Environmental Science and Pollution Research (2021) 28:6898–6912
https://doi.org/10.1007/s11356-020-11051-0

RESEARCH ARTICLE

Study on coupling coordination and spatiotemporal heterogeneity between economic development and ecological environment of cities along the Yellow River Basin

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Received: 28 April 2020 / Accepted: 28 September 2020 / Published online: 3 October 2020

Abstract

The Yellow River Basin (YRB) is an important ecological barrier and an important economic zone in China. Under the new requirements of realizing ecological protection and high-quality development of the YRB, the coordinated development of basin economic development and ecological environment is an urgent research topic. Taking 36 cities along the Yellow River Basin as samples, this paper constructs an evaluation index system of economic development and ecological environment. The coupling coordination model and geographical weighted regression were adopted to analyze the coupling coordination relationship between economic development and ecological environment from 2008 to 2017, and the influencing factors were analyzed. The results showed that (1) the coupling coordination of urban economic development and ecological environment along the YRB showed significant regional heterogeneity, forming a low-value sag of the Loess Plateau; (2) the regional hot spots in the downstream of the YRB continuously extended inland, while these in the midstream converged; (3) the coupling coordination degree between economic development and ecological environment is affected by factors such as population size, openness, and advanced industrial structure, and the intensity varies significantly among regions.

Keywords Economic development · Ecological environment · Coupling coordination · Geographical weighted regression (GWR) · The Yellow River Basin (YRB)

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Introduction

At present, China puts forward a major national strategy for economic development and ecological protection coexisting in harmony of the YRB, stressing the idea of "Lucid waters and lush mountains are invaluable assets," persisting in green development, ecological priority, and promoting high-quality development of the whole basin. In 2008, the GDP of the YRB was about 9 trillion CNY, accounting for 27.02% of the nation. By contrast, the GDP in 2018 was about 23.9 trillion CNY, accounting for 26.5% of the nation, which has achieved rapid progress. Among them, cities include Qingdao, Zhengzhou, Jinan, Yantai, Weifang, and Zibo, with GDP of more than 500 billion CNY, mainly concentrated in the downstream of YRB in Henan and Shandong.

However, with the rapid development of regional urbanization and industrialization, the YRB is also faced with such problems as excessive exploitation of natural resources (Yin et al. 2016), fragile ecological environment (Ma et al. 2019), lagging pace of transformation and upgrading of traditional industries (Jin et al. 2020), insufficient endogenous driving forces (Chen et al. 2012), and unbalanced economic development within the basin. The contradiction between ecological environment and economic development is increasingly prominent.

To achieve high-quality development of YRB, the coordinated road of ecological environmental protection and economic-social development must be taken. Therefore, the analysis of coupling coordination relationship of cities along YRB and diagnosis of influencing factors will be helpful to achieve the high-quality development in YRB, and benefit to cultivate YRB a new growth pole.

However, in reality, the gap between cities in YRB has been large and the economic imbalance in the basin has been prominent for a long time (Zhou and Xia 2008). On one hand, scholars generally believe that this is closely related to the reform and opening up process, in which the distribution of income and land is uneven (Li et al. 2011). And the economy of YRB is booming, at the cost of excessive exploitation of natural resources, leading to the degradation of the ecosystem (Wohlfart et al. 2016). On the other hand, the spatial heterogeneity is also important factors of unbalanced economic development.

Based on this, this paper uses 36 cities in 9 provinces of the YRB in 2008–2017, to construct evaluation index system of economic development and ecological environment. Firstly, we calculated the coupling degree of the two by using the coupling coordination degree model, and then used the exploratory spatial data analysis (EDSA) model to analyze the spatiotemporal heterogeneity. Finally, GWR is applied to diagnose the influencing factors. Through those, the evolution index system in this paper is credible, the factors are convincing, and the conclusions are reliable. Hence, this paper attempts to find a way for the coexisting development of economic growth and ecological environment.

The paper will be expanded as follows: the first to appear is the literature review. The following section introduces the coupling coordination model, the selection of evaluation indicators, and data sources. The fourth section analyzes the coupling relationship and spatiotemporal evolution of hotspot. The fifth section calculates coordinated coupling degree of influencing factors in each city, and analyzes the spatial heterogeneity. The last part is the conclusion and recommendations.

Literature review

High-quality economic development in YRB

High-quality development is regarded as a new development mode and development strategy, and a new development concept with the value orientation of quality and benefit (Tian 2018). Its connotation and evaluation index system have been the focus of academic research (Zhao et al. 2019; Han et al. 2019). However, studies on high-quality economic development in YRB are still in its infancy. Since the proposal of high-quality development strategy in YRB, scholars carried out studies on the connotation and promotion strategy of high-quality development and ecological protection in the YRB (Jin 2019). Some scholars believe that the protection of ecological environment provides an important guarantee for the high-quality development of the YRB (Xu et al. 2020), while others hold that high-quality development in YRB can be seen from the following six aspects: ecological priority, effective market, dynamic energy conversion, industrial support, regional coordination, and being people-oriented (An and Li 2020).

Ecological development of YRB

As for ecological environment of YRB, most studies focus on ecological environment quality assessment (Wang et al. 2007; Song et al. 2012), water resources utilization efficiency and rational development (Di et al. 2019; Feng et al. 2012; Cai and Rosegrant 2004), soil and water conservation (Jiang et al. 2015; Fu et al. 2017), etc. Studies have proved that human activities have both positive and negative effects on vegetation change in the Loess Plateau. Major ecological restoration projects in recent years have changed land use patterns and expanded vegetation coverage, and the dynamic changes of vegetation in different land types are also different (Wang et al. 2019). However, with the acceleration of urbanization and industrialization, water shortage, pollution, and overexploitation of energy resources and other such problems have been aggravated. Fortunately, the positive impacts outweigh the negative impacts (Li et al. 2019).

High-quality economic development and ecological development in YRB

Literatures on economic development and ecological environment mostly focus on the environmental Kuznets curve (EKC) theory (Hao and Liu 2016; Ma et al. 2016; Balsalobre-Lorente et al. 2018; Xie et al. 2019; Egbetokun et al. 2020). However, there are clear differences of opinions. Pessimists believe that economic growth comes at the expense of the environment, emitting a large number of pollutants, which will lead to the deterioration of environmental quality (Antonakakis et al. 2017; Hasanov et al. 2019). Optimists argue that economic development is constantly driving technological upgrading, which facilitates the transformation and utilization of the ecological environment, and there is no need to give up economic growth just for reducing carbon emissions (Dogan and Turkekul 2016; Soytas and Sari 2009; Zhou et al. 2019a, b).

In addition, some scholars believe that the judgment of the relationship between economic development and ecological environment should pay more attention to the stage of regional economic development and the state of ecological environment (Shi et al. 2019). Therefore, a large number of scholars have conducted empirical studies on coupling coordination. Research methods include analytic hierarchy process (Xu et al. 2019), entropy weight-topsis method (Chen et al. 2019; Liu et al. 2018a, b), evaluation models include coupling coordination evaluation model (Li et al. 2017a, b) and system dynamics model (Cheng et al. 2018; Xing et al. 2019), and mutation technology model (Sun et al. 2018). The study samples included countries (Shi et al. 2020; Sharma et al. 2020), regions (Cui et al. 2019), provinces (Liu et al. 2018a, b), and cities (Lin and Zhao 2019; Ke and Xia 2019).

Summary

To sum up, the research on coupling coordination relationship between urban economic development and ecological environment along YRB is a little insufficient. It is especially rare to use EDSA to analyze the spatiotemporal heterogeneity of river basin and diagnose the influencing factors. Considering the heterogeneity of different regions in YRB, it is difficult to adopt a unified model to achieve coordinated development. Therefore, different development plans and strategies need to be introduced. Compared with the existing literature, the innovation and contribution of this paper are as follows: (1) research perspective: at present, the ecological environment of YRB is relatively fragile, and the economic and social development is distributed in a ladder pattern: backward upstream, rising middle, and developed downstream. Therefore, how to solve the contradiction between development and environmental protection is an urgent practical problem; (2) research results: the coupling coordination development index is calculated, and the influence factors are analyzed using the GWR model.

Methods and data

Measurement of coupling coordination degree

Coupling coordination model

Entropy method is widely used in objective weighting method. This method determines the weight by analyzing the degree of correlation between the indicators and the amount of information of the indicators. In information theory, information entropy can represent the degree of signal dispersion (Zhang et al. 2019a, b). The greater the corresponding discretization, the greater the impact on the comprehensive evaluation is, and vice versa. The entropy method is used to measure the comprehensive level of economic development and ecological environment of cities along the YRB. The coupling degree is obtained by using the coupling coordination degree model.

First, this paper uses range method to standardize original data. Since there are positive and negative indicators, the standardization is:

Positive indicator:

$$x_{ij}^{'} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})} \quad (1)$$

Negative indicator:

$$x_{ij}^{'} = \frac{\max(x_{ij}) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})} \quad (2)$$

where x_{ij} is the original value of the ith index in the jth city, $x_{ij}^{'}$ is the normalized value, max(x_{ij}) and min(x_{ij}) are the maximum and minimum values.

Second, calculate entropy value e_j for index x_{ij}:

$$e_j = -k \sum_{i=1}^{n} p_{ij} \times \ln\left(p_{ij}\right) \quad (3)$$

In formula (3), $p_{ij} = \frac{x_{ij}^{'}}{\sum_{i=1}^{n} x_{ij}^{'}}$, $k = \frac{1}{\ln(n)}$, satisfy $e_j > 0$.

Third, calculate the comprehensive evaluation index S_i of each region:

$$S_i = \sum_{j=1}^{m} w_j \times x_{ij} \quad (4)$$

In formula (4), $w_j = \frac{d_j}{\sum_{j=1}^{m} d_j}$ is the weight of index j, while $d_j = 1 - e_j$. According to this, calculate $S_{JJFZ,\ i}$ and $S_{STHJ,\ i}$, respectively.

Fourth, coupling coefficient C_i and coupling coordination coefficient D_i of the comprehensive evaluation indexes were calculated:

$$C_i = 2\sqrt{\frac{S_{JJFZ,i} \times S_{STHJ,i}}{\left(S_{JJFZ} + S_{STHJ}\right)^2}} \quad (5)$$

$$D_i = \sqrt{C_i \times T_i}, \quad T_i = \frac{S_{JJFZ,i} + S_{STHJ,i}}{2} \quad (6)$$

In formula (5), the range of C_i is (0,1). The greater the C_i is, the higher the coupling degree. D_i can better reflect the coordination between the two indicators.

Selection of evaluation indicators

Quantitative studies on coupling coordination degree are conducive to regulate and control timely, and provide scientific support for formulating economic development and environmental protection policies. Many scholars have studied the coupling relationship between them and constructed different evaluation index systems (Xu et al. 2019). In reference on them, follow the principle of scientific, availability, representativeness, etc. This paper constructs economic development evaluation index system including economic scale, economic benefit, and economic structure, and ecological environment evaluation index system including green environmental protection, environmental management, and environmental pollution (Li et al. 2009; Yang and Hu 2019), as shown in Table 1. To ensure the continuity of data, interpolation is used to fill in the missing data. All data are filtered one by one to remove outliers.

Analysis of factors influencing the coupling coordination degree between economic development and ecological environment

Research design

ESDA is a frequently used method to research spatial data distribution characteristics. It determines regional adjacency relationship based on spatial weight matrix, and reflects spatial dependence or heterogeneity of geographical phenomena through spatial data distribution characteristics (Rey and Janikas 2005; Ye and Rey 2013). In this paper, we use the global Moran's I index to explore the spatial correlation characteristics of the coupling coordination degree of cities along YRB, and the spatial agglomeration trend was analyzed. Getis-Ord G_i^* index are selected YRB to measure the spatial correlation and difference degree along the YRB, and to identify spatial distribution of hot spot and cold spot. The calculation formulas are:

$$I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\left(x_i - \overline{x}\right)\left(x_j - \overline{x}\right)}{S^2 \sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}} \tag{7}$$

$$G_i^*(d) = \frac{\sum_{j=1}^{n} w_{ij}(d) x_j}{\sum_{j=1}^{n} x_j} \tag{8}$$

In formula (7), I is the global Moran's I, $\overline{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$; n is the number of regions, x_i and x_j represent coupling coordination degree in region i and region j, respectively. W_{ij} is spatial weight matrix. In formula (8), Z test for G_i^* shows that $Z\left(G_i^*\right)$ is positive and the value is significant, indicating that the values around position i are greater than the mean and belong to the high-value spatial clustering (hot spot). Otherwise, it is the low-value spatial clustering (cold spot).

GWR is a spatial variable coefficient estimation method, which is used to test the regression relationship between two or more variables with spatial distribution characteristics, and to replace global parameter estimation with local parameter estimation to better evaluate the non-stationary state of spatial data, which is conducive to the exploration of spatial variation characteristics and spatial law. Therefore, GWR is adopted to study the spatial heterogeneity of coupling coordination. The formula is:

Table 1 The evaluation index system of coordinated urban economic development and ecological environment development along the YRB

First class indicator	Second class indicator	Third class indicator	Unit	Max	Min	Mean
Economic development	Scale of economic	GDP	100,000,000 CNY	692.03	119.10	169.841
	Economic benefits	Average wages of staff and workers	1000 CNY	42.59	12.44	27.396
		Per capita disposable income of urban residents	1000 CNY	25.495	10.655	15.916
	Economic structure	Proportion of secondary industry	%	80.70	21.86	53.26
		Proportion of tertiary industry	%	75.26	11.99	38.44
Ecological environment	Green environmental protection	Total water resources	10,000,000 million stere	268	2.50	95.69
		Green coverage rate of built-up area	%	71.81	14.48	37.66
		Green area	100 hectare	196.43	2.00	44.99
	Environmental governance	Household garbage harmless disposal rate	%	100	6.10	87.75
		Comprehensive utilization of industrial solids	%	100	17.09	76.37
	Environment pollution	Industrial wastewater discharge	1000 tons	19.21	0.229	6.445
		Industrial sulfur dioxide emissions	100,000,000 tons	31.60	0.1016	8.1372

Value variables have all been deflated

$$Y_i = \alpha_0(u_i, v_i) + \sum_{j=1}^{k} \alpha_j(u_i, v_i)x_{ij} + \varepsilon_i \tag{9}$$

In formula (9), Y_i is global dependent variable, x_{ij} is independent variable, $\alpha_0(u_i, v_i)$ is a constant term, (u_i, v_i) is the spatial coordinates of the ith area, and $\alpha_j(u_i, v_i)$ is variable parameter of x_{ij} (jth explanatory variable in the ith region).

Variable selection

The coupling coordination degree of urban economic development and ecological environment along YRB has a strong spatial consistency with the development level of each subsystem. This paper measures economic development from three aspects of economic scale, economic benefits, and economic structure, and measures ecological environment quality of cities along YRB from three aspects of green environmental protection, environmental governance capacity, and environmental pollution. Therefore, based on the key factors that affect both of them, this paper analyzes the effect of these factors on the degree of coupling coordination. The specific indicators include population scale, the level of consumption, investment, openness, financial situation, and industrial structure advanced level (Table 2). Taking the coupling coordination degree as dependent variable, the above six influencing factors as independent variables, this paper uses GWR to analyze the reasons for the coupling coordination difference in cities along YRB.

(1) Population size: population agglomeration reflects the attractiveness and competitiveness of a city (Li et al. 2017a, b). Population agglomeration provides sufficient labor force for cities, which has an important impact on economic development, and also causes resource pressure and environmental pollution.
(2) Consumption level: consumption level is an important driving force of economic growth, which can even directly reflect the level of economic development (Hui et al. 2018). At the same time, people's consumption activities have impacts on the environment.
(3) Investment level: the more fixed asset investment there is, the more attractive the business environment in a region will become and the sustained and rapid economic growth will be driven (Qin et al. 2006). Investment in fixed assets has also gradually improved the ecological environment of cities, giving a strong impetus to the transformation of economic and social development to green development (Deng et al. 2019).
(4) Openness: opening up is the premise of rapid economic development, and the level of opening up is an important reflection of the regional economy's international competitiveness (Yanikkaya 2003). The research shows that expanding openness also improves the environmental quality.
(5) Level of financial resources: the level of financial resources can directly reflect the local economic development (Zhou et al. 2019a, b). Fiscal revenue is an important indicator of a region's financial resources. The more fiscal revenue a government has, the stronger its financial resources will be, and the stronger its ability will be to control environmental pollution and improve the ecological environment.
(6) Industrial structure advanced level: the more advanced the level of industrial structure, the more reasonable the allocation of resources and the better the benefits of industrial structure (Wang and Yang 2015). Industrial restructuring, transformation, and upgrading can enhance the industrial structure to a higher level, enhance the vitality of economic innovation and core competitiveness, and effectively control environmental pollution and improve the ecological environment.

Data sources

The data were collected from the *China City Statistical Yearbook*, the *Statistical Yearbook of Cities* along YRB, and the *Bulletin of National Economic and Social Development*. Given the availability of the data, we exclude Linxia, Gannan, Huangnan, Hainan, Goluo, Yushu, and Aba. Eventually, the

Table 2 The index system of influencing factors on the coupling coordination between economic development and ecological environment

Influence factor	Variable	Unit	Max	Min	Mean
Population size (X_1)	Total population at the end of the year	1,000,000 persons	10.14	0.56	3.925
Consumption level (X_2)	Total per capita consumer goods	1000 CNY	66.357	5.663	25.637
Investment level (X_3)	Total fixed asset investment per capita	1000 CNY	20.075	11.026	57.779
Openness (X_4)	Total export-import volume	100,000,000 dollars	596.3545	0.4541	45.1227
Level of financial resources (X_5)	Per capita local government revenue	100 CNY	223.027	9.787	54.145
Industrial structure advanced level (X_6)	Added value of secondary and tertiary industries /GDP	%	99.79	82.53	95.15

Source: China city statistical yearbook

sample size is 36 cities, as shown in Fig. 1. In addition, variables related to GDP, average wages, per capita disposable income of urban residents, investment in fixed assets, imports and exports, local fiscal revenue etc., were all adjusted and reduced exponentially based on 2008.

Study area

The YRB is an important energy base and heavy industry base as well as an important ecological corridor across the three regions of east and west China. The industrial structure of the YRB in 2018 was 8.2:43.1:48.7; among them, the proportion of primary industry and secondary industry proportion is higher than the national industry, and because of the YRB, such as coal, natural gas, oil, and non-ferrous metal resources are rich, that shaped the industry structure is the basic pattern of “heavy,” brings great pressure feed water resources and ecological environment, leading to social economic development on the ecological environment has higher dependence. However, the economic base and ecological environment of nine provinces in the YRB are obviously different, and the provincial data will cause a large error. Therefore, this paper chooses 36 cities along the YRB as the research objects.

The empirical result and analysis

Spatiotemporal evolution of coupling coordination between economic development and ecological environment

We first calculate coupling coordination degree of cities along YRB from 2008 to 2017. Then using natural discontinuities classification method, values can be divided into high coupling coordination, relative high coupling coordination, moderate coupling coordination, and low coupling coordination. Figure 2 presents the spatial distribution of the coupling coordination degree.

Figure 2 shows the low degree of coupling coordination in 2008. The high and the relative high coupling coordination zones were concentrated in 13 cities, such as Jinan, Zhengzhou, Hohhot, and Baotou. The moderate coupling coordination zone is concentrated in midstream and downstream of YRB, including 12 cities such as Heze, Sanmenxia, Yan’an, and Yulin. The low coupling coordination zone is distributed in 11 cities including Baiyin, Zhongwei, Wuzhong, Bayannur, Luliang, and Weinan.

In 2011, the distribution of high coupling coordination zone and relative high coupling coordination zone remained consistent with that of 2008, and the Shandong Peninsula in downstream of YRB gradually spread. The number of moderate coupling coordination zone increased in midstream of YRB, while that of low coupling coordination zones gradually decreased.

In 2014, the high coupling coordination zone and the relative high coupling coordination zone expanded in midstream, while the moderate coupling coordination zone and low coupling coordination zone further decreased.

In 2017, the high coupling coordination zone and the relative high coupling coordination zone showed an improvement trend in the whole basin, while the moderate coupling coordination zone and low coupling coordination zone were roughly the same as that in 2014.

The spatiotemporal evolution characteristics of coupling coordination degree of cities along YRB show the following characteristics: (1) the coupling coordination is increasing in general, and the whole basin is gradually improving. (2) The

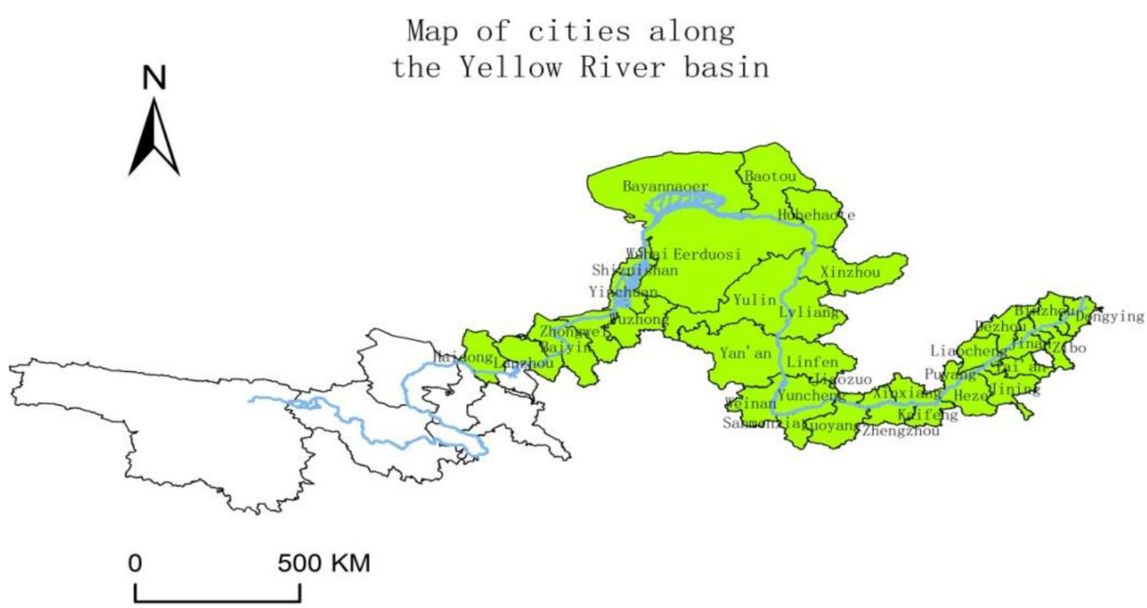

Fig. 1 Urban distribution along YRB

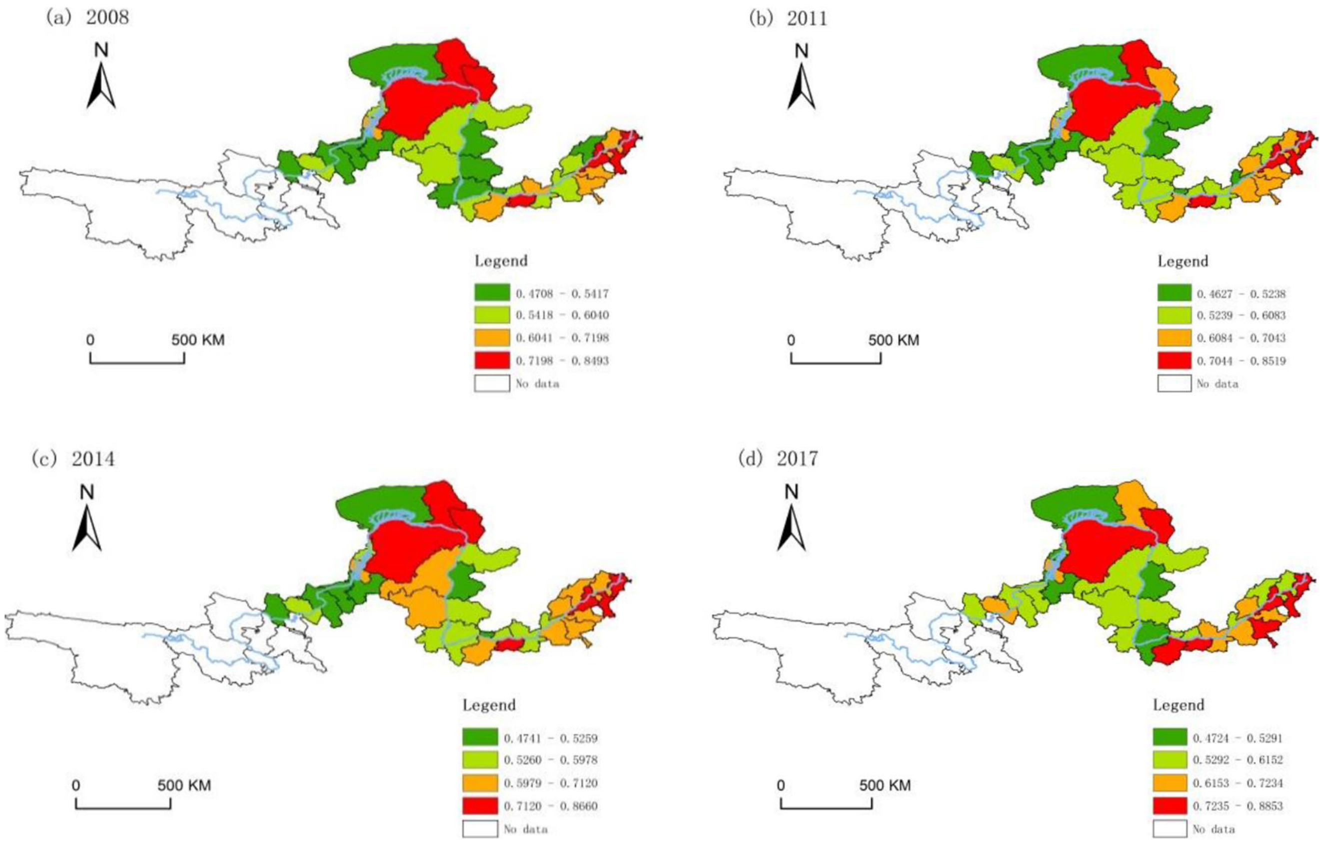

Fig. 2 The spatiotemporal evolution of the coupling coordination development between economic development and ecological environment in 2008, 2011, 2014, and 2017

high coupling coordination zone and the relative high coupling coordination zone spread from the coast to the inland. (3) Part of the moderate coupling coordination zone gradually increased to the relative high coupling coordination zone, while the number of cities in low coupling coordination zone remained almost unchanged.

Spatiotemporal correlation analysis of the coupling coordination degree between economic development and ecological environment

For further analysis of spatiotemporal evolution characteristics of cities along YRB, this paper calculates the global Moran-I's index of coupling coordination degree in 2008, 2011, 2014, and 2017. The values are 0.2432, 0.2992, 0.3197, and 0.2030, all of which pass the test under 95% confidence levels, indicating an obvious positive spatial correlation. The global spatial autocorrelation is used to judge spatial correlation of coupling coordination relationship as a whole, while it cannot identify the differentiation of spatial autocorrelation of different cities. Therefore, we introduce Getis-Ord G_i^* index, through which the whole sample is divided into four zones, named hot, secondary hot, secondary cold, and cold areas. Hence, the hotspot evolution maps of spatial pattern of coupling coordination degree are generated in Fig. 3.

From the evolution of hot spot and secondary hot spot, it was mainly distributed in Baotou, Hohhot, Ordos, Zhengzhou, Jinan, and Dongying in 2008. In 2011, Heze and Liaocheng were added to the secondary hot spot, while Hohhot and Xinxiang jumped from hot spot to the secondary hot. In 2014, the hot spots and secondary hot spots in downstream of the Yellow River gradually spread inland, and in 2017, the hot spots and secondary hot spots in midstream of the Yellow River converged.

From the evolution of cold and secondary cold regions, the cold spot in 2008 is mainly concentrated in upstream of YRB and the Loess Plateau. In 2011, Linfen and Weinan were added to the secondary cold spots. In 2014, the number of cold spots and secondary cold spots decreased on the whole, but the distribution in upstream of YRB hardly changed. In 2017, the cold spots spread northwest along midstream of YRB and the overall distribution was similar to that in 2014.

The spatiotemporal evolution characteristics of coupling coordination degree of cities along YRB show the following characteristics: (1) hot spots and cold spots have been expanded or shrunk nearby, showing some continuity in their changes from 2008 to 2017; (2) in downstream of the Yellow River, hot spots and secondary hot spots gradually spread inland; (3)

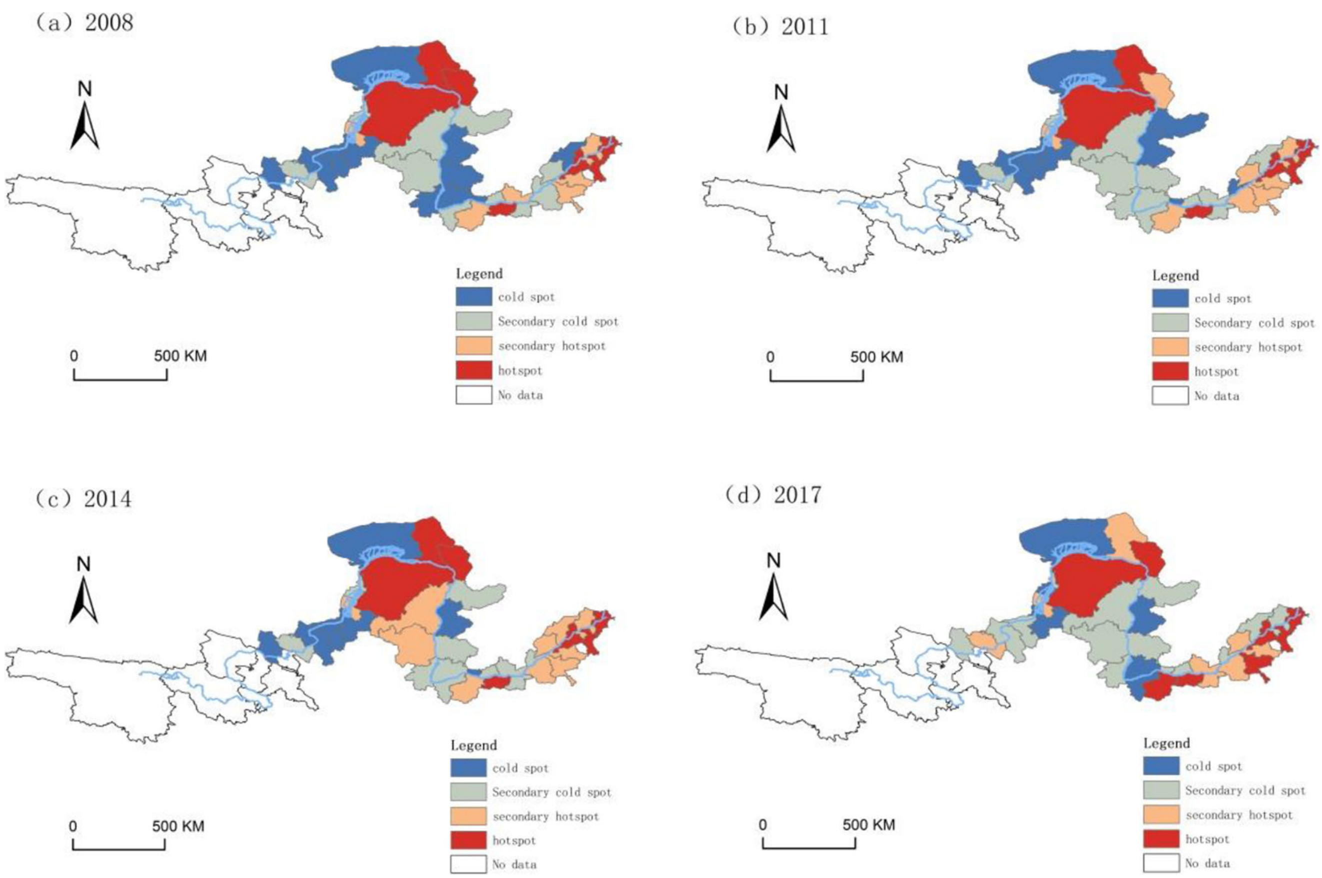

Fig. 3 Spatiotemporal evolutions of hot spots of coupling coordination degree in 2008, 2011, 2014, and 2017

the cold spots and the secondary cold spots fluctuated slightly in upstream and midstream of YRB, while remained unchanged; they converged in the downstream.

Analysis of GWR model regression results

The spatial least square model was used to conduct global regression analysis on the factors affecting coupling coordination degree: The R^2 is 0.8307 and adjusted R^2 is 0.8060. Compared with this, the R^2 and adjusted R^2 of GWR are 0.8559 and 0.8171, respectively. By comparing the two regression models, it can be seen that the GWR model fits better. From Table 3, we can clearly see the data analysis results of the GWR model and the influence factors on the coupling coordination degree are analyzed through descriptive statistics.

Empirical analysis

From the quantile regression results (Table 3), the effects of population size, consumption level, investment level, opening level, financial level, and advanced industrial structure on the coupling coordination degree are all positive at different quantile levels, and the model presents strong stability. The positive influence degree is increasing with the quantile level. Mean values reflect the average influence degree of factors on

Table 3 Results of GWR model of the coordination degree

Influence factor	Max	Min	Lower quartile	Median	Upper quartile	Mean	Standard
Population size	0.1739	0.1570	0.1644	0.1679	0.1717	0.1676	0.0046
Consumption level	0.2196	0.1851	0.1979	0.2073	0.2154	0.2063	0.0100
Investment level	0.0339	0.0303	0.0313	0.0317	0.0323	0.0318	0.0008
Openness	0.0533	0.0274	0.0305	0.0371	0.0452	0.0379	0.0080
Level of financial resources	0.1607	0.1336	0.1427	0.1482	0.1552	0.1485	0.0076
Industrial structure advanced level	0.0216	0.0134	0.0140	0.0147	0.0179	0.0161	0.0024

coupling coordination. From the mean values of GWR regression, all coefficients are positive and the order from large to small is as follows: consumption level > population size > level of financial resources > openness > investment level > industrial structure advanced level.

Spatiotemporal heterogeneity analysis of influencing factors

Combined with the analysis in the previous section, this section gradually analyzes the spatiotemporal heterogeneity of the influencing factors on coupling coordination degree one by one.

The spatiotemporal characteristics of population size on the coupling coordination degree From the spatial distribution of regression coefficient (Fig. 4a), the influence of population size on coupling coordination degree shows an increasing distribution trend from upstream, midstream to downstream of YRB, with regression coefficient distribution between 0.1570 and 0.1739. This shows that population size has positive effect on coupling coordination degree. The main reason is that the spatial distribution characteristics of the impact of population size on coupling coordination degree are related to population flow, among which Zhengzhou, Luoyang, Zibo, Dongying, and Jinan have a high level of economic development and are prone to form population agglomeration zones, which promote the growth of urban economy through knowledge and human capital. At the same time, residents with high education and income have higher requirements for living environment. This directly and indirectly improves people's awareness of environmental protection, thus having a positive impact on the coupling coordination degree. In Haidong, Lanzhou, Baiyin, and Wuzhong, backward economic development and prominent population outflow result in the reduction of urban population size. Therefore, the impact of population size on the coupling coordination degrees shows significant spatial heterogeneity.

The spatiotemporal characteristics of consumption level on the coupling coordination degree From the spatial distribution of regression coefficient (Fig. 4b), the positive influence of consumption level on the coupling coordination degree is manifested as a trend of gradual increase from west to east, with coefficient distributed between 0.1850 and 0.2196. The spatial distribution characteristics of consumption level on coupling coordination degree mainly related to the economic development status and stage. The urbanization and economy in Shandong peninsula, Zhengzhou, Luoyang, and Kaifeng, downstream of YRB, are high, which attracted a large number of labors and technical workers. Hence, agglomeration effect and scale effect are formed. Simultaneously, with the growth of consumer demand and economic growth, these cities began to pursue environmentally friendly products. Contrast to this, Haidong, Zhongwei, Yinchuan, and Bayannur, which are located in upstream of YRB, have relatively backward economy, as well as low in consumption level and utilization efficiency of resources. Their production and living have small impact on ecological environment, and thus have small impact on coupling coordination degree.

The spatiotemporal characteristics of investment level on the coupling coordination degree From the spatial distribution of regression coefficient (Fig. 4c), the impact of investment on coupling coordination is positive and the n coefficients are between − 0.0303 and 0.0338. Specifically, the high-value areas are distributed in upstream of YRB, such as Lanzhou, Haidong, Jinan, Zibo, and Jining, while low-value areas are mainly concentrated in Bayannur, Xinzhou, Luliang, and Hu-Bao-E-Yu (Hohhot, Baotou, Ordos, and parts of Yulin in Shanxi Province) city group. The main reason is that production scale and production capacity can be increased through fixed asset investment, so as to expand effective supply and accelerate economic growth. Coastal cities enjoy rapid urbanization, relatively sound infrastructure construction, and reasonable industrial structure, and high efficiency of fixed assets investment, which have a great impact on the coupling coordination. However, economic growth in Bayannur, Luliang, and Baotou is still in the extensive development mode. The efficiency of fixed assets investment is low, as well as the impact on coupling coordination degree.

The spatiotemporal characteristics of openness level on the coupling coordination degree From the spatial distribution of regression coefficient (Fig. 4d), impact of openness level on coupling coordination degree shows gradually increasing from east, central to west, and all values are positive between 0.0273 and 0.0533. The upstream of the Yellow River, represented by Haidong, Lanzhou, and Yinchuan, are most affected by the openness level, followed by the midstream of the Yellow River, represented by Hohhot, Yan'an, and Yulin. The smallest marginal impact locates in the downstream of Yellow River represented by Zhengzhou and Jinan. Currently, there is great relation between geographical distribution and openness level. Shandong Peninsula located in downstream of the Yellow River with high openness level, which is the front line of China's participation in regional cooperation in northeast Asia. Zhengzhou is an important transportation hub city in China. With high-speed railway in all directions and aviation port area, Zhengzhou provides a window of opening to the outside world for the central plains economic zone and even the central and western regions, forming a new highland in the inland areas. They have a higher openness level, and further improving the marginal impact of openness on the coordination degree. In contrast, cities in upstream of the Yellow River, such as Haidong, Zhongwei, and Shizuishan, are located in the hinterland; the

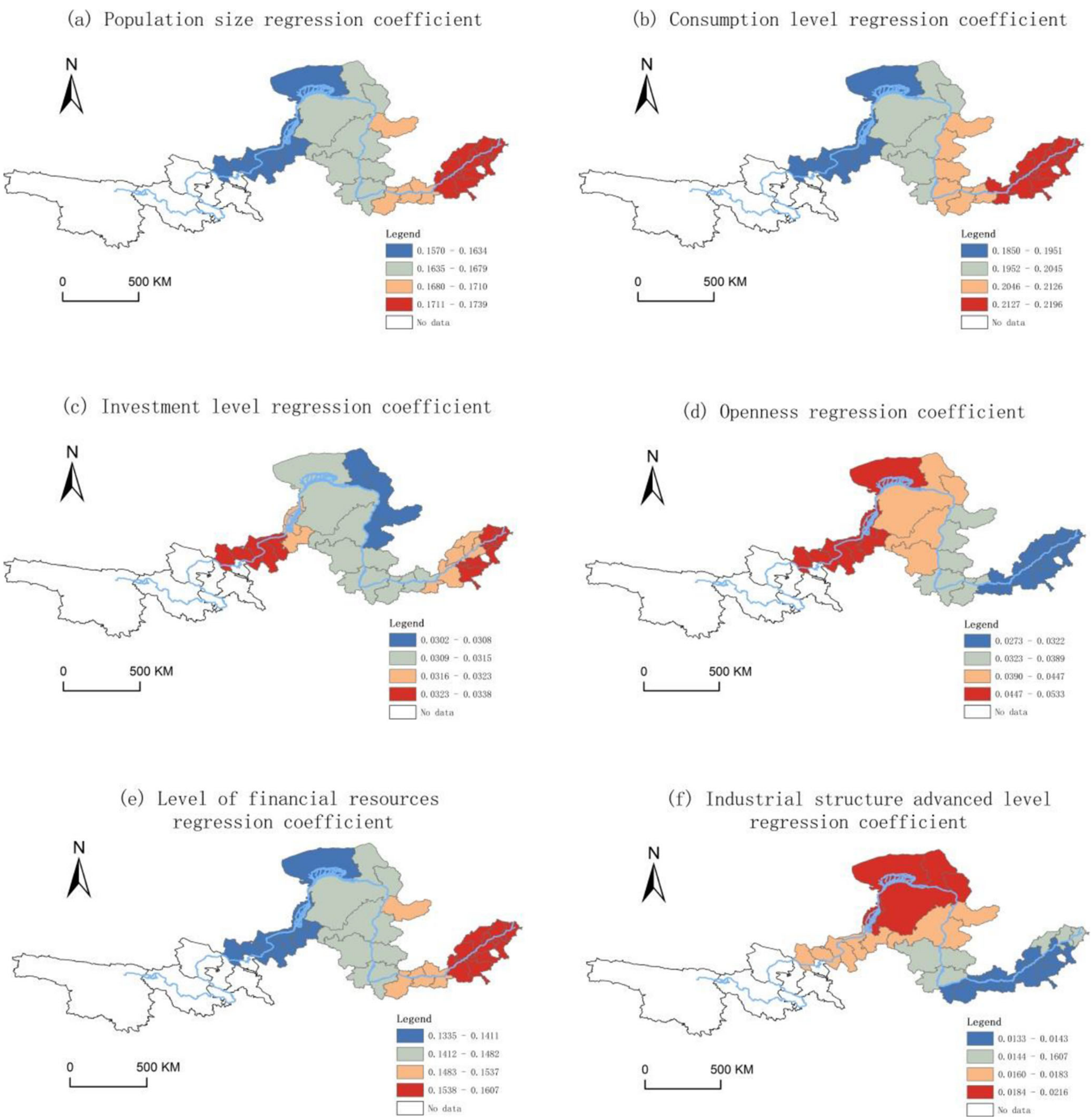

Fig. 4 The spatiotemporal distribution of regression coefficients

overall openness level is relatively low. Therefore, the influence of openness level on the coupling coordination degree presents obvious spatiotemporal heterogeneity.

The spatiotemporal characteristics of financial resources level on the coupling coordination degree From the spatial distribution of regression coefficient (Fig. 4e), there are significant differences of the influence of financial resources on coupling coordination, on the space forming spatial pattern of gradually increasing from upstream, midstream to downstream in YRB. The regression coefficient varies between 0.1335 and 0.1607. In specific, Shandong peninsula, Zhengzhou, and Kaifeng belong to the high-value zone, while low-value areas are mainly distributed in Haidong, Lanzhou, and Baiyin, midstream of YRB. The main reason is that the spatial distribution of the influence of financial resources on the coupling coordination degree is mainly related to economic development quality. Economy is the basis of finance. Jinan, Dongying, and

Zhengzhou will vigorously develop new industries, accelerate the development of new drivers, stimulate local economic vitality, and provide support and guarantee for local fiscal revenue growth. However, the industrial economy of Haidong, Zhongwei, and Yinchuan is relatively weak. The quality and efficiency of economic development need to be improved, and the investment in ecological and environmental governance is relatively less. Therefore, the financial level of latter cities has little impact on coupling coordination degree.

The spatiotemporal characteristics of industrial structure on the coupling coordination degree From the spatial distribution of regression coefficient (Fig. 4f), there is a positive correlation between high-level industrial structure and coupling coordination, with obvious regional difference, and the distribution of regression coefficient between 0.0133 and 0.0216. Cities with high-level industrial structure concentrated in Wuhai, Bayannur, Baotou, Hohhot, and Lanzhou. Among them, Bayannur and Baotou rely on local resources endowment, industrial structure is too single, and the optimization of industrial structure is beneficial to improve coupling coordination degree. Most cities in the lower reaches of the Yellow River, such as Jinan, Zibo, Zhengzhou, and Kaifeng, belong to low-value areas. The industrial system in this area is sound and complete. The adjustment of industrial structure has a small marginal impact on coupling coordination. Luliang and Yuncheng are also in the low-value area; however, too single industrial structure (almost only coal) seriously hinders the development of coupling coordination.

Conclusions and discussions

Conclusions

Based on data of 36 cities along YRB from 2008 to 2017, this paper measures the coupling coordination degree of economic development and ecological environment by constructing indicator evaluation system, and analyzes the spatiotemporal evolution characteristics. This paper further uses GWR model to decompose spatiotemporal heterogeneity of the influence factors on coupling coordination degree in cities along YRB.

First, from the time tendency, mean values of coupling coordination were 0.6161, 0.6037, 0.6259, and 0.6340 in 2008, 2011, 2014, and 2017, respectively. From the perspective of spatial distribution, high-value areas are mainly concentrated in core cities such as Hu-Bao-E-Yu city group, Zhengzhou and Jinan, while low-value areas are mainly distributed in Haidong, Baiyin, Yan'an, Linfen, and Yuncheng, forming the low-value sag of the Loess Plateau as a whole. Cities with high coupling coordination degree show a trend of expanding from downstream to upstream and inland areas of YRB.

Second, the Moran's I index values of the coupling coordination degree of urban economic development and ecological environment along the YRB were 0.2432, 0.2992, 0.3197, and 0.2030 in 2008, 2011, 2014, and 2017, respectively, which all passed the test at the level of 95% confidence, showing positive spatial autocorrelation in spatial pattern. Based on the analysis of the coupling coordination degree, the hot spots are mainly distributed in Zhengzhou, Shandong Peninsula, Hu-Bao-E-Yu city group, etc. The regional economic development level and ecological environment level are both high, and coupling coordination degree is also high. The cold spots are mainly concentrated in the Loess Plateau, where the gap is large, resulting in low coupling coordination degree.

Third, according to the regression results of the GWR model, the driving forces of the coupling coordination in cities along YRB show significant spatiotemporal heterogeneity. Population size, consumption, and fiscal level have positive impact on coupling coordination degree in downstream of YRB, while these effects are not significant in upstream. The tendency varying from upstream to downstream is increasing gradually. The investment level has a weak influence on the coupling coordination in midstream and upstream of the Yellow River, while it has a significant influence in Shandong Peninsula. The influence of openness on the coupling coordination presents a pattern of increasing gradually from east to west. The impact of industrial structure on coupling coordination degree also shows significant regional heterogeneity.

Discussions

It is of great reference value to measure and analyze spatiotemporal heterogeneity and driving mechanism of coordinated development of economy and ecological environment in YRB. From research results of this paper, urban agglomeration of Hu-Bao-E (Huhhot, Baotou, and Ordos), Shandong Peninsula, Zhengzhou, and Lanzhou belong to the region with high coupling coordination, while the cities in the Loess Plateau region, such as Yan'an, Yuncheng, Zhongwei, and Baiyin, belong to region with low coupling coordination. Due to the effects of population size, consumption level, openness, and other factors, the spatiotemporal heterogeneity of the coupling coordination degree index is relatively obvious. Efforts should be made in the following aspects in the future:

First, improve the level of population agglomeration. According to the impact of spatiotemporal variation characteristics of population size on the coupling coordination degree, we should pay attention to the positive effect of population size. Local cities should take effective measures to promote population agglomeration based on the existing conditions. Zhengzhou and Jinan with abundant population resources should make overall plans for population, economy, and society to achieve coordinated development. At the same time, optimize business environment, introduce and support high-quality enterprises, create more jobs, guide the return of talents, attract more high-tech talents, improve the population structure, and create a siphon effect of talents. Cities such as Haidong, Lanzhou, Baiyin, and Wuzhong should accelerate the process of urbanization, constantly improve the function of urban agglomeration, increase urban employment, and attract rural labor force to cities. At the same time, it is necessary to integrate existing educational resources, expand basic investment in education, speed up the training of highly skilled employees and vocational and technical workers, and cultivate more learning, compound and innovative technicians, so as to improve the quality of the population and meet the needs of industrial transformation and upgrading and green development in YRB. This series of measures is conducive to improving the coupling coordination degree of economic development and ecological environment. In addition, it is worth noting that the YRB is a concentrated distribution area of the poor population, especially the upper reaches and parts of the middle reaches, showing the characteristics of high poverty rate, deep poverty, and high poverty return rate. Therefore, it is one of the ways to improve the economic development and ecological protection of the YRB to focus on solving the problem of poor people. Within the sustainable range of the ecological environment and based on the local natural resources and production conditions, policies and resources should be targeted to households and people to give full play to their subjective initiative, effectively stimulate sustainable endogenous power, and achieve a win-win situation of ecology and poverty alleviation. Second, build a high-quality market. By improving fiscal and tax support policies conducive to promoting household consumption, improving quality and efficiency of financial services, and deepening reform of the income distribution system, we will further stimulate consumption potential, increase the size and strength of the market, and create a strong market attraction for industrial development. Among them, Jinan and Zhengzhou should comply with the trend of consumption upgrade, persistent to the market demand as the guide; rely on a complete industrial system; promote technological innovation and product innovation; cultivate and develop famous brand; create new forms, new products, new models, product upgrades, and service; and meet the increasing grow consumption demand of residents. For example, we will encourage the transformation of traditional shopping malls and old factory areas into new multi-functional and comprehensive consumer carriers; actively cultivate new consumption hotspots such as new-energy vehicles, cultural tourism, and health and old-age care; and support the development of young consumption such as the "night economy" and e-sports. At the same time, we will vigorously promote environmental products, new energy vehicles, and other green consumer products; strengthen the publicity and education of green consumption in the whole society; raise awareness of green consumption; and stimulate green production with green consumption demand. Area such as Lanzhou and Yinchuan should strengthen the infrastructure construction, expand the depth and breadth of network, establish and improve the mechanism of the consumption system, guide the enterprises' innovation, and encourage and guide the rural residents' consumption, such as traffic, communication, culture, and automobile. Further expand the consumer market, release the potential consumption capacity, and strengthen the basic driven role of consumption to economic development.

Third, improve the scale, quality, and efficiency of investment. Optimize the regional investment environment, rationally expand effective investment, constantly optimize the investment structure, and improve the quality and efficiency of investment. It is also worth noting that continuous innovation of investment methods is also an effective way to improve the quality and efficiency of investment. We will actively guide nongovernmental capital and credit funds to participate in major projects to replace old growth drivers with new ones in various forms in the YRB, and speed up the investment of funds in project construction and in areas where people's livelihood infrastructure is weak. To be specific, Zhengzhou, Luoyang, Jinan, and Zibo in downstream of YRB should expand investment in high-end manufacturing, high-tech industries, and strategic emerging industries; promote the upgrading of economic structure; accelerate the formation of a complete system (Huang et al. 2020); and support industrial ecosystem moving to the middle and high end of the global industrial chain gradually. In Baiyin, Zhongwei, Shizuishan, Bayannur, and Baotou, more investment should be made in education, health, and other areas related to people's livelihood, and efforts should be made to improve the running conditions and medical services in these areas. At the same time, as urbanization continues to accelerate, more attention should be paid to investing in a series of public services, including housing and transportation infrastructure, to gradually improve people's living conditions. In addition, in view of the rapid development of digitization, informatization, and intelligentization, the construction of digital infrastructure, information infrastructure, and intelligent infrastructure should be vigorously strengthened. We should promote the development of energy conservation and environmental protection industries in Luliang, Linfen, and Yan'an: increase investment in clean energy, ecological and environmental protection, and pollution prevention and control; transform the pattern of economic and social development; and achieve high-quality economic development.

Fourth, create conditions for openness along YRB. To strengthen the construction of YRB's internal and external opening platforms, actively align major national development strategies, and guide regional division of labor and coordinated development in YRB. According to resources endowment and industrial foundation in YRB, implement differentiation multi-level opening-up forms. First of all, internally, we should strengthen the cooperation between key regions and areas in the upper and lower reaches of the river basin, and make use of the convenience of the Yellow River Passage and general aviation to form a synergy of opening-up and break the trend of widening economic development gap. Secondly, externally speaking, we should make full use of regional advantages, especially cities along the "One Belt And One Road" line, actively integrate into the international market, deepen the economic and trade cooperation between Europe and Europe, and build the YRB into the hub of "One Belt And One Road" opening to the west. Among them, Dongying, Zibo, and Jinan should make full use of the location conditions, and cooperate with Zhengzhou and Xi'an to build sea-rail transit base, so as to build three core areas along YRB in the east, middle, and west, and form a golden channel for sea-rail intermodal transport. Zhengzhou and Luoyang should take advantage of the transportation location in the central plains, seize the opportunity of "Belt and Road Initiative," and further improve the four "new silk roads" of air, land, online, and sea, so as to form a new highland open to the outside world in the inland areas. Yinchuan, Zhongwei, and Ordos should grasp the development opportunity of "Belt and Road Initiative," rely on inland port (Ordos, Xinjuyuan) and international land port Gansu, Lanzhou) to promote all-round multi-level internal opening to the outside world, build new heights inland China opening to the outside world, and accelerate economic and ecological environment coordinated development.

Fifth, make the industrial structure greener and more advanced. Take into account the differences in resource endowments, industrial bases, and external conditions in different regions; adjust measures to local conditions; make overall plans to optimize the distribution of industries; promote green industrial development; and facilitate economic transformation and upgrading. From the perspective of the whole basin, first, accelerate the development of high-end equipment manufacturing, information technology, new energy, and new materials and other strategic emerging industries; second, we will accelerate the implementation of the "three major transformations" of green, smart, and technological development in traditional industries, and work to cut overcapacity. Third, we will vigorously develop modern service industries and efficient agriculture. Specifically speaking, in central cities such as Jinan and Qingdao, we should give play to the agglomeration effect of advanced production factors, actively use advanced technologies to transform and upgrade traditional manufacturing, and promote industrial transformation and upgrading. Accelerate the development of new models of manufacturing and service-oriented manufacturing, and strive to improve the development of the electronic information industry in equipment manufacturing. Guided by green development, innovation, and development, actively foster strategic emerging industries and promote industrial transformation and structural adjustment in YRB. In the important agricultural areas and commodity grain bases in Baotou and Wuhai, build agricultural and animal husbandry production bases with regional characteristics and competitive advantages. At the same time of promoting agricultural modernization, actively undertake the eastern industrial transfer according to local conditions. The Hu-Bao-E is geographically close to the Beijing-Tianjin-Hebei, so they should give play to the advantages of energy and resource enrichment to provide strong support for the coordinated development of the Beijing-Tianjin-Hebei region. Meanwhile, actively undertake the transfer of industrial projects in the Beijing-Tianjin-Hebei region, and develop modern manufacturing and high-end service industries. Weinan and Yuncheng should speed up the reform of the industrial structure of "only rely on coal"; give play to the advantages of resources; build a green coal industry based on the concept of circular economy, ecological industry, and clean production; improve the industrial supporting system; and constantly improve the level of industry intelligence, automation, and greening.

Authors' contributions Ke Liu (first author): conceptualization, formal analysis, project administration, funding acquisition, resources, supervision, writing–review and editing.

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Tao Shi (coauthor): formal analysis, methodology, project administration, supervision, writing–original draft.

Qian Zhou (corresponding author): project administration, funding acquisition, supervision, visualization, writing–review and editing.

Funding This work was supported by grants from National Social Science Foundation of China (16CJY045); National Natural Science Foundation of China (NSFC71974125, NSFC71661137004, NSFC71573166); Philosophy and Social Science Planning Project of Henan Province, China (2018BJJ062); and Major Projects of Philosophy and Social Science Research of Hubei Province (19ZD044).

Data availability The data is available when the reader asks for it.

Compliance with ethical standards

Competing interests The authors declare that they have no competing interests.

Ethical approval The work does not involve any hazards, such as the use of animal or human subjects' issue.

Consent to participate All of the authors of the paper have participated in certain substantive aspects of this study, and they are acknowledged or listed as contributors.

Consent to publish The paper has not been and will not be submitted simultaneously to other journals. The paper is entirely original works conducted by us without copying or plagiarism issues. The information reported in the paper is accurate according to our best knowledge. A single study do not be split up into several parts to increase the quantity of submissions and submitted to various journals or to one journal over time. We consent to publish.

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