logic, i.e. the higher the indicator value, the higher the level of high quality development. Based on 10 secondary indicators and 24 sub-indicators R_{ij} under 5 primary indicators of the four provinces (cities and districts) in the YRD from 2010 to 2021, we construct a matrix of n evaluation objects and m evaluation index to determine the level of quality growth in the YRD integrated central cities. In formula **(1)** : $r_{ij} = g_{ij} \times \omega_{ij}; i = 1,2\cdots n; j = 1,2\cdots m; \omega_j$ is the weight of the j the index.

$$R = \begin{bmatrix} r_{11}\cdots r_{13}\cdots r_{1m} \\ r_{21}\cdots r_{23}\cdots r_{2m} \\ r_{31}\cdots r_{33}\cdots r_{3m} \\ r_{n1}\cdots r_{n3}\cdots r_{nm} \end{bmatrix}_{n\times m} \tag{1}$$

In the second step, the indicators for assessing the quality development level of the four provinces (cities and regions) in the Yangtze River Delta are categorized into positive and negative indicators. The larger the value of the positive indicator, the higher the quality development level index. The smaller the value of the negative indicator, the lower the quality development level index. To make the indicator data comparable, the treatment of positive and negative indicators, and the value of the processed indicators is between $[0-1]$. Equation (2) j is the positive indicator, and equation (3) j is the negative indicator. The calculation formula is:

$$R_{ij} = \frac{R_{ij} - \min_i(R_{ij})}{\max_i(R_{ij}) - \min_i(R_{ij})} \tag{2}$$

$$R_{ij} = \frac{\max_i(R_{ij}) - R_{ij}}{\max_i(R_{ij}) - \min_i(R_{ij})} \tag{3}$$

In the third step, R_{ij} sets the j impact factor for the normalized result that affects prevention and control. In equations (4)、（5）、(6), f_{ij} is the weight of the I item indicator under the j indicator is given. For a given influence element, its entropy of information is formulated H_j is:

$$H_j = -k\sum_{i=1}^{m} f_{ij} \bullet \ln f_{ij} \tag{4}$$

$$f_{ij} = \frac{R_{ij}}{\sum_{i=1}^{m} R_{ij}} \tag{5}$$

$$k = \frac{1}{\ln m} \tag{6}$$

In the fourth step, in equation **(7)**, the weights W_{ij} of each factor are calculated:

$$W_j = \frac{1 - H_j}{\sum_{j=1}^{n}(1 - H_j)} = \frac{1 - H_j}{n - \sum_{j=1}^{n} H_j} \tag{7}$$

In the fifth step, the positive and negative desired results of the exponent are calculated. Calculate V^+ and V^- for equations **(8)** and **(9)** respectively:

$$V^{+} = \{\max v_{ij} | i = 1, 2, \cdots, m\} \tag{8}$$

$$V^{-} = \{\min v_{ij} | i = 1, 2, \cdots, m\} \tag{9}$$

In the sixth step, the Euclidean distance of each scheme from D_j^{+} and D_j^{-} is calculated. Calculate equation **(10)** and equation **(11)** as:

$$D_j^{+} = \sqrt{\sum_{j=1}^{m} (V_{ij} - V_j^{+})^2} (i = 1, 2, \cdots, n) \tag{10}$$

$$D_j^{-} = \sqrt{\sum_{j=1}^{m} (V_{ij} - V_j^{-})^2} (i = 1, 2, \cdots, n) \tag{11}$$

The seventh step is based on the closeness of the object to be evaluated, i.e. the measured value. The formula for this is (12):

$$F_i = \frac{D_i^-}{D_i^+ + D_i^-} \tag{12}$$

In the equation: F_i refers to the value of the object to be evaluated, the smaller it is the worse the object is and the lower the level.

2.4.2. Exploratory spatial data analysis

Exploratory Spatial Data Analysis (ESDA) has become a widely used method in recent years to identify the presence of spatial correlations between regions. By visually analyzing the spatial distribution patterns of phenomena and describing the mechanisms of interaction between observed objects, ESDA provides a holistic reflection of overall spatial correlations and differences of observations in a region, while also exploring local spatial variations and the evolution of spatial data.

In the first step of this analysis, the Global Moran's I was employed as a spatial autocorrelation indicator in the first phase of this study to assess and quantify the spatial correlation features of the degree of quality growth in the YRD region. The calculation for this is as follows(13)：

$$Moran's\ I = \frac{n \sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij}(X_i - \overline{X})(X_j - \overline{X})}{S^2 \sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij}} \tag{13}$$

From 2010 to 2021, the Global Moran's I was used to examine the overall amount of geographical reliance in the HQD of the YRD city cluster.

While the Global Moran's I provide a useful measure of the overall degree of spatial dependence across a given spatial extent, it may not account for imbalances between local units. To address this, we will utilize the Local Moran's I statistic, which describes the spatial relationship between a specific spatial unit and its domain. This approach will be complemented by the LISA agglomeration map, which visualizes the agglomeration significance of HQDs within the YRD city cluster.

The following is the Local Moran's I statistic formula (14):

$$Moran's\ I = \frac{n(X_i - \overline{X}) \sum_{i=1}^{n} W_{ij}(X_j - \overline{X})}{\sum_{i=1}^{n} (X_i - \overline{X})^2} \tag{14}$$

Local spatial autocorrelation analysis is a powerful technique for examining the degree of spatial clustering of similar attribute values among neighboring spatial units. This analysis effectively captures the correlation characteristics of variables across different spatial scales and spaces. To better identify the types and locations of spatial agglomeration within the YRD urban agglomeration in terms of high HQD, LISA clustering diagrams are utilized to characterize the spatial local correlation.

The LISA clustering diagram provides an intuitive visual representation of local clusters of high HQD within the region. A positive value on the diagram indicates that a particular city is located near other cities with similar attributes, while a negative value suggests that it is closer to cities with different attribute types. By analyzing the LISA clustering diagram, we can gain deeper insights into the spatial patterns and locations of agglomeration within the region, which can inform decision-making processes related to the future development and growth of the YRD city clusters.

3. Result analysis

3.1. Comprehensive results analysis

In this study, TOPSIS and entropy weight method were used to comprehensively evaluate the HQD level of each city cluster in the Yangtze River Delta region. Table 2 and Fig. 3 show the results of the analysis, where D+ and D-denote the distance between the evaluated units and the ideal scenario, and C denotes the relative proximity of the evaluated units to the optimal scenario. The rankings in Table 2 and the indicators in Fig. 3 show that 2017 has the highest score, followed by 2021, while 2010 has the lowest score. Fig. 4 shows the longitudinal trajectory of HQD levels in the YRD urban agglomeration. Overall, the HQD measurements of the four YRD provinces (including cities and districts) show an upward trend from 2010 to 2021. This rise is associated with China's strategic shift to an innovation-driven and ecologically sustainable development model. There was a significant rise in HQD levels in two years, 2013 and 2018, and these rises may be partly due to the economic downturns and challenges that the YRD urban agglomeration encountered during this period.

3.2. Individual dimension analysis

Table 3 and Table 4 offer a comparative analysis of the varying degrees of HQD across provinces and cities in the YRD region from 2010 to 2021, utilizing the established framework for quality development measurement. These tables illuminate both the differential performance and the extent of progress achieved by individual provinces and cities over this time frame.

(1) Innovation-driven: The level of innovation-driven development varies significantly among provinces in the Yangtze River Delta urban agglomeration. Jiangsu led the index with 0.524, mainly due to the large amount of research expenditure, the number of projects, and the number of invention patents granted. Shanghai's city innovation index is better, at about 0.516. The innovation-driven index of Anhui (0.476) and Zhejiang (0.426) is similar, and the level of innovation-driven development is low. In the future, Anhui and Zhejiang need to increase the implementation of innovation-driven transformation strategy, increase science and technology capital and talent support, and enhance the ability to transform science and technology.

(2) Coordinated development: Among the Yangtze River Delta city clusters, Shanghai led with 0.531 points, followed by Jiangsu (0.462) and Zhejiang (0.440), and Anhui was the lowest with 0.394 points. This is due to Shanghai's high per capita disposable income and low consumer spending. The coordinated development of Jiangsu benefits from the coordinated development of regions and the balanced development of urban and rural areas. Zhejiang and Anhui have the highest per capita disposable income, but they face the challenge of coordinated development due to the unbalanced development of urban and rural areas and regional coordination.

(3) Economic development: Zhejiang (0.484) leads the economic development, followed by Shanghai (0.464), Jiangsu (0.440) and Anhui (0.435). The economic development of the Yangtze River Delta region is more balanced. Zhejiang has maintained rapid economic development by strengthening foreign economic cooperation and improving the level of national economy, promoting foreign trade and export. Economic activity in Jiangsu Province has contributed to China's GNI. Shanghai, with its high GDP and high level of household consumption, plays a role in economic development. Anhui is prominent in terms of foreign trade and GDP, and its economy has developed rapidly. At present, the four areas of the Yangtze River Delta have little difference in market economy, showing a trend of balanced economic development.

(4) Green development: Anhui leads in green development with a score of 0.557, among which Anhui has achieved good results in effectively controlling industrial pollution, improving the harmless treatment rate of municipal solid waste, extensive afforestation and nature protection. It was followed by Jiangsu and Shanghai, with scores of 0.518 and 0.506, respectively. In contrast, Zhejiang ranked last with a score of 0.431, mainly due to insufficient pollution reduction and failure to promote green development. Nevertheless, all provinces have made progress in green development, which shows the importance the Yangtze River Delta region attaches to sustainable development and ecological protection.

Table 2
TOPSIS HQD assessment in the YRD cities cluster 2010–2021.

Year	D+	D-	C	Sort results
2010	4.40	1.54	0.259	12
2011	4.10	1.46	0.263	11
2012	3.73	1.75	0.318	10
2013	3.08	2.45	0.442	8
2014	3.26	2.49	0.433	9
2015	2.92	2.63	0.474	7
2016	2.53	3.04	0.545	6
2017	2.02	3.61	0.642	1
2018	2.18	3.42	0.610	5
2019	2.23	3.56	0.616	3
2020	2.26	3.59	0.615	4
2021	2.28	4.04	0.639	2

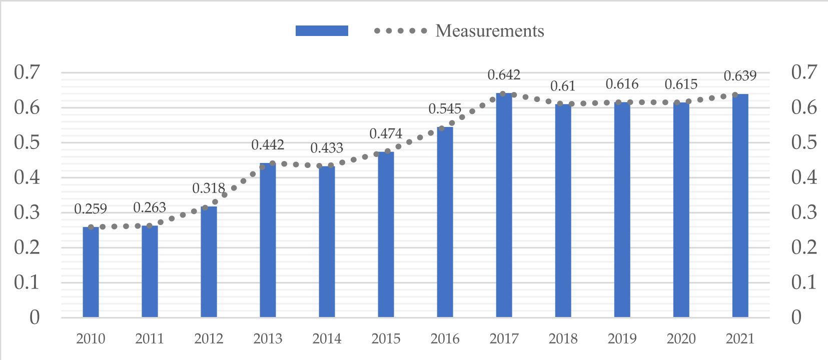

Fig. 3. HQD levels in the YRD Integrated Cities Cluster, 2010–2021.

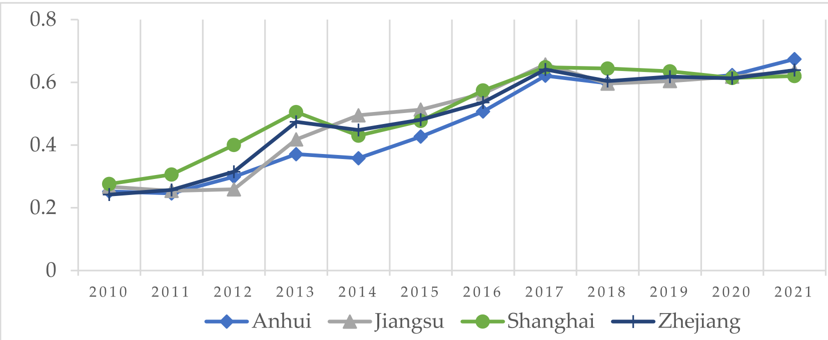

Fig. 4. Shifting patterns in HQD in the YRD's three provinces and one city, 2010–2021.

Table 3
Specific analysis of HQD among provinces in the YRD region, 2010–2021.

Target level	Primary index	Secondary index	Shanghai	Jiangsu	Zhejiang	Anhui
Innovation-driven	Innovation investment	Research and development expenditure	0.646	0.556	0.416	0.457
		Number of research and development product projects	0.541	0.632	0.398	0.332
	Innovative output	Patent authorization for invention	0.566	0.595	0.415	0.617
		Technology market transaction	0.342	0.281	0.673	0.297
Harmonious development	Regional coordinated development	Per capital disposable income of residents	0.579	0.476	0.607	0.607
		Household consumption expenditure	0.138	0.668	0.138	0.138
	Coordinated development between urban and rural areas	Urban-rural income gap	0.581	0.467	0.423	0.517
		Urban-rural consumption gap	0.55	0.511	0.409	0.499
Economic development	National economy	Consumption level of residents	0.543	0.502	0.508	0.519
		Gross domestic product	0.47	0.439	0.465	0.48
		Gross national income	0.433	0.531	0.422	0.502
	Open structure	Foreign trade coefficient	0.461	0.555	0.467	0.617
		External investment dependence	0.303	0.293	0.314	0.303
Green development	Pollution reduction	Control of industrial pollution	0.104	0.104	0.104	0.104
		The harmless treatment rate of municipal solid waste	0.823	0.723	0.445	0.86
	Green environmental protection	Afforestation area	0.546	0.548	0.552	0.559
		Basic information of nature protection	0.55	0.696	0.622	0.704
Improving people's livelihoods	Life well-being	Income dominance	0.477	0.442	0.433	0.426
		Social security employment expenditure	0.518	0.55	0.562	0.561
		Urban unemployment ratio	0.598	0.625	0.578	0.637
	Public resource	Medical and health conditions	0.439	0.455	0.433	0.541
		Public transport resources	0.567	0.705	0.632	0.368
		Cultural infrastructure	0.507	0.555	0.461	0.498
		Education investment	0.494	0.403	0.61	0.614

Table 4
HQD of the four provinces of the YRD urban agglomeration and their average water values in each dimension, 2010–2021.

Provinces dimension	Innovation-driven	Coordinated development	Economic development	Green development	Improving people's livelihoods
Shanghai	0.516	0.531	0.464	0.506	0.534
Jiangsu	0.524	0.462	0.442	0.518	0.514
Zhejiang	0.426	0.440	0.484	0.431	0.521
Anhui	0.476	0.394	0.435	0.557	0.530

(5) In terms of the improvement of people's livelihood, all four areas scored above 0.500, reflecting a high happiness index and abundant public resources. Shanghai topped the list with a score of 0.534, due to its good distribution of income. Anhui followed with a score of 0.530, thanks to its strong investment in education, good health care and low urban unemployment. Zhejiang and Jiangsu are slightly behind, with 0.521 and 0.514 respectively, but they also have a good performance, with Jiangsu benefiting from rich public transportation resources, and Zhejiang benefiting from large social security and employment expenditure and education investment. In the future, the Yangtze River Delta region should continue to strengthen public service guarantee, coordinate the social and economic development of urban and rural areas, and narrow the development gap between urban and rural areas.

3.3. Analysis of spatial differences

To assess and compare the HQD levels of the YRD urban agglomerations, this study conducted a basic classification based on the average composite score. The basic classification was performed by cluster analysis using the natural discontinuity hierarchy method of ArcGIS software, which is based on the natural groupings inherent in the data, and the classification intervals were determined by maximizing the differences between classes. The YRD region was divided into four areas, and the classification intervals were determined by maximizing the differences between class divisions based on the groupings inherent in the data.

The HQD comprehensive score from 2010 to 2021 was sorted and the average comprehensive score of each year was calculated. The classification results are shown in Fig. 5. Based on color shades, we can see differences in HQD scores in the region. The darkest color represents a score of 0.6–0.7, followed by 0.5–0.6, then 0.4–0.5 again, and the lightest color represents a score of 0.2–0.4. In terms of time, most regions improved their scores between 2010 and 2021. Over time, the areas with high scores have expanded. In 2010, most of the Yangtze River Delta region showed a score of 0.4–0.5, with only a few cities scoring between 0.6 and 0.7. From 2011 to 2013, the area with a score of 0.5–0.6 increased year by year. From 2014 to 2016, regions with scores of 0.6–0.7 began to expand, especially in coastal areas of Jiangsu Province. From 2017 to 2019, there is a decrease in areas with scores of 0.5–0.6, while areas with scores of 0.6–0.7 continue to expand. From 2020 to 2021, regions with scores of 0.4–0.5 are significantly reduced, while regions with scores of 0.5–0.6 and 0.6–0.7 become dominant. From the perspective of spatial distribution, the coastal areas, especially the coastal areas of Jiangsu, performed better in the whole period, with scores mostly between 0.6 and 0.7. Regarding inland regions, from 2010 to 2014, most inland regions scored between 0.4 and 0.5, but over the next few years, inland scores began to improve. Regarding major cites, such as Shanghai, Suzhou and other cities, their color is always darker, and the score is high throughout the period, mainly between 0.6 and 0.7. Regarding marginal regions, places such as southern Zhejiang and northern Anhui, as shown in the figure, have slightly lower scores in most periods, ranging from 0.4 to 0.6. In general, HQD scores in the Yangtze River Delta region continued to rise between 2010 and 2021, and HQD scores seemed to be generally high in coastal areas and around some major cities. Inland or more remote areas scored lower.

3.4. Spatial association analysis

From our comprehensive analysis, it's evident that substantial regional disparities exist in HQD levels among the provinces within the YRD region over the study period. To address this, we incorporated spatial correlation among these provinces. Utilizing a spatial weight matrix based on geographic distances, this study employed Moran's I statistic through the Exploratory Spatial Data Analysis (ESDA) technique to scrutinize both spatial autocorrelation and local agglomeration of HQD levels in the YRD urban cluster. Calculations were performed using ArcGIS software.

Table 5 shows that, except for 2010, the HQD level of global Moran's I in the Yangtze River Delta urban agglomeration presents a significant positive correlation under the geographical distance matrix. This indicates that there is a significant spatial positive correlation between HQD levels in the Yangtze River Delta urban agglomerations, which rules out the possibility of random distribution. During the whole sample period, significant spatial aggregation was observed in most years. The global spatial agglomeration effect shows a certain volatility, which is manifested as rising first, then declining, and finally rising. Notably, with the exception of 2010, Moran's I has consistently exceeded 0.4000 during the study period, peaking in 2021. This indicates that the spatial agglomeration trend of HQD level in the Yangtze River Delta urban agglomerations is increasing, and the spatial difference is gradually narrowing.

In order to deeply portray the spatial clustering characteristics of HQD levels of urban clusters in theYRD region from 2010 to 2021, this study selected 2010 (at the beginning) and 2021 (as of) as the time points to construct LISA clustering distribution maps using ArcGIS software(Fig. 6) (Table 6) . By analyzing the differences in HQD among regions, we can see more clearly the advantages and shortcomings of each region in the development process. According to the LISA clustering distribution map, it is divided into four types: double-high (H–H), low-high (L-H), double-low (L-L) and high-low (H-L). (1) Double-high type (H–H): mainly in Shanghai,

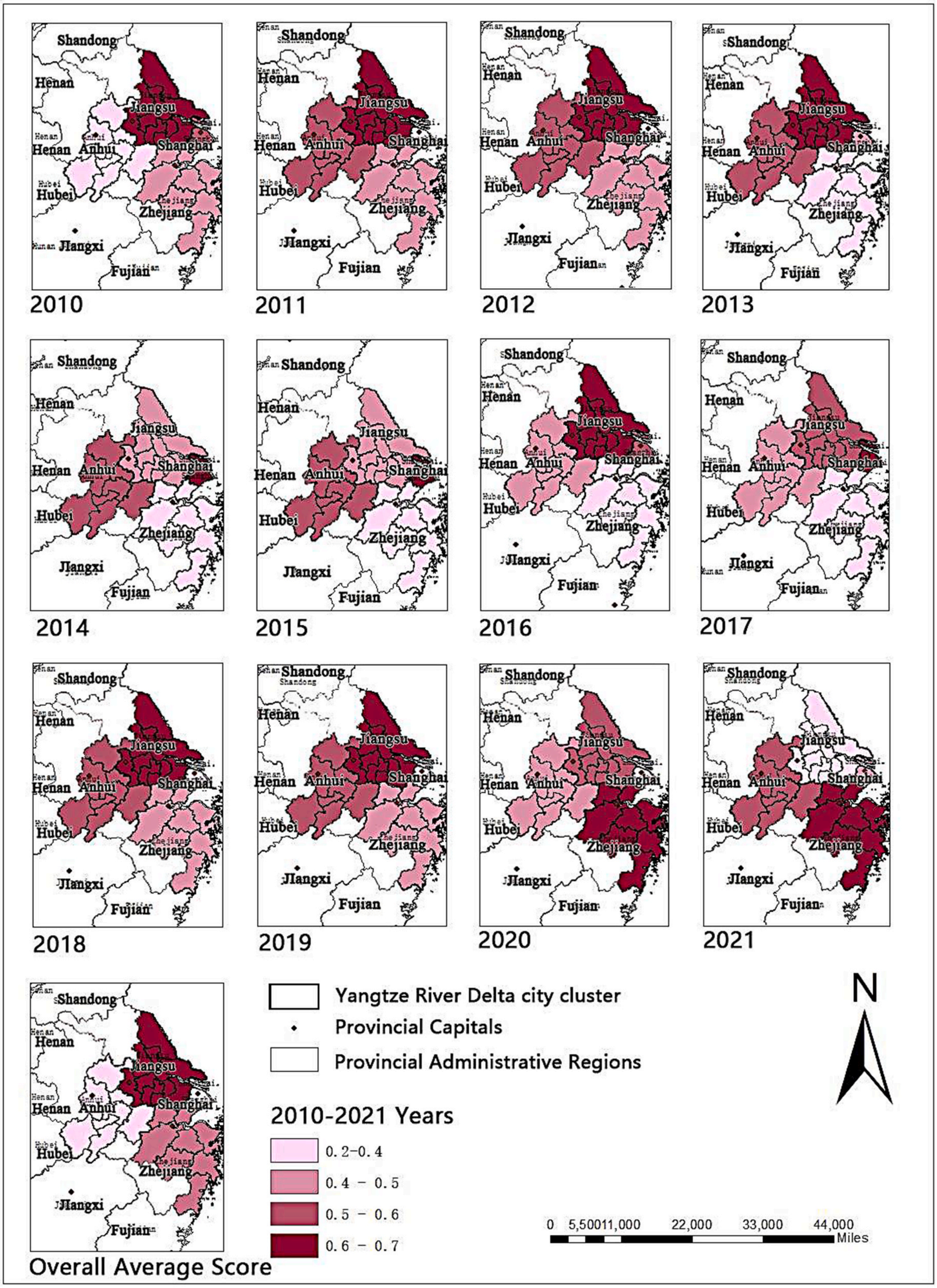

Fig. 5. Spatial distribution of HQD levels by provinces in the YRD city cluster, 2010–2021.

Table 5
A global Moran's I on the HQD in the YRD urban agglomeration, 2010–2021.

Year	2010	2011	2012	2013	2014	2015
Morans I	0.0297	0.4965	0.4299	0.4966	0.4741	0.4410
Z statistic	0.4463	4.2461	3.7067	4.2461	4.0526	3.7802
P	0.6553	0.000	0.000	0.000	0.000	0.000
Year	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Morans I	0.4483	0.4729	0.4927	0.4828	0.4029	0.5145
Z statistic	3.8395	4.4377	4.1885	4.114	3.4706	4.3711
P	0.000	0.000	0.000	0.000	0.000	0.000

Suzhou, Nanjing, Maanshan, Zhenjiang, Changzhou and other places for H–H type. These cities have achieved remarkable results in HQD, and may also have a radiating effect on the surrounding areas, promoting the HQD of the whole YRD region. These regions generally have strong economies and superior policy environments, which can attract and maintain a large number of talents and resources. (2) High-low type (H-L): mainly Jinhua Huaibei, Suzhou, Wenzhou, etc. as H-L type. These have achieved some success in HQD, but their neighboring regions are relatively lagging behind. (3) Low-High type (L-H): Hefei and Taizhou are L-H type. These areas have a low level of high quality development, but are in a stage of transformation or development, and their neighboring areas have a high level of high quality development. (4) Low-low type (L-L): mainly in North China, Suzhou, Ningbo as L-L type. These regions perform relatively poorly in HQD, and these regions have a weaker foundation for economic development compared to other regions. Overall, through detailed analysis of the four types, these results not only reveal the characteristics and differences in the spatial distribution of urban agglomerations in the YRD region in terms of HQD, but also provide a clearer picture of the strengths and weaknesses of each region in the development process. It helps policy makers and researchers to understand more deeply the current development status of the YRD urban agglomerations, especially the problems and challenges in terms of HQD.

4. Discussion

4.1. Similarities and variations with present studies

This study measures the high quality development level of the YRD city cluster and reveals the dynamic process of its development through spatio-temporal correlation analysis. In contrast to similar research results for other urban agglomerations in China, in some studies, researchers focus on the economic, social, and environmental aspects of the PRD region to assess the quality of its development. Also in some studies, relevant research on the Beijing-Tianjin-Hebei region focuses on the region's economic development and environmental protection, and the relationship between the two. Its advantages lie in its strong economic strength, remarkable technological innovation capacity and policy support, and its disadvantages lie in traffic pressure and industrial upgrading pressure. The reasons behind this include geographical advantage, historical accumulation, and policy orientation. A comparative study with the high quality development of urban agglomerations in other regions of China in the past allows us to consider the differences and the reasons behind them from the following aspects:

Firstly, research perspective and focus: The YRD study focuses on the construction of a five-dimensional HQD level evaluation system of innovation-driven, coordinated development, economic development, green development, and people's livelihood development, and the evaluation and analysis of HQD from 2010 to 2021, focusing on multidimensional HQD measurement and spatio-temporal correlation analysis. In contrast, the studies of Beijing-Tianjin-Hebei and Pearl River Delta may focus more on specific areas of high quality development, such as environmental protection, transportation, and industrial upgrading. We find that the YRD city cluster shows advantages in innovation-driven and economic development compared to other major city clusters in China (e.g., Pearl River Delta, Beijing-Tianjin-Hebei). This can be partly attributed to the YRD region's deep economic foundation and advanced science and technology innovation capabilities, which are consistent with the region's long-standing emphasis on innovation-driven development strategies. However, compared to urban agglomerations such as the Pearl River Delta and Beijing-Tianjin-Hebei, the YRD urban agglomerations have disadvantages in terms of green development and sustainable livelihood. These challenges mainly stem from the excessive pursuit of economic development at the expense of environmental protection and social justice. This suggests that the YRD urban agglomerations need to focus on balanced social and environmental development while pursuing high rates of economic development.

Secondly, in terms of research methodology and framework, this study is innovative in the research methodology and framework of urban agglomerations in China. The indicators mainly used to measure the level of HQD not only include hard indicators of economic development, but also consider soft indicators such as environment and social welfare. In addition, by using two software programs, SPSSAU and Arcgis 10.8, our study is able to understand and reveal the dynamic process of urban agglomeration development in a deeper way. The study was able to conduct more in-depth spatio-temporal correlation analysis and dynamic process understanding. The use of these tools not only improved the accuracy of the analysis, but also provided new perspectives to reveal the complex mechanisms of urban agglomeration development. In contrast, the PRD and Beijing-Tianjin-Hebei studies may have used different data and analytical methods, leading to differences in findings and interpretations.

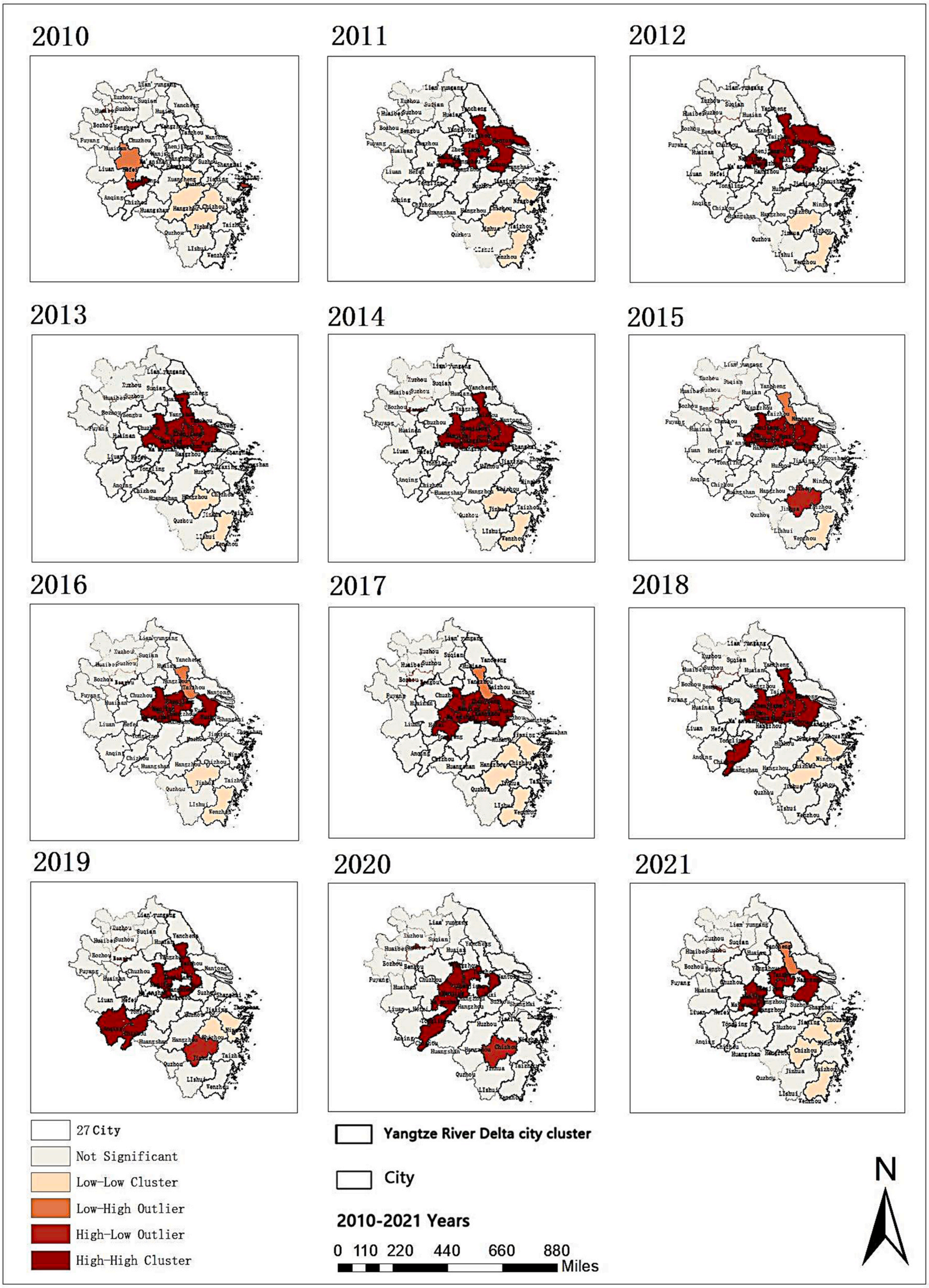

Fig. 6. LISA clustering and heterogeneous distribution of the HQD of cities in the YRD urban agglomeration, 2010–2021.

Table 6
Local Moran's I distribution of HQD levels in the YRD urban agglomeration, 2010–2021.

Year	H–H	L-L	H-L	L-H
2010	Tongling	Huzhou, Hangzhou, Shaoxing, Jinhua	Zhoushan	Hefei
2011	Shanghai, Suzhou, Maanshan, Zhenjiang, Changzhou, Taizhou, Nantong	Zhoushan, Ningbo, Jinhua, Wenzhou		
2012	Shanghai, Suzhou, Maanshan, Zhenjiang, Changzhou, Taizhou, Nantong	Jinhua, Wenzhou		
2013	Shanghai, Suzhou, Nanjing, Maanshan, Zhenjiang, Changzhou, Wuxi, Taizhou, Nantong	Suizhou, Jinhua, Wenzhou		
2014	Shanghai, Suzhou, Nanjing, Maanshan, Zhenjiang, Changzhou, Wuxi, Taizhou, Nantong	Suzhou, Jinhua, Wenzhou		
2015	Shanghai, Suzhou, Nanjing, Maanshan, Zhenjiang, Changzhou, Wuxi, Nantong	Suizhou, Wenzhou	Jinhua	Taizhou
2016	Shanghai, Suzhou, Nanjing, Maanshan, Zhenjiang, Changzhou	Suzhou, Jinhua, Wenzhou		Taizhou
2017	Shanghai, Suzhou, Nanjing, Wuhu, Maanshan, Zhenjiang, Wuxi, Changzhou	Jinhua, Shaoxing, Ningbo, Wenzhou		Taizhou
2018	Shanghai, Suzhou, Maanshan, Nanjing, Zhenjiang, Taizhou, Wuxi, Changzhou, Chihuahua	Jinhua, Shaoxing, Ningbo		
2019	Shanghai, Nanjing, Zhenjiang, Taizhou, Wuxi, Anqing, Chihuahua	Shaoxing, Ningbo	Jinhua	
2020	Shanghai, Nanjing, Maanshan, Zhenjiang, Wuxi, Wuhu, Chizhou		Jinhua	
2021	Shanghai, Suzhou, Wuhu, Maanshan, Zhenjiang, Changzhou	Jinhua, Shaoxing, Ningbo, Wenzhou		Taizhou

4.2. Problems and shortcomings

In this study, we have conducted an in-depth measurement and spatio-temporal correlation analysis of the high-quality development level of the Yangtze River Delta city cluster. It is worth noting that in the course of the study, we also recognize a series of problems and shortcomings, which are manifested in three aspects. First, the classification of indicators lacks rigor. In terms of the indicator system and fact-collecting techniques, the study lacks a strict guideline for categorizing indicators due to different statistical records in specific years and different research directions in various fields. This may lead to bias or error in the assessment results. Future studies may consider introducing or referring to internationally widely recognized standards or guidelines to ensure the objectivity and fairness of the measurement.

Second, there is insufficient cross-disciplinary cooperation. Although high-quality development is a multidirectional concept covering a wide range of economic, social, and ecological domains, this study has relatively little cooperation with other domains in exploring the measurement implementation path and optimization options. In order to gain a more comprehensive and in-depth understanding, future studies will work more closely with experts in fields such as ecology and economics.

Finally, regional comparative limitations. Although the Yangtze River Delta (YRD), Pearl River Delta (PRD) and Beijing-Tianjin-Hebei (BTH) are all the focus of China's economic development, they are significantly different in several dimensions. This study was conducted primarily based on the data and context of the YRD urban agglomeration, so the findings may not be fully applicable to other regions. Future research should focus more on the differences between these regions and consider a broader regional comparison to ensure the generalizability of the study.

5. Conclusion

This study offers a comprehensive evaluation of HQD across the urban agglomerations in China's YRD, encompassing four areas: Shanghai, Jiangsu, Zhejiang, and Anhui. Utilizing statistical and vector data spanning from 2010 to 2021, we devised a multi-dimensional assessment framework focusing on five key areas: innovation-driven growth, coordinated development, economic advancement, environmental sustainability, and shared prosperity. Employing advanced analytical tools such as SPSSAU and ArcGIS 10.8,we investigated spatial autocorrelations, LISA clustering, and heterogeneity in the YRD's HQD composite index, and drew the following conclusions:

(1) The overall HQD composite level of the YRD region shows an upward trend, which reflects the region's firm pursuit in the direction of HQD despite fluctuations due to the influence of strategic adjustments in specific periods.
(2) The strengths and weaknesses of different provinces in terms of innovation-driven, coordinated development, economic growth, green development and livelihood improvement are obvious, which provides a direction for further optimization of strategic planning.
(3) The results of the spatial analysis highlight the spatial variability and correlation of HQD in the YRD region, such as the double-high region in Shanghai and Jiangsu area versus the low-low region in the interior of Anhui, as well as the high-low region in Zhejiang, which are findings that can help to more accurately locate the priority direction of regional cooperation and resource allocation.
(4) This study not only emphasizes the importance of measuring the level of HQD in the YRD urban agglomeration, but also provides a new perspective to understand and promote HQD in the region through spatio-temporal correlation analysis. This study not only provides a scientific basis for the future spatial layout and strategic planning of the Yangtze River Delta region, but also provides valuable experience for the study of HQD in other urban agglomerations.

Data availability statement

The experimental data used to support the findings of this study are included in the article.

CRediT authorship contribution statement

Yanlong Guo: Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Conceptualization. **XueMei Jiang:** Writing – original draft, Data curation. **Yelin Zhu:** Methodology, Data curation. **Han Zhang:** Writing – original draft, Data curation.

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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