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Research Article

Carbon Emissions, Ecological Efficiency, and the Economic Development Stage: Evidence from the Yellow River Basin

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This paper has explored the relationship between CO_2 emissions, eco-efficiency, and economic growth, which has important theoretical and practical significance for realizing high-quality development of the Yellow River Basin (YRB). Based on the data of 99 prefecture-level cities in the YRB from 2003 to 2017, this paper analyses the temporal and spatial variation and agglomeration characteristics of CO_2 emissions and eco-efficiency in the YRB. The spatial Durbin model (SDM) with fixed effects is used to test the relationship between CO_2 emissions, eco-efficiency, and economic growth in the YRB by using new structural economics theory and the EKC hypothesis. The results show that (1) the YRB is in a stage of extensive economic development with the coexistence of high CO_2 emissions and low eco-efficiency and shows a trend of transformation and upgrading to a stage of high-quality economic development; (2) CO_2 emissions and eco-efficiency are spatially heterogeneous; CO_2 emissions and eco-efficiency in the upper reaches are low, and the middle maintains relatively high eco-efficiency and high CO_2 emissions while the lower reaches have both high CO_2 emissions and low eco-efficiency; (3) the relationship between CO_2 emissions and economic growth is N-shaped, and there is an inflection point of accelerated increase (per capita GDP is 45,558 yuan). The YRB has crossed this inflection point, and CO_2 emissions are accelerating with economic development at this stage. The relationship between eco-efficiency and economic growth is U-shaped, with the inflection point of per capita GDP at 46,483 yuan. The YRB has just crossed the point, and eco-efficiency will subsequently steadily rise with economic development.

1. Introduction

The Yellow River Basin (YRB) is an important ecological barrier, economic zone, energy and chemical industry, and grain production base in China. It also plays a significant role in the national economic development pattern, accounting for 27.3 percent role in the national economic development pattern, accounting for 27.3% of the country's area, 23.3% of the country's population, and 21.8% of the total economic output, as well as 23.8% and 17.8% of the fixed assets investment of the whole society and local finance and public budget revenue, respectively, in 2018 [1]. However, the ecosystem of the YRB is fragile due to its position, the natural geographical environment, and other factors. There is a serious shortage of available water resources, and the contradiction between supply and demand is obvious. At the same time, the industrial structure dominated by energy-based raw materials and coal-dominated energy consumption results in high CO_2 emissions and severe air pollution in densely populated areas. In 2019, ecological protection and high-quality development of the YRB became a major national strategy. Therefore, how to improve the quality of economic development and eco-efficiency, reduce CO_2 emissions, and achieve a win-win situation of economic development and environmental protection under the constraints of resources and the environment is the most important matter for the YRB, which has great meaning for realizing the high-quality development of the whole basin.

A wide number of studies have examined the total amount [2, 3], footprint [4, 5], intensity [6], and performance [7] of CO_2 emissions from various perspectives and geographical scales, revealing the evolutionary characteristics and drivers of the spatial and temporal patterns of CO_2 emissions [8–10]. The main views of academics are that economic growth promotes the increase of CO_2 emissions in the long and short term [10] and that the energy consumption structure dominated by fossil energy and the industrial structure dominated by secondary industries are the main reasons [11, 12]. The literature demonstrates that improving the energy consumption structure [13], enhancing the efficiency of energy use [14], optimizing the industrial structure [15], and improving the production technology of manufacturing industries [16] can all effectively reduce CO_2 emissions. Many studies have confirmed the hypothesis of the Environmental Kuznets Curve (EKC), which suggests that the relationship between CO_2 emissions and economic growth is inverted U-shaped [17, 18], but some scholars have found that the relationship between CO_2 emissions and economic development is not necessarily the standard, inverted U-shaped, but U-shaped [19] or N-shaped [20], the shape of the curve is dependent on the economic development state, industrial structure, and energy consumption structure of the specific region.

Eco-efficiency is a quantitative indicator that integrates integrated economic and environmental indicators. By incorporating resource consumption and pollutant emissions into the evaluation system, it effectively evaluates whether a country (region) can achieve sustainable development, that is, to ensure economic growth while minimizing resource consumption and pollutant emissions [21–23]. According to the theory of coordinated development and sustainable development, some academics have built an evaluation system for urban eco-efficiency based on factors like urbanization level, economic development, social welfare, resource utilization, energy consumption, pollutant emission, industrial structure, and fiscal decentralization [5, 24, 25]. The evaluation methods of urban eco-efficiency mainly include the input-output model [26], the grey system model [27], the coupling coordination model [28], and data envelopment analysis (DEA) [29]. Some scholars discussed the eco-efficiency of cities according to their geographical location, population size, and urban category [30, 31]. Other scholars have also explored the relationship between economic development and eco-efficiency [32], arguing that the relationship between economic development and eco-efficiency was not a simple linear relationship and that the specific patterns are influenced by the industrial structure and energy consumption structure of cities [33].

The contribution of this paper is mainly reflected in the following three points: (1) This paper creatively constructs the theoretical framework between CO_2 emissions, eco-efficiency and economic development, and theoretically analyses the relationship between the three from the perspective of structural economics, which expands the research perspective in related fields to meet the current “low-carbon” and “high-quality” economic development requirements; (2) We use the spatial analysis model to analyze the relationship between the three, so as to avoid the neglect of spatial heterogeneity in the previous literature, which is a useful supplement to the empirical research field of sustainable development in China; (3) This paper fills the gap in the existing literature about the relationship between fitting the three, and the conclusions of this paper can provide empirical support and policy recommendations for China to determine the current stage of the YRB and formulate targeted policies in the future.

The rest of this paper is organized as follows. The theoretical model and hypotheses are presented in Section 2. Section 3 describes the empirical analysis method, and Section 4 presents the results and discussion. The conclusions and policy implications are discussed in Section 5.

2. Theoretical Model

According to the new structural economics theory, the external performance of economic development is the improvement of the per capita income level, and the internal essence is the introduction of new technologies and the rise of the capital-labour ratio. Industrial upgrading reflects the continuous transfer of production factors from labor- (or natural resources) intensive industries to capital-intensive industries and further upgrading to technology-intensive industries [34–36]. For a certain stage of economic development, given a series of endowments, such as natural resources, labor force, human capital, material capital, and the corresponding endowment structure, the industrial structure is endogenously determined by the factor endowment structure of that stage. Therefore, different stages of economic development have different factor endowment structures, and then the different optimal industrial structure levels are determined [35].

In the primary stage of economic development, there is usually a factor endowment structure in which labor or natural resources are relatively abundant, but capital is relatively scarce, and production is mostly concentrated in labor or resource-intensive industries such as agriculture, animal husbandry, fishery, and mining. At this stage, the consumption of fossil energy is relatively small, and the industrialization level is low, so the emissions of CO_2 and major pollutants are relatively small, and the levels of economic development and eco-efficiency are relatively low.

In the extensive development stage, with the gradual increase in the capital-labor ratio, the factor endowment and its structure also change. Enterprises will produce more capital-intensive goods to replace labor-intensive goods, and the industrial structure has completed the process of upgrading from labor-intensive or resource-intensive industries to capital-intensive industries. At this stage, the level of technology has improved, but the focus of industrial development falls on basic industrial sectors with high energy consumption, high pollution, and high emissions, such as the petrochemical industry, iron and steel, and nonferrous metals. The massive consumption of fossil energy has led to a substantial increase in CO_2 and industrial “three wastes” emissions, and eco-efficiency is further

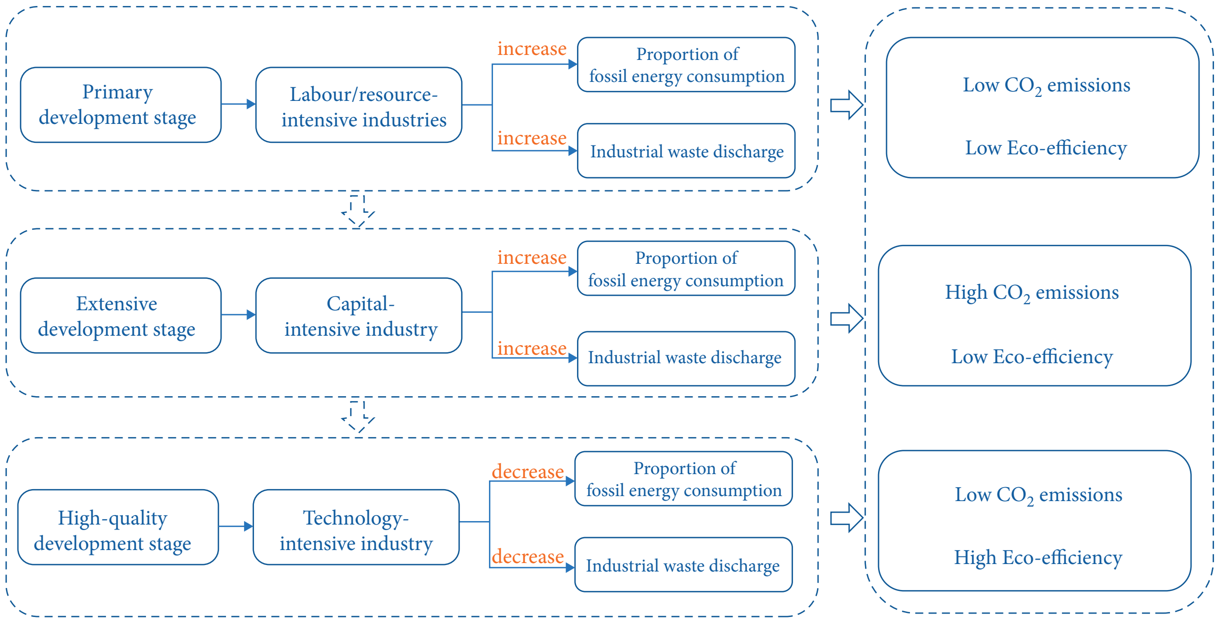

FIGURE 1: Economic development, CO_2 emissions, and eco-efficiency: a framework based on new structural economics.

reduced due to the restriction of energy consumption and environmental pollution.

In the stage of high-quality development, with the continuous development of enterprises and industries, enterprises pay more attention to independent research and the development of new products and technologies, further change the factor endowment structure, and change the industrial structure characteristics to technology-intensive industries. Because of their high technical level, these industries are mostly environmentally friendly. Therefore, industrial energy consumption and emissions of major pollutants can be effectively controlled at this stage, CO_2 emissions are gradually decreasing, eco-efficiency is gradually increasing, and economic development is moving towards a high-quality development stage driven by innovation (Figure 1).

The relationship between CO_2 emissions, eco-efficiency, and economic growth is not simply linear, but its specific shape is influenced by the resource endowment structure, industrial structure, and energy consumption structure at different stages of economic development. The proportion of capital and labor-intensive industries in the YRB is relatively high, while the proportion of technology-intensive industries is relatively low [37, 38]. The economic development stage of the YRB is still in the extensive development stage, but there is a tendency to transform and upgrade to the stage of high-quality development [39]. Based on the characteristic of the industrial structure and economic development model in the YRB, this paper puts forward the following assumptions:

*H*1: The change trends of CO_2 emissions and eco-efficiency in the YRB are opposite, and there is spatial heterogeneity.

*H*2: The relationship between CO_2 emissions and economic growth in the YRB is N-shaped.

*H*3: The relationship between eco-efficiency and economic growth in the YRB is U-shaped.

3. Methods and Materials

3.1. Eco-Efficiency

3.1.1. Eco-Efficiency Index System. Eco-efficiency requires cities to generate as much economic output as possible with minimal resource consumption and environmental costs to achieve sustainable development. Referring to the existing literature [5, 23, 25, 30], this paper constructs the evaluation system of eco-efficiency from two dimensions: input and output. Inputs are divided into four dimensions: capital, labor, technology, and resource. To measure whether the city can achieve resource conservation in the development process, energy is included as a resource factor in the input index. Outputs are divided into expected outputs and nonexpected outputs. Expected outputs are constructed from three perspectives: economic benefits, social benefits, and environmental benefits; unexpected outputs are industrial CO_2 emissions, industrial wastewater emissions, and industrial smoke (dust) emissions. The description of the variables is shown in Table 1.

3.1.2. Measurement of Eco-efficiency. This paper adopts the super-efficient SBM model to measure eco-efficiency. The super-efficient SBM model was proposed by Tone based on the traditional DEA model, which incorporates nonradial, nonangular slack Tone also added nonradial, nonangular relaxation variables to the objective function, thus solving the problem of equiproportional increase and decrease of inputs and outputs in the traditional DEA model, so that its economic implication is profit maximization instead of efficiency proportional maximization [40]. Tone also added nondesired outputs to the SBM model so that the model can better fit the role of negative externalities in constraining economic

Table 1: Eco-efficiency evaluation indicators.

Target layer	First-level indicators	Second-level indicators	Index definition	Unit	Mean	Standard deviation	Minimum value	Maximum value
Input	Capital elements	Fixed capital stock	Total social investment in fixed assets	10 million yuan	8648.62	10743.22	212.43	94042.40
	Labor factor	Number of employees per unit	Number of employees at the end of the year, number of employees in the private sector	Thousands	670.24	771.20	55.83	8684.63
	Technical elements	Patent authorization amount	Number of patent applications authorized by various places	Pcs	1920.39	5998.96	3.00	95632.00
	Resource elements	Land input	Urban built-up area	Km^2	88.46	142.58	1.00	4129.00
		Energy input	Electricity consumption of the whole society	Million kWh	6056.42	7796.48	80.55	103539.25
Output	Expected output	Economic benefits	Gross domestic product (GDP)	Billion yuan	116.08	141.49	3.18	1388.94
		Social efficiency	Average wages of employees and total retail sales of social consumer goods	Yuan	33095.92	17628.83	4958.00	137085.58
		Environmental benefit	Green space coverage rate	%	34.36	9.67	0.36	95.25
	Unexpected output	Environmental pollution	Sulfur dioxide emissions	tons	63721.71	52244.29	628.00	337164.00
			Industrial smoke emissions	tons	40313.00	183113.76	450.00	5168812.00
			Wastewater discharge	10000 tons	5349.24	5628.51	99.00	53421.00

development and can effectively analyze the impact of pollutant emissions, ecological damage, and other "bad outputs" in economic activities on economic development [41]. When using the super-efficiency SBM model to measure efficiency, the relevant variables need to be defined. It is assumed that there are N decision-making units in the YRB, namely DMU_j ($j = 1, 2, \ldots, n$). Each decision unit contains I input vectors, S desired output vectors, and Q nondesired output vectors, and the decision unit is constructed as a super-efficient SBM model based on nondesired outputs as follows:

$$\begin{cases} \min \rho = \dfrac{1}{m}\displaystyle\sum_{i=1}^{m}\left(\dfrac{\overline{x}}{x_{ik}}\right)\dfrac{1}{r_1 + r_2}\left(\dfrac{\sum_{s=1}^{r_1}\overline{y^d}}{y_{sk}^{d}} + \dfrac{\sum_{q=1}^{r_2}\overline{y^u}}{y_{qk}^{u}}\right) \\ \overline{x} \geq \displaystyle\sum_{j=1,\neq k}^{n} x_{ij}\lambda_j; \overline{y^d} \leq \sum_{j=1,\neq k}^{n} y_{sj}^{d}\lambda_j; \overline{y^d} \geq \sum_{j=1,\neq k}^{n} y_{qj}^{d}\lambda_j \\ \overline{x} \geq x_k; \overline{y^d} \leq y_k^d; \lambda_j \geq 0; i = 1, 2 \cdots m; \\ j = 1, 2, \cdots n; s = 1, 2, \cdots r_1; q = 1, 2, \cdots, r_2, \end{cases} \tag{1}$$

where, among N DMUs, each corresponds to input M, the expected output r_1 and unexpected output r_2; x, y^d, and y^u are elements in the matrix of the corresponding input, expected output, and unexpected output; ρ is the efficiency value.

3.2. Spatial Correlation Model. In this paper, the Moran's I of CO_2 emissions and eco-efficiency are tested based on a distance-based weight matrix, and the formula is as follows:

$$\text{Moran's I} = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\left(X_i - \overline{X}\right)\left(X_j - \overline{X}\right)}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\left(X_i - \overline{X}^2\right)}. \tag{2}$$

A Moran's I greater than 0 indicates a positive correlation between the measured indices, less than 0 indicates a negative correlation, and close to 0 indicates that there is no spatial correlation between the measured indices.

3.3. Spatial Econometric Model. In this paper, the Hausman test, LM test, and LR test are adopted to determine the specific form of the spatial econometric model (Table 2). According to the results of the Hausman test, the fixed effects model is selected. According to the LM test results, the model has the characteristics of both spatial lag and spatial error. Comprehensive LR test results show that neither degenerates the spatial Durbin model (SDM) into a spatial lag model (SLM) or a spatial error model (SEM). Therefore, we use the spatial Durbin model (SDM) with fixed effects for the empirical analysis of spatial measurements. The specific use of individual fixed effects, time fixed effects, or two-way fixed effects depends on the goodness of fit of the regression

Table 2: Spatial measurement model selection test.

	CO_2 emissions		Eco-efficiency	
	Statistic	P Value	Statistic	P Value
Hausman test	139.070	0.001	52.150	0.001
LM layer	4427.625	0.001	126.903	0.001
LR-LM layer	2500.029	0.001	42.072	0.001
LM-error	2078.957	0.001	160.626	0.001
LR-LM-error	151.361	0.001	34.660	0.001
LR-spatial lag	153.88	0.001	59.75	0.001
LR-spatial error	230.68	0.001	58.35	0.001

results. Combined with the hypothesis of the EKC curve and the corresponding theoretical analysis, the quadratic term and cubic term of GDP per capita are included in the regression model. If the cubic term is not significant, the cubic term is removed for regression again. The basic model is set as follows:

$$\begin{aligned}\ln CO_{2it} = {} & \beta_0 + \beta_1 lnPy_{it} + \beta_2 (lnPy_{it})^2 + \beta_3 (lnPy_{it})^3 + \beta_4 X_{it} + \rho W \ln CO_{2it} + \theta_1 W lnPy_{it} + \theta_2 W (lnPy_{it})^2 \\ & + \theta_3 W (lnPy_{it})^3 + \theta_4 W X_{it} + u_i + \gamma_t + \varepsilon_{it},\end{aligned} \tag{3}$$

$$\begin{aligned}\ln Score_{it} = {} & \beta_0 + \beta_1 lnPy_{it} + \beta_2 (lnPy_{it})^2 + \beta_3 (lnPy_{it})^3 + \beta_4 X_{it} + \rho W \ln Score_{it} + \theta_1 W lnPy_{it} + \theta_2 W (lnPy_{it})^2 \\ & + \theta_3 W (lnPy_{it})^3 + \theta_4 W X_{it} + u_i + \gamma_t + \varepsilon_{it},\end{aligned} \tag{4}$$

where i represents the municipal section unit, t represents the time, CO_{2it} is CO_2 emissions, Score is the eco-efficiency value, Py_{it} is GDP per capita, X_{it} is control variable, u_i stands for regional fixed effects, and ε_{it} is random error term. W is the spatial weight matrix. This paper selects the commonly used distance-based weight matrix, which is expressed by the reciprocal of the square term of the distance between centroid points in each city (d_{ij}), namely:

$$W = \begin{cases} \dfrac{1}{d_{ij}^2}, i \neq j, \\ 0, i = j. \end{cases} \tag{5}$$

3.4. Variables and Data Sources. The research scope of this paper covers 9 provinces in the YRB, including Sichuan, Qinghai, Gansu, Ningxia, and Inner Mongolia in the upper reaches, Shanxi and Shaanxi in the middle reaches, and Henan and Shandong in the lower reaches, totaling 99 cities. Due to missing data, areas excluded are Aba Tibetan and Qiang Autonomous Prefecture, Ganzi Tibetan Autonomous Prefecture, Liangshan Yi Autonomous Prefecture, Haidong City, Haibei Tibetan Autonomous Prefecture, Huangnan Tibetan Autonomous Prefecture, Hainan Tibetan Autonomous Prefecture, Guoluo Tibetan Autonomous Prefecture, Yushu Tibetan Autonomous Prefecture, Haixi Mongolian and Tibetan Autonomous Prefecture, Linxia Hui Autonomous Prefecture, Gannan Tibetan Autonomous Prefecture, Xing 'an League and Xilingol Autonomous Prefecture, and Alexa League.

In this paper, CO_2 emissions and eco-efficiency values are used as the explained variables, and eco-efficiency is calculated based on the SBM model. CO_2 emissions data come from the China Carbon Accounting Database (CEAD) (https://www.ceads.net/data/county/), which is inversed by the night light data of DMSP/OLS and NPP/VIIRS provided by the National Geophysical Earth Data Center (NGDC) [42]. These data have the advantages of a long-time span and wide geographical coverage.

We take GDP per capita as the core explanatory variable. Control variables include the following:

(1) Foreign direct investment (FDI) reflects the development level of the foreign capital economy in various places by the ratio of the actual amount of foreign capital used each year to the regional output value. The impact of the foreign capital economy on the environment is uncertain, and there are two diametrically opposite views. One view is that the introduction of foreign capital will bring more advanced energy saving and emissions reduction technologies. On the other hand, foreign businessmen often transfer highly polluting industries to countries with weak environmental regulations, which will lead to pollution.

(2) Educational investment (EDU) represents the intensity of urban education investment by the ratio of government education expenditure to the regional gross output value, and the level of educational investment determines the educational level of citizens. A high level of education helps raise citizens' concerns about the environmental situation, thus forcing the government to take more stringent environmental supervision measures.

(3) Industrial structure (INDUS) is expressed by the proportion of the added value of the secondary industry to urban GDP. Because the secondary industry contains many resource-intensive and environment-intensive industries, correspondingly,

Table 3: Descriptive statistics.

Variable name	Symbol	Sample number	Mean value	Standard deviation	Minimum value	Maximum value
CO_2 emissions (million tons)	CO_2	1485	24.633	18.920	1.633	108.480
Eco-efficiency	EE	1485	0.823	0.316	0.038	2.041
Per capita GDP (ten thousand yuan)	PCGDP	1485	3.100	2.603	0.189	21.549
Foreign direct investment	FDI	1485	0.026	0.026	0.000	8.302
Input in education	EDU	1485	0.033	0.023	0.000	0.0252
Industrial structure	INDUS	1485	0.499	0.117	0.0975	0.8488
Population density (person/Km^2)	POP	1485	408.740	384.477	4.700	5935
Energy consumption structure	ENE	1485	0.789	0.104	0.489	0.931

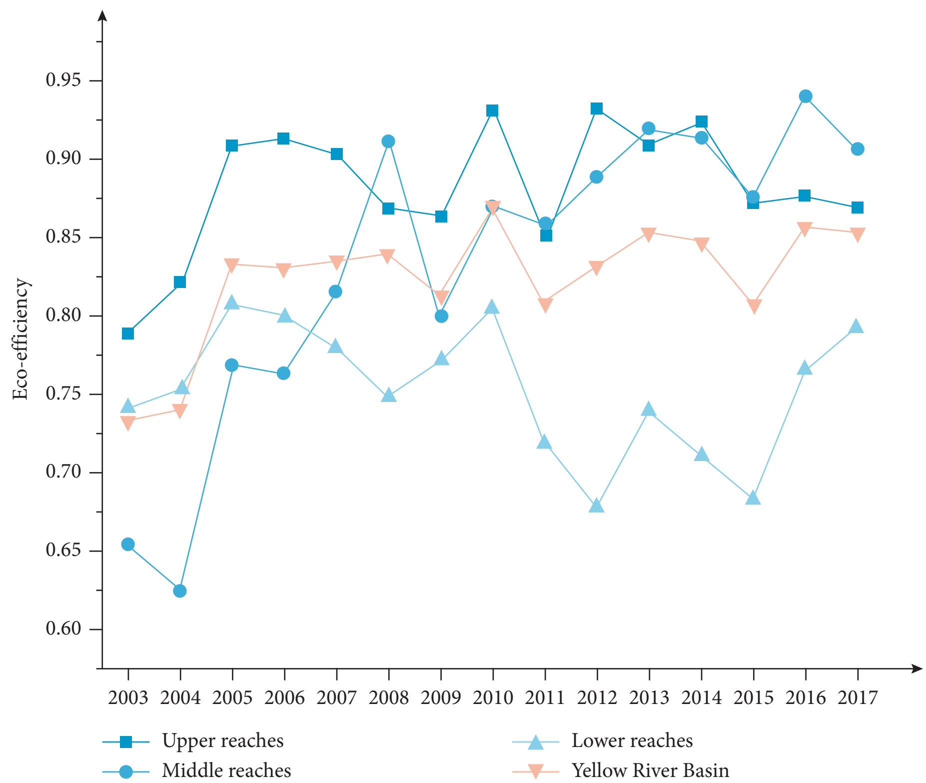

Figure 2: Evolution trend of eco-efficiency in the YRB from 2003 to 2017.

the proportion of coal consumption is higher, and the discharge of industrial pollutants is also higher.

(4) Population density (POP) directly affects the scale of economic activity and energy demand, thus affecting energy utilization and the CO_2 emissions level.

(5) The energy consumption structure (ENE) is expressed by the ratio of coal consumption to all energy consumption. Cities with a higher coal consumption share will have a higher economic growth rate and possibly more serious environmental pollution.

Socioeconomic variable data mainly come from the China Urban Statistical Yearbook, China Energy Statistical Yearbook, provincial statistical yearbooks, and statistical yearbooks of various prefecture-level cities from 2003 to 2017. Some missing data are supplemented by the geometric growth rate method and mean value method. To reduce the heteroscedasticity and eliminate the dimensional influence of variables, all variables in this paper are normalized by using the natural logarithm. Table 3 shows the basic statistics of each variable.

4. Results and Discussion

4.1. Eco-Efficiency and CO_2 Emissions Change Trend Analysis. The average change trends of urban eco-efficiency in the upper, middle, and lower reaches of the YRB are shown in Figure 2. Overall, the level of urban eco-efficiency in the YRB showed a trend of slow increase. The eco-efficiency of the whole basin began to fluctuate and decrease after reaching the peak value of 0.85 in 2010 and was in a state of production inefficiency during the whole inspection period (2003–2017). Economic development was still in the extensive development stage. There was obvious heterogeneity of eco-efficiency among regions, and the level of eco-efficiency in the middle reaches was always higher than that in the upper and lower reaches. From the evolution trend, the

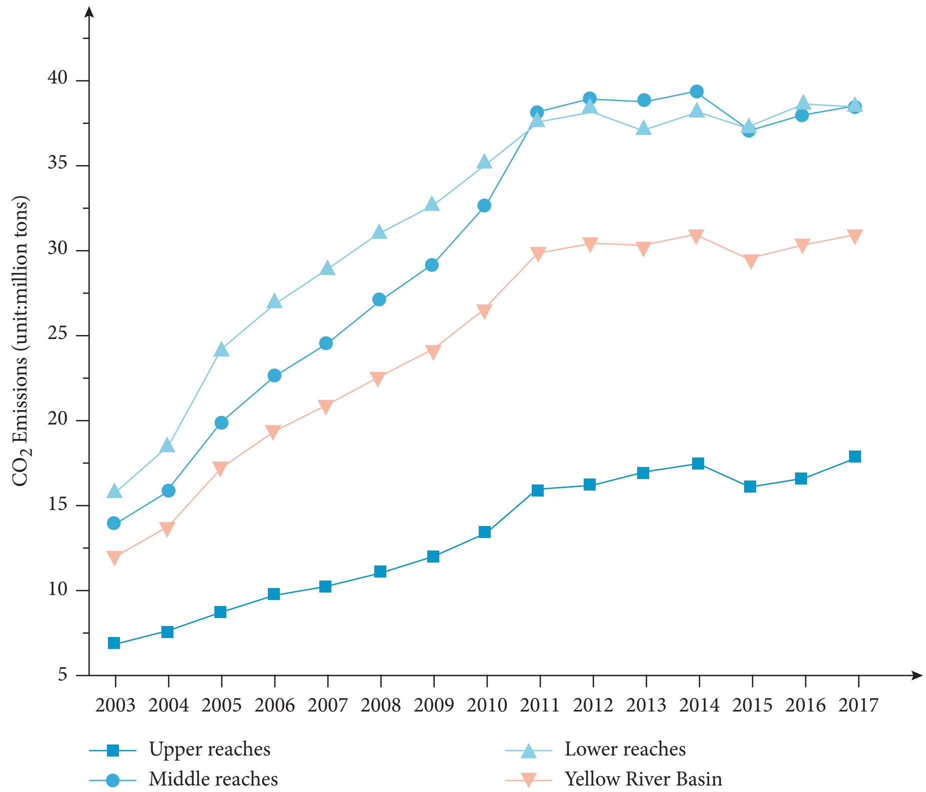

FIGURE 3: Evolution trend of CO_2 emissions in the YRB from 2003 to 2017.

eco-efficiency of the middle and lower reaches fluctuated between 0.6 and 0.85, and the eco-efficiency of the middle reaches fluctuated between 0.85 and 0.95 after rising to 0.9 in 2008. Since 2010, the eco-efficiency of both upper and lower reaches has clearly declined, and the lower reaches have been at the lowest level in the whole basin for five years from 2010 to 2015 and have gradually increased since 2015.

Figure 3 shows the trend of CO_2 emissions of cities in the upper, middle, and lower reaches of the YRB. Overall, CO_2 emissions in the YRB are on the rise. Before 2011, the CO_2 emissions in the YRB increased rapidly, and the growth rate gradually slowed after 2011. Regionally, the overall CO_2 emissions in the upper reaches are low, which is lower than the average level of the whole basin during the whole inspection period. Generally, the emissions in the middle and lower reaches are much higher than the average. Before 2011, the CO_2 emissions in the lower reaches were slightly higher than those in the middle reaches. After 2011, the CO_2 emissions in the two regions were basically the same. The regional differences in CO_2 emissions in the YRB are mainly determined by the resource endowment, industrial structure, and energy consumption structure of each region.

4.2. Spatial Coupling Analysis of Eco-Efficiency and CO_2 Emissions. In this paper, we use ArcGIS 10.2 to spatially couple the eco-efficiency and CO_2 emissions of 99 cities in the YRB in 2003, 2007, 2012, and 2017, as shown in Figure 4.

The eco-efficiency of the YRB fluctuated upwards from 2003 to 2012, represented by cities such as Erdos, Longnan, Dazhou, Nanyang, and Linfen. From 2012 to 2017, eco-efficiency in the YRB changed downward as cities like Bayannur, Xinzhou, Yangquan, and Guyuan went from being more efficient to be less efficient. As CO_2 emissions increased in the middle and lower reaches of the YRB, small initial spatial differences between cities began to emerge gradually. As a result, CO_2 emissions showed spatial characteristics of low in the west and high in the east, with the largest increases in CO_2 emissions occurring in cities like Hohhot, Erdos, Yulin, Jinan, Taiyuan, Luliang, and Linyi.

The YRB's spatial distribution of eco-efficiency and CO_2 emissions demonstrates two trends: first, eco-efficiency is on the decline from west to east, and the trend of CO_2 emissions is gradually intensifying from west to east. Second, during the study period, CO_2 emissions increased to high levels and then stabilized, whereas the eco-efficiency of the YRB went through two stages of large increase and then volatility. With Ningxia in the upper reaches, Shanxi and Inner Mongolia in the middle reaches, Shandong and Henan provinces in the lower reaches, and Ningxia province in the upper reaches, the YRB is a significant energy reserve base in China. CO_2 emissions and eco-spatial efficiency's evolution: The YRB's heavy, homogenous industrial structure and careless energy economy are objectively reflected in the spatial evolution of eco-efficiency and CO_2 emissions, which has increased CO_2 emissions and had a detrimental effect on the ecological environment.

In summary, the trend and spatial distribution characteristics of CO_2 emissions and eco-efficiency in the YRB verify hypothesis 1; that is, the trends of CO_2 emissions and eco-efficiency in the YRB are opposite, and there is a large spatial difference. Specifically, the eco-efficiency and CO_2

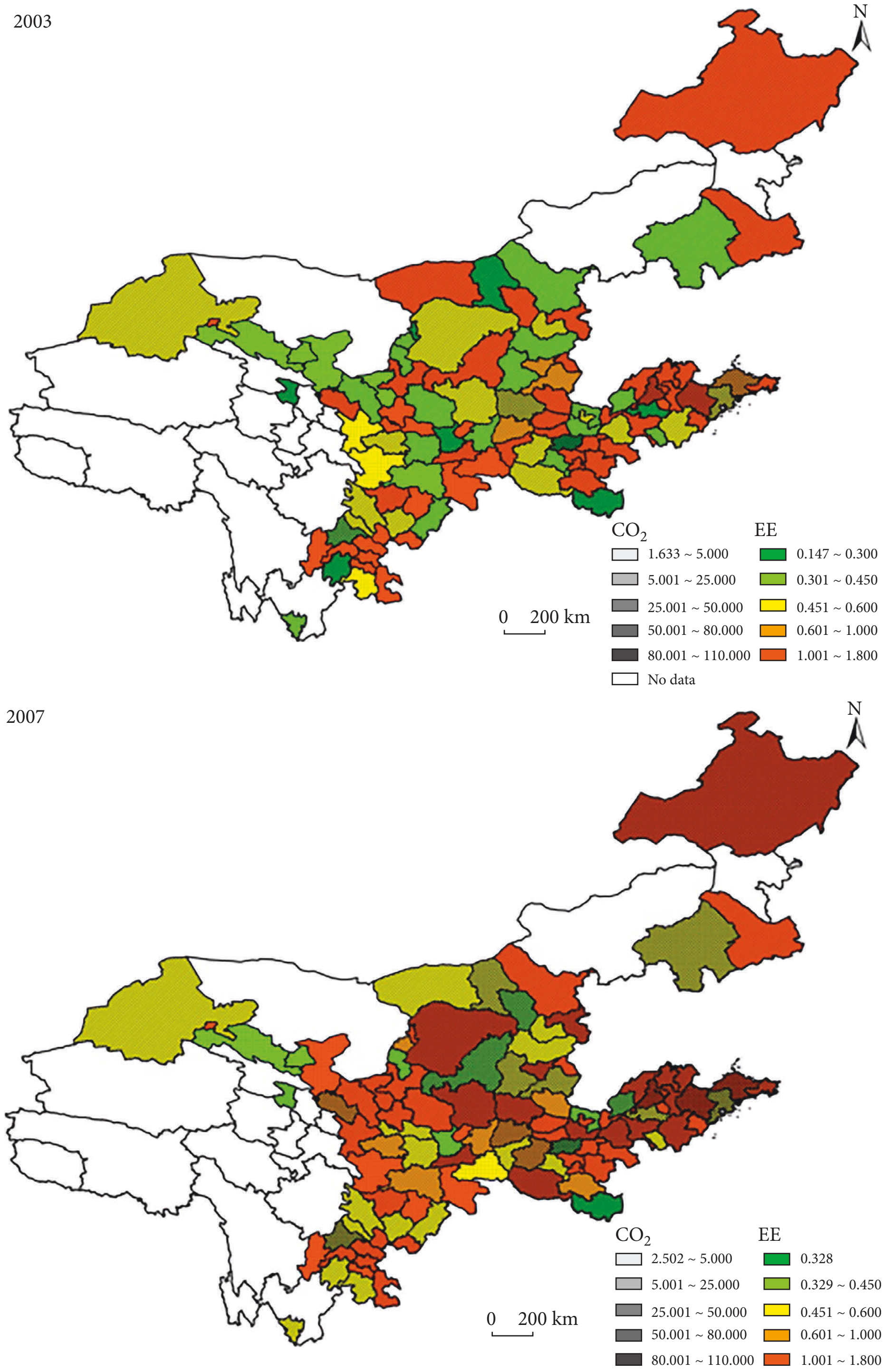

Figure 4: Continued.

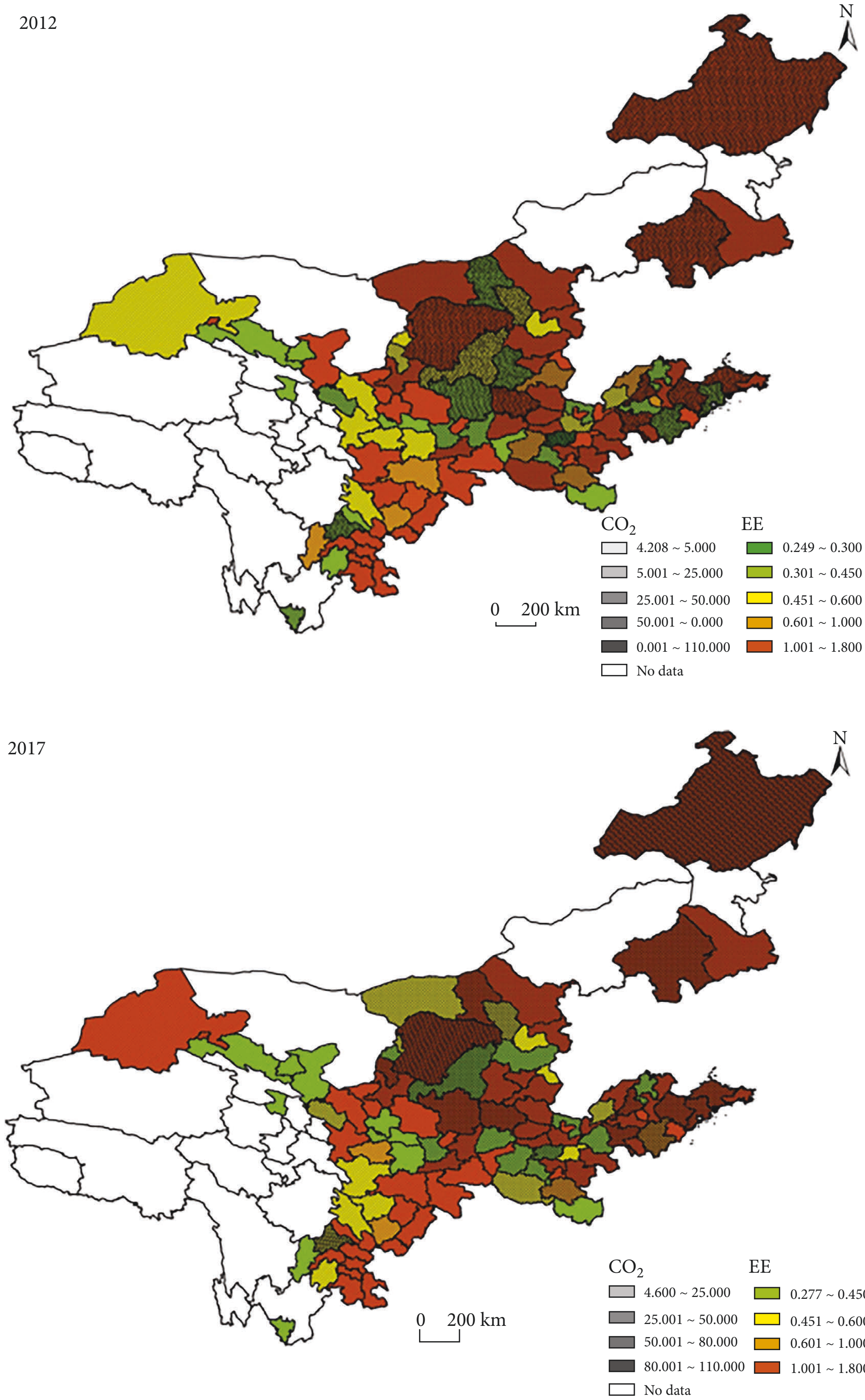

Figure 4: Spatial analysis of CO_2 emissions and eco-efficiency in the YRB.

emissions in the upper reaches are low, which is caused by poor resource endowment and a low level of economic development in the upstream region. The eco-efficiency and CO_2 emissions in the middle reaches are at the highest level of the whole basin, while the eco-efficiency in the lower reaches is low, and the CO_2 emissions are high. The reason for this difference is that the core industries in the middle and lower reaches are different. The middle reaches are the energy bases for coal and natural gas exploitation in China, while the lower reaches are the locations of most equipment

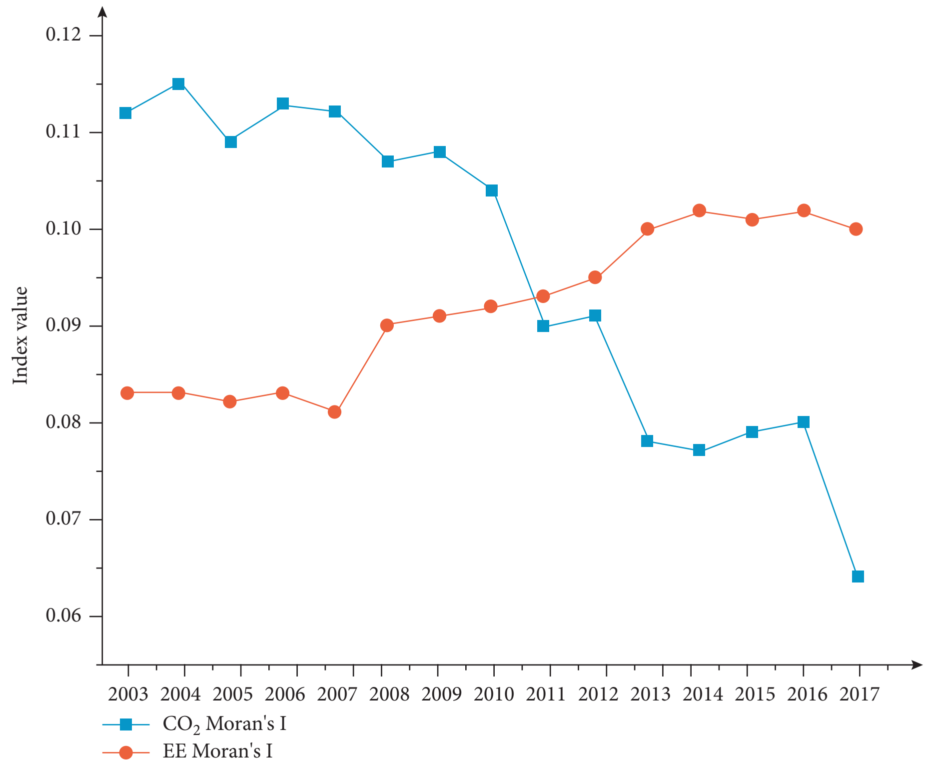

Figure 5: Moran'I of CO_2 and eco-efficiency.

manufacturing industries. Therefore, compared with the middle reaches, the discharge of "three wastes" in the lower reaches is higher, and correspondingly, the eco-efficiency is lower. It is worth noting that even in the middle reaches with the highest eco-efficiency, the eco-efficiency value is still lower than 1; that is, the YRB is still in the stage of production inefficiency during the inspection period.

4.3. Spatial Correlation Test. The global Moran index of CO_2 and eco-efficiency from 2003 to 2017 is drawn as shown in Figure 5. Moran index of CO_2 emissions and eco-efficiency are significantly higher than 0 at the 1% level. This shows that there is a positive spatial autocorrelation between CO_2 emissions and eco-efficiency.

4.4. Results

4.4.1. Estimation Results. In this paper, the spatial Durbin model with one-way fixed effects is used for econometric regression. After comparing the goodness of fit of the models, the spatial Durbin model with individual fixed effects is finally selected to regress CO_2 on economic development, and the spatial Durbin model with time fixed effects is selected to regress eco-efficiency on economic development. The results show that the cubic term of per capita GDP in the eco-efficiency model is not significant, and it is removed for regression. Table 4 shows the final regression results. Model (1) shows the regression results of CO_2 emissions and model (2) shows the regression results of urban eco-efficiency.

The regression results show that the relationship between CO_2 emissions and per capita GDP in the YRB is N-shaped (Figure 6(a)), and there is no inflection point of a declining trend but an inflection point of accelerating growth (45,558 yuan), which verifies hypothesis 2. When the per capita GDP is less than 45,558 yuan, CO_2 emissions will slow down with economic growth. When GDP per capita exceeds 45,558 yuan, CO_2 emissions will increase rapidly with economic development. Limited by the industrial structure and energy consumption structure of the YRB, the relationship between CO_2 emissions and per capita GDP in the YRB during the investigation period is not inverted and U-shaped, as assumed by the traditional EKC curve, but with the development of the economy, CO_2 emissions continue to rise. In 2017, the average per capita GDP in the YRB was 51,864 yuan, which means that the YRB has crossed the accelerating inflection point and entered a stage where CO_2 emissions are accelerating with economic development, and interrupting the trend of continuous growth of CO_2 emissions in the YRB in line with economic development, the YRB should focus on developing technology-intensive industries with low energy consumption and low emissions while improving the energy use efficiency of its traditional advantageous industries. Therefore, how to control the accelerated growth of CO_2 emissions and achieve regional energy conservation and emissions reduction will be the focus of the work in the next stage of the YRB.

The relationship between urban eco-efficiency and per capita GDP in the YRB is U-shaped (Figure 6(b)), which is consistent with the general EKC curve, and the corresponding inflection point is 46,483 yuan, which verifies

Table 4: Empirical results of CO_2 emissions, eco-efficiency, and economic development.

Variable	(1) Ln CO_2	(2) Ln EE
Ln PCGDP	0.7761*** (10.17)	−0.2635*** (−5.49)
(Ln PCGDP)^2	−0.3735*** (−8.60)	0.0907*** (6.65)
(Ln PCGDP)^3	0.0821*** (8.73)	
FDI	0.0166*** (1.82)	0.0334** (2.02)
EDU	1.3929*** (5.18)	1.9828*** (6.71)
INDUS	0.5722*** (9.56)	−0.0284 (−0.55)
POP	0.0000 (0.33)	0.0000 (0.84)
ENE	1.1790*** (20.73)	0.0645 (1.05)
W × Ln PCGDP	2.1450*** (6.04)	−0.3930 (−1.17)
W × (Ln PCGDP)^2	−0.1277 (−0.46)	0.0501 (0.44)
W × (Ln PCGDP)^3	−0.1248* (−1.77)	
W × FDI	0.3967*** (7.85)	0.0394 (0.34)
W × EDU	−15.8385*** (−12.19)	6.0447** (2.08)
W × INDUS	−1.6106*** (−9.39)	1.5407*** (3.13)
W × POP	−0.0001 (−0.98)	−0.0003* (−1.75)
W × ENE	2.1693*** (11.03)	1.3382*** (5.69)
P	−0.2023*** (−2.64)	−0.6885*** (−4.15)
Sigma2_e	0.0072*** (27.25)	0.0257*** (27.23)
Individual effect	YES	NO
Time fixed effect	NO	YES
Sample size	1485	1485
R^2	0.906	0.269

Note. *, ** and *** represent the significance levels of 10%, 5%, and 1%, respectively, and the t-statistic value is in brackets.

hypothesis 3. When per capita GDP is less than 46,483 yuan, eco-efficiency decreases with increasing per capita GDP. At this stage, the industrial structure was composed of main labor (resource)-intensive industries and capital-intensive industries. The economic development model tends to be an extensive development model of high input and high emissions. When the per capita GDP is higher than 46,483 yuan, eco-efficiency increases with the improvement of the economic development level, and economic growth gradually enters the stage of high-quality development. The YRB had just crossed this inflection point, before which the eco-efficiency gradually declined with economic development. Consistent with the characteristic facts of eco-efficiency observed earlier, eco-efficiency will gradually increase with the development of the economy, the contradiction between economic development, resource conservation, and environmental protection will gradually slow down, and the economic development model will gradually change to an environmentally friendly high-quality development model.

4.4.2. Analysis of Spatial Effect Decomposition. The spatial effects of the regression results are further decomposed and analyzed, and the results are shown in Table 5. Among them, the direct effect indicates the regional spillover effect, while the indirect effect indicates the spatial spillover effect.

From the perspective of CO_2 emissions, the effect of economic development on CO_2 emissions is significant both in terms of direct and indirect effects. The direct effect between economic development and CO_2 emissions is N-shaped, and there is only one accelerating inflection point that affects the rate of change, meaning that CO_2 emissions increase at a decelerating rate and then at an accelerating rate as the economy grows. The indirect effect between economic development and CO_2 emissions is inverted N, with two inflection points that change the trend, meaning that as the local economy grows, CO_2 emissions in the neighborhood go through three stages: decline, then growth, and then decline again. The possible reason for this is that the initial agglomeration effect of a region's economic development can attract factors of production from neighboring regions to that region [43], thus leading to an increase in CO_2 emissions in that region and a decrease in CO_2 emissions in neighboring regions. However, excessive agglomeration of production materials may have a congestion effect [44], which may lead to the flow of production factors to other regions, resulting in higher CO_2 emissions from neighboring regions. The indirect effect of FDI is significantly positive, implying that locally targeted FDI causes a significant increase in CO_2 emissions in neighboring regions, as foreign investment brings more advanced production technologies to local manufacturers, thus promoting low-carbon energy efficiency in local production activities. The direct effect of investment in education is significantly positive, while the indirect effect is significantly negative, suggesting that government investment in local education attracts families from neighboring areas that value youth education to relocate, thereby increasing local CO_2 emissions. A secondary industry-based industrial structure can significantly push up local CO_2 emissions while lowering those of neighboring areas, implying that local industrial agglomeration can give full play to its agglomeration effect and attract industrial enterprises from neighboring areas to move in.

From the perspective of eco-efficiency, economic development has only a significant direct effect on eco-efficiency, and the indirect effect has not yet been revealed. The direct effect between economic development and eco-efficiency is U-shaped, which means that the local eco-efficiency decreases and then increases with economic development, which is consistent with the hypothesis of the EKC curve.

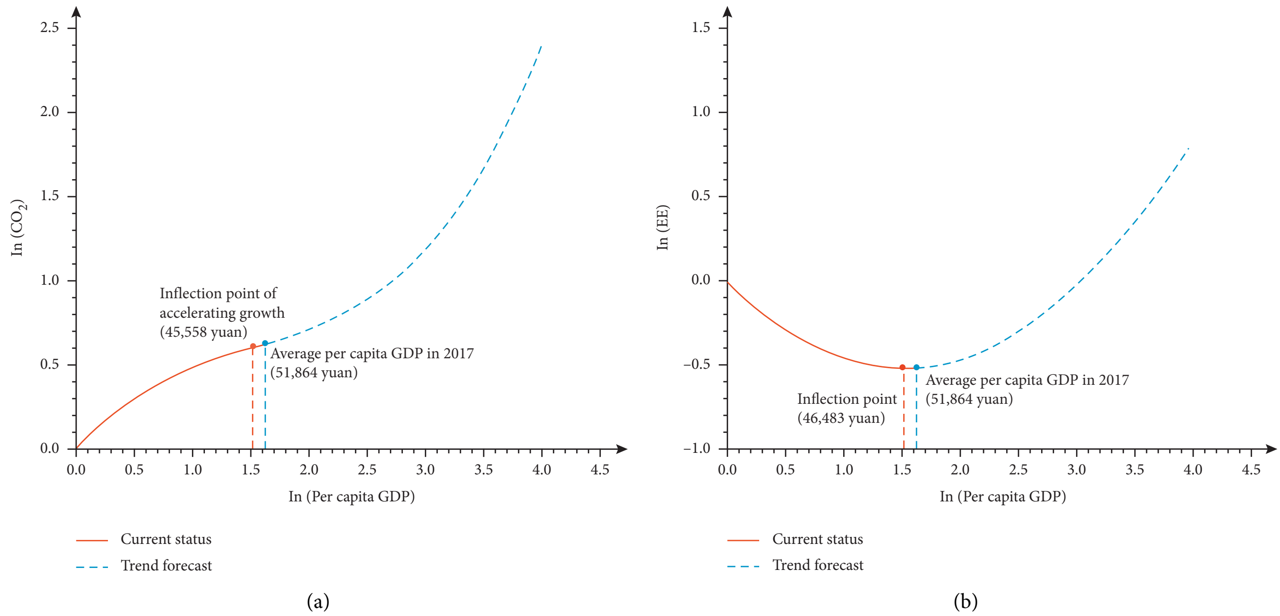

Figure 6: CO_2 emissions, eco-efficiency, and economic development. (a) CO_2 emissions and economic development. (b) Eco-efficiency and economic development.

Table 5: Decomposition of spatial effects.

Variable	(1) Ln CO_2	(2) Ln EE	(1) Ln CO_2	(2) Ln EE	(1) Ln CO_2	(2) Ln EE
	Direct effect		Indirect effect		Total effect	
Ln PCGDP	0.1763*** (9.25)	−0.1684*** (−3.87)	0.7577*** (20.19)	−0.1243 (−0.79)	0.9340*** (29.87)	−0.2927* (−1.93)
$(\text{Ln PCGDP})^2$	−0.0356*** (−5.83)	0.0800*** (5.67)	0.1266*** (4.38)	−0.0652 (−0.77)	0.0910*** (3.22)	0.0148 (0.18)
$(\text{Ln PCGDP})^3$	0.0215*** (8.99)		−0.1130*** (−6.73)		−0.0915*** (−5.33)	
FDI	0.0132 (1.51)	0.0829** (2.03)	0.3616*** (6.76)	0.0180 (0.10)	0.3748*** (6.97)	0.1009 (0.56)
EDU	1.2121*** (4.53)	4.3737*** (5.97)	−13.6831*** (−13.49)	8.4993* (1.92)	−12.4710*** (−12.27)	12.8730*** (2.83)
INDUS	0.5994*** (10.47)	−0.0701 (−0.55)	−1.5641*** (−8.42)	2.7013*** (3.34)	−0.9647*** (−5.01)	2.6312*** (3.15)
POP	0.0000 (0.55)	0.0000 (0.63)	−0.0002 (−1.61)	−0.0004 (−1.58)	−0.0002 (−1.52)	−0.0004 (−1.55)
ENE	1.1555*** (22.11)	0.1886 (1.19)	1.7779*** (8.39)	2.0642*** (4.49)	2.9334*** (12.86)	2.2528*** (5.69)

Note. *, ** and *** represent the significance levels of 10%, 5%, and 1%, respectively, and the t-statistic value is in brackets.

FDI has a significant effect on local eco-efficiency, implying that FDI will bring more advanced pollutant treatment technology to the local area and improve the productivity of enterprises. Investment in education has a significant positive direct and indirect effect on eco-efficiency, suggesting that increased investment in education can significantly raise residents' awareness of environmental protection, thus promoting eco-efficiency in both local and neighboring areas. An industrial structure dominated by secondary industries has a significant contribution to the eco-efficiency of neighboring areas, implying that the industrial parks in the region can exert their agglomeration effect to attract industrial enterprises from neighboring areas [43], thus improving the eco-efficiency of neighboring areas by reducing the number of polluting enterprises in the neighboring areas.

On the whole, although the linear relationship between CO_2 emissions, eco-efficiency, and economic development is completely different and their "inflection point" values are quite different, they all reflect that the YRB is still in development mode with high CO_2 emissions and low eco-efficiency. The energy structure with coal as the main energy source and the industrial structure with labor (resource)-

Table 6: Empirical test of using Queen contiguity.

Variable	(1) Ln CO_2	(2) Ln EE
Ln PCGDP	0.250*** (13.74)	−0.359*** (−10.09)
$(\text{Ln PCGDP})^2$	−0.033*** (−4.73)	0.144*** (9.26)
$(\text{Ln PCGDP})^3$	0.021*** (7.60)	
W×Ln PCGDP	0.387*** (6.12)	0.264*** (5.31)
ρ	0.146 (1.79)	0.232*** (7.13)
Sigma2_e	0.010*** (27.25)	0.180*** (26.92)
Controls	YES	YES
Individual effect	YES	NO
Time fixed effect	NO	YES
Sample size	1485	1485
R^2	0.822	0.235

Note. *, ** and *** represent the significance levels of 10%, 5%, and 1%, respectively, and the t-statistic value is in brackets.

intensive industries and capital-intensive industries as the main industries urgently need to be changed.

4.4.3. Robustness Test. In the previous analysis, the reciprocal of the square term of the distance between the centroid points of each province was mainly used as the distance-based weight matrix. In the robustness test, a contiguity-based spatial weight matrix is used to analyze the above results. The corresponding regression results are shown in Table 6. The results show that the fitting curve obtained by regression using Queen contiguity for the spatial matrix is consistent with the previous curve, so we will not repeat it because of space limitations.

5. Conclusions and Policy Implications

Ecological protection and high-quality development of the Yellow River Basin is one of the major national development strategies in China. Accelerating the efficient utilization of energy, further reduction of pollutant emissions, and promoting green and low-carbon development in the region are the key points to promoting the construction of ecological civilization in the YRB. Compared to relative literature putting more emphasis on the relationship between CO_2 emissions, eco-efficiency, and economic development, in this paper, we attempt to put the three in a united framework and analyze the relationship among them from the perspective of new structural economics, which is a further expansion of previous literature. In particular, we creatively fitted the curves of CO_2 emissions, eco-efficiency, and economic development, judged the development trend of the three and the current stage of the YRB, and further confirmed the existence of the environmental EKC curve based on the prefecture data of 99 cities in the YRB from 2003 to 2017, which provided theoretical support for further formulating more practical policy measures. The main conclusions are as follows:

(1) The trends of CO_2 emissions and eco-efficiency in the YRB are opposite, and there is spatial heterogeneity. The CO_2 emissions continued to rise during the investigation period, and the eco-efficiency value fluctuated and then decreased. From the perspective of spatial distribution, the CO_2 emissions and eco-efficiency in the upper reaches were low. The CO_2 emissions and eco-efficiency in the middle reaches were higher, while those in the lower reaches were higher and lower. This difference is determined by the resource endowment structure, industrial structure, and energy consumption structure of the YRB.

(2) There is an N-shaped relationship between CO_2 emissions and economic development in the YRB, and there is no decreasing range. There is only one "acceleration" inflection point (45,558 yuan); that is, when the per capita GDP is less than 45,558 yuan, CO_2 emissions will slow down and increase with economic development, and when the per capita GDP is higher than 45,558 yuan, CO_2 emissions will accelerate and increase with economic development. The YRB has crossed this acceleration inflection point, and at this stage, CO_2 emissions in the YRB are accelerating in line with economic development.

(3) There is a U-shaped relationship between eco-efficiency and economic development in the YRB, and the inflection point is 46,483 yuan; that is, when the per capita GDP exceeds 46,483 yuan, the eco-efficiency of the YRB will gradually increase with economic development. The YRB is in the critical stage of crossing this inflection point. It is predicted that the contradiction between resource conservation, environmental protection, and economic development will be further eased in the development process of the YRB. The economy will gradually transform and upgrade to an environmentally friendly, high-quality development stage.

Based on the calculation and empirical analysis of relevant indicators, this paper expounds on the development status and main existing problems of the YRB and provides the following suggestions for the eco-efficiency characteristics of high CO_2 emissions and fluctuating decline in the YRB.

First, encourage the improvement and modernization of industrial sectors and create distinct plans for spatial growth. The upper reaches of the YRB should prioritize fully utilizing the economic, cultural, and humanistic advantages of Sichuan, Gansu, and the ethnic and humanistic advantages of Ningxia and Qinghai, as well as forming a humanistic exchange base for South and Central Asian nations. This is because they are a key area for the construction of "The Belt and Road Initiative" and an important recharge area for the Yellow River. The production capacity along "The Belt and Road Initiative" will receive the nonferrous metal processing industry. The middle reaches should control the intensity of coal development, ensure the orderly and effective development of the energy base resources in the middle reaches, and determine the production scale of the energy industry based on water resources and the ecological carrying capacity of the environment while actively promoting the development of the energy and chemical industry towards refinement, deep processing, and high-end. Building industrial cooperation platforms that work in harmony with the middle and upper reaches, enhancing the development of technology-intensive manufacturing sectors like the Internet, communications, and other electronic equipment manufacturing, and raising the rate at which the Internet, artificial intelligence, and big data are incorporated into tr should be the focus of two provinces in the lower reaches.

Second, improve the energy consumption structure and accelerate the transformation of the energy consumption structure. In important coal-using businesses like the coking and coal chemical sectors, increase the clean, effective, and fractionated use of coal. Encourage the use of renewable energy to replace fossil fuels in qualified industrial park businesses throughout the basin or the conversion of coal to gas. Utilize the abundant wind and solar energy resources in the upstream provinces of Qinghai, Gansu, and Sichuan, and intensify the promotion of wind power generation and photovoltaic power parks in the upstream areas to aid in green, low-carbon development and further increase the capacity and guarantee mechanism of clean energy consumption and outward transmission.

Third, optimize the physical arrangement of industries and encourage the comprehensive, well-coordinated growth of the YRB. We will actively encourage the development of information technology infrastructures like the Internet, 5G, and fiber optic access to homes, improve the ability to coordinate between locations and connect up between areas within the basin and utilize the free flow of information to optimize the spatial layout of the entire basin. Enhance the basin-wide transportation system, optimize and modernize the current system, and make plans to add any missing routes and eliminate bottlenecks in the YRB. Use the Gansu Lanbai Economic Zone, Ningxia Yinchuan-Shizuishan, Jinshan-Shaanxi-Yuangtze Golden Triangle, and Jinshan-Shaanxi-Yuangtze Golden Triangle as demonstration zones for industrial transfer, and take full advantage of the upper and middle provinces' geographic advantages as important channels and key nodes in the construction of "The Belt and Road Initiative" to increase the basin's capacity for domestic and international industries. The relative overcapacity industries of petrochemicals, iron, and steel, and nonferrous metals will be moved to developing nations along the "Belt and Road" and those with higher infrastructure investment needs.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

Authors' Contributions

Y.H. and X.W. conceptualized the study; Y.H. developed the methodology; Y.H. and C.Z. collected the resources; X.W. and C.Z. carried out formal analysis; X.W. and C.Z. wrote and prepared the original draft; Y.H., X.W., and C.Z. wrote, reviewed, and edited the study All authors have read and agreed to the published version of the manuscript.

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