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Spatiotemporal Evolution and Obstacle Factors of Coupling Coordination Among Low-Carbon Logistics, Regional Economy, and Ecological Environment Systems in the Yellow River Basin

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Abstract

Under the background of the “dual carbon” strategy and regional coordinated development, the synergistic evolution of low-carbon logistics, regional economy, and ecological environment in the Yellow River Basin has become a key pathway to achieving high-quality development. Taking nine provinces (autonomous regions) within the basin as the study area, this paper constructed a coupling coordination evaluation index system for the LREES (Low-carbon Logistics–Regional Economy–Ecological Environment System), and measured the comprehensive development level of each subsystem using the entropy weight method. Based on the coupling coordination degree model, the temporal evolution of the three systems from 2010 to 2024 was systematically evaluated. In addition, global and local spatial autocorrelation models were introduced to identify spatial clustering patterns, while the obstacle degree model was used to identify key constraints at both the criterion and indicator levels. The results revealed that: the overall development level of the LREES systems steadily increased, with reduced regional disparities; the coupling coordination degree showed a trend of “fluctuating rise–gradual coordination,” with the average value increasing from 0.450 to 0.623, indicating continuously enhanced synergy; spatially, a gradient pattern of “downstream > midstream > upstream” emerged, accompanied by significant positive spatial autocorrelation; resource endowment and development scale were major constraints, while construction level, operational efficiency, and governance capacity were secondary. High-frequency obstacle indicators included per capita water resources, total import and export volume, and urban sewage treatment capacity. These findings offer theoretical support and policy guidance for promoting green transformation, enhancing system synergy, and advancing coordinated regional development in the Yellow River Basin.



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1. Introduction

Against the dual backdrop of increasingly pressing global climate change and resource-environmental constraints, promoting a comprehensive green and low-carbon transformation of economic and social development has become an international consensus. China

has set the goals of “peaking carbon emissions and achieving carbon neutrality” as a key strategic direction for advancing high-quality economic development, raising higher requirements for industrial restructuring, energy system optimization, and coordinated regional development. The implementation of the “Outline for Ecological Protection and High-Quality Development in the Yellow River Basin” has further elevated green transformation and ecological security enhancement in the Yellow River Basin to a major national strategic task. The Yellow River Basin spans multiple geomorphic units such as the Qinghai–Tibet Plateau, the Loess Plateau, and the North China Plain, and encompasses nine provinces (autonomous regions) namely Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan, and Shandong. It is not only an important ecological security barrier and resource-rich region in China, but also a core carrying area for the country’s energy, grain, heavy industry, and labor-intensive industries. The topography of the basin declines progressively from west to east and from high to low, with remarkable spatial heterogeneity in resource endowments and ecological carrying capacity. The upper reaches of the river feature prominent ecological functions but a relatively weak economic foundation, while the middle and lower reaches exhibit a high degree of industrial agglomeration and face tightening environmental constraints. This highlights an urgent need to shift from traditional resource-dependent development pathways toward green and low-carbon models. With the in-depth advancement of the major national strategy of “Ecological Protection and High-Quality Development of the Yellow River Basin”, accelerating its transformation from the traditional resource-dependent mode to the green and low-carbon mode has become a crucial pathway to realizing regional coordinated development and the construction of ecological civilization. As a fundamental platform supporting the efficient operation of the regional economy, the low-carbon development of the logistics system not only directly affects energy consumption and carbon emission levels, but also plays a pivotal role in improving resource utilization efficiency and promoting the optimization of industrial structure. The development of the regional economy not only relies on the efficient operation of the logistics system, but also puts forward higher requirements for the quality of the ecological environment. As an important pivotal measure for green transformation, low-carbon logistics not only reflects the friendly response of the logistics field to the ecological environment, but also serves as a key dimension for measuring the regional sustainable development capacity. Therefore, systematically exploring the synergistic mechanisms and coupling relationships among low-carbon logistics, regional economy, and the ecological environment in the Yellow River Basin, and identifying their spatiotemporal evolution characteristics and influencing factors, holds important theoretical significance and practical value for promoting the coordinated advancement of basin ecological protection and green development, and constructing a high-quality, integrated, and multi-factor synergistic regional development pattern.

This paper takes the nine provinces (regions) in the Yellow River Basin as the research subjects, constructing a three-dimensional analytical framework of “low-carbon logistics—regional economy—ecological environment.” It conducts a comprehensive analysis of their synergistic evolution process and spatial differentiation patterns, with a focus on revealing the interactive characteristics and constraint mechanisms at different stages and regional scales. The research contributions are mainly reflected in three aspects: first, it delineates the overall trends and regional differences in the synergistic evolution of multiple systems within the basin, providing empirical insights for analyzing green transition pathways in resource-dependent basins; second, it identifies structural weaknesses that hinder synergistic enhancement, offering a basis for differentiated policies and region-specific governance; third, it proposes targeted policy recommendations based on empirical findings, thereby enhancing the practical guidance value of the study.

2. Literature Review

In advancing the green transformation and high-quality development of the Yellow River Basin, the coordinated evolution of three major systems—low-carbon logistics, regional economy, and ecological environment—has become a key focus in policy formulation and academic research. Scientifically identifying the interactive mechanisms among these systems and their spatio-temporal differentiation is crucial not only for optimizing development pathways but also for effectively implementing ecological security and regional coordination strategies. In recent years, scholars worldwide have conducted multidimensional explorations on the coordinated development of regional logistics, economies, and ecosystems. Relevant research primarily focuses on three aspects: First, the dual impact mechanism of low-carbon logistics on regional economic development and ecological environments. It is argued that low-carbon logistics can drive green transformation by reducing energy consumption and carbon emissions while enhancing economic efficiency. For instance, Zhou Tai (2021) constructed a regional logistics–ecosystem model using Sichuan Province as a case study, emphasizing the importance of green transportation for ecological coordination [1]. Liu Xue (2024) empirically demonstrates that the low-carbon transformation of the logistics sector contributes to economic–environmental coordination in the Yellow River Basin [2]. Zhang Lanyi (2024) explores the coupling relationship between carbon emissions in China’s logistics sector and high-quality development based on the spatiotemporal evolution characteristics of carbon emissions, providing insights for optimizing regional low-carbon logistics pathways [3]. Li Xiangrong (2024) constructs a mechanism framework for the co-evolution of logistics and economic systems from a green logistics perspective, emphasizing the transformation toward greener and more coordinated development through enhanced institutional supply and policy guidance [4]. Second, analyzing the evolutionary relationship between economy and ecological environment from a regional coordination perspective. Research often employs spatial econometric methods to identify interactions and spatial differentiation characteristics between regional economies and ecological environments. For instance, Cui Liang (2023) highlights from a digital economy perspective that the coupling between regional economic development and ecological governance increasingly relies on the integration and empowerment of data elements [5]. Chen Yuxuan (2023) uses Fujian Province as a case study, employing the super-efficiency SBM model and spatial econometric models to analyze the spatial pattern of energy efficiency in Fujian and its coupling with economic development [6]. Third, constructing multi-system coupling coordination models to explore interaction intensity and evolutionary trends. For instance, Dong Qianli (2021) employed the SBM–Undesirable model to assess the ecological efficiency and emission reduction potential of the logistics industry in the Yellow River Basin, indicating that the overall ecological efficiency of the logistics sector in western regions remains low, with significant room for green transformation and pollution reduction [7]. Liang Wen (2022) systematically analyzed the synergistic relationships among regional economy, logistics development, and ecological environment in the Yangtze River Economic Belt, highlighting that promoting cross-regional factor mobility and institutional coordination are key pathways to achieving high-quality development [8]. Yang Yang (2023) constructed a “low-carbon logistics–economy–ecological environment” system coupling model using Yunnan Province as a case study, revealing generally low coordination levels in central and western Yunnan [9]. Li Xiaomei (2022) empirically examined the coupling mechanisms among digital logistics, carbon environmental governance, and regional economies using 30 provincial panel data, finding significant policy adjustment effects [10]. Liu Cong et al. (2025) [11] constructed a multi-system evaluation model integrating regional logistics, ecological environment, and regional economy using Hebei Province as a case study. Based on vector autoregression analysis, they

empirically revealed a long-term stable interactive relationship among the three under the “dual carbon” context, demonstrating that regional logistics significantly promotes both economic growth and ecological environment improvement [11]. In summary, existing research has established a relatively comprehensive theoretical framework and empirical analysis system. It predominantly employs technical approaches such as coupling coordination degree models, SBM, spatial autocorrelation, and spatial econometrics to reveal the dynamic evolution characteristics and spatial differentiation patterns of multi-system coordination. However, in terms of the research subjects and regions, existing studies have predominantly focused on eastern or economically developed regions, there has been a notable lack of attention to the central and western regions, which exhibit high dependency on resources, limited ecological carrying capacity, and more complex development constraints. Particularly, targeted empirical analyses on low-carbon logistics and multi-system coordination mechanisms remain scarce. Therefore, this study examines nine provinces (regions) in the Yellow River Basin. It constructs a comprehensive evaluation index system covering low-carbon logistics, regional economy, and ecological environment. The entropy weight method is employed to measure the overall development level of the system. The coupling coordination degree model is used to assess the interactive relationships among the three-dimensional systems. Combined with spatial autocorrelation and the obstacle degree model, systematically analyzes their evolutionary characteristics, spatial agglomeration patterns, and influencing factors. This aims to provide theoretical support and policy references for the green transformation and high-quality development of the Yellow River Basin.

3. Study Design

3.1. Data Sources and Processing

This study examines the Yellow River Basin spanning nine provinces (autonomous regions) from 2010 to 2024, constructing a panel dataset encompassing a three-dimensional system of low-carbon logistics, regional economy, and ecological environment. Data primarily originate from authoritative sources including the China Statistical Yearbook, Provincial (Autonomous Region) Statistical Yearbooks, China Energy Statistical Yearbook, China Ecological Environment Status Bulletin, China Logistics Development Report, provincial/municipal transportation yearbooks, and carbon emissions databases. To address the issue of a small number of missing indicators in certain years due to publication lags in statistical releases, this paper employs smoothing techniques to impute the missing data. This process, conducted under the principles of maintaining data continuity and consistency, ensures the integrity of the time series and the stability of the analytical results [12]. Meanwhile, in the measurement of indicators related to the low-carbon logistics system, for metrics such as carbon emissions from the logistics industry that cannot be directly obtained from statistical yearbooks, this paper draws on the research methodology of Gao Ziyang et al. [13] and employs the IPCC carbon emission coefficient method to estimate the logistics industry's carbon emissions. This is based on data for major energy consumption sources such as raw coal, coke, gasoline, diesel, and natural gas, and is calculated in combination with parameters including the net calorific value, carbon content coefficient, and carbon oxidation rate of these energy sources [14].

3.2. Indicator System Construction

To scientifically measure the development levels and coupling coordination relationships among the three-dimensional systems of low-carbon logistics, regional economy, and ecological environment in the Yellow River Basin, this study constructs a three-dimensional system centered on low-carbon logistics (LCL), regional economy (RE), and ecological

environment (EE)—referred to as the LREES system—by adhering to principles of scientific rigor, systematic approach, timeliness, and operational feasibility, while considering the basin’s developmental realities and data availability. Building upon a systematic review and integration of the existing literature, and drawing references from Liang Wen [8], Yang Yang [9], Zhou Nan [15] and Yang Yongfang [16], research findings and methodological approaches in the field of multi-system coupling coordination were utilized. Indicators were established across dimensions including the construction level, operational level, and green capacity of the logistics industry; the scale, capacity, and quality of economic development; and the ecological resource base, environmental pollution levels, and governance capacity. This resulted in the construction of a comprehensive evaluation indicator system for the LREES system in the Yellow River Basin, encompassing 30 indicators across 9 secondary dimensions (see Table 1).

Table 1. Comprehensive evaluation index system of the LREES in the Yellow River Basin.

Subsystem	Primary Indicator	Secondary Indicators	Indicator Description	Attribute	Weight
Low-Carbon Logistics System (LCL)	Construction Level (L_1)	Logistics Industry Fixed-Asset Investment (L_{11})	Measuring Capital Intensity in Logistics (RMB billion)	+	0.1852 ^{A,B}
		Number of Logistics Industry Employees (L_{12})	Measures labor input scale in the logistics industry (10,000 persons)	+	0.1332 ^B
		Grade Highway Mileage (L_{13})	Measures logistics accessibility and infrastructure level (10,000 km)	+	0.0919 ^A
	Operational Level (L_2)	Energy consumption intensity of logistics industry (L_{21})	Measuring Energy Consumption per Unit Output (Tons of Standard Coal/10,000 RMB)	-	0.0567 ^C
		Freight Volume (L_{22})	Measures total logistics transportation capacity (10,000 tons)	+	0.1163 ^A
		Freight turnover (L_{23})	Measures transportation efficiency (billion ton-kilometers)	+	0.1632 ^A
	Green Capacity (L_3)	Value Added of Logistics Industry (L_{31})	Measures the economic output level and industrial development capacity of the logistics sector (in billions of yuan)	+	0.1945 ^A
		Electricity consumption in the logistics industry (L_{32})	Measures the level of clean energy utilization in logistics operations (100 million kWh)	-	0.0263 ^C
		Carbon emissions in the logistics sector (L_{33})	Measure the total carbon emissions from logistics operations (in 10,000 tons of standard coal equivalent)	-	0.0326 ^{C,D}
Regional Economic System (RE)	Development Scale (R_1)	Regional GDP (R_{11})	Measures the overall scale of the regional economy (in billions of yuan)	+	0.1155 ^{A,B}
		Total Retail Sales of Consumer Goods (R_{12})	Measures residents’ consumption capacity and market activity (billion yuan)	+	0.1286 ^{A,B}
		Total Fixed-Asset Investment (R_{13})	Reflects capital accumulation and investment-driven growth (billion yuan)	+	0.1269 ^B
		Total imports and exports (R_{14})	Measures regional openness to the outside world (billion yuan)	+	0.2159 ^{A,B}

Table 1. Cont.

Subsystem	Primary Indicator	Secondary Indicators	Indicator Description	Attribute	Weight
Ecological Environment System (EE)	Development Capacity (R_2)	Per capita GDP (R_{21})	Per capita output level measuring economic development (yuan/person)	+	0.0447 ^{A,B} .
		Per capita disposable income of residents (R_{22})	Measures residents' living standards and income capacity (yuan/person)	+	0.0446 ^{A,B} .
		Added value of high-tech industries (R_{23})	Measures innovation-driven development and emerging industry growth capacity (billion)	+	0.1670 ^{A,B} .
	Development Quality (R_3)	Share of Tertiary Industry in GDP (R_{31})	Reflecting the development of the service sector and the degree of industrial structure optimization (%)	+	0.0272 ^{A,B} .
		GDP growth rate (R_{32})	Reflects economic growth rate and vitality (%)	+	0.0275 ^{A,B} .
		Fixed-Asset Investment Growth Rate (R_{33})	Measures investment efficiency and potential for sustained growth (%)	+	0.0089 ^A .
		Registered urban unemployment rate (R_{34})	Measures regional employment conditions and economic stability (%)	-	0.0215 ^{A,B} .
		Patent Applications per 10,000 People (R_{35})	Measures regional technological innovation activity and independent R&D capability (applications/10,000 people)	+	0.0716 ^{A,B} .
	Resource Foundation (E_1)	Forest Cover Rate (E_{11})	Measures ecosystem stability and green resource base (%)	+	0.0854 ^{A,B} .
		Per capita park green space area (E_{12})	Measures urban living environment quality and ecological livability (m^2 /person)	+	0.0766 ^{A,B} .
		Per capita water resources (E_{13})	Measuring the sustainable use capacity of water resources (cubic meters per person)	+	0.4124 ^{A,B} .
	Pollution Level (E_2)	Carbon Dioxide Emissions (E_{21})	Measures the overall carbon emission level of the region, reflecting environmental pressure (10,000 tons)	-	0.0479 ^{C,D} .
		Industrial wastewater treatment rate (E_{22})	Measures industrial wastewater treatment standards and environmental protection capacity (%)	+	0.0206 ^C .
		Industrial Solid Waste Generation (E_{23})	Measures regional industrial activity intensity and environmental load (10,000 tons)	-	0.0371 ^C .

Table 1. Cont.

Subsystem	Primary Indicator	Secondary Indicators	Indicator Description	Attribute	Weight
Governance Capacity (E_3)		Green coverage rate in built-up areas (E_{31})	Measuring urban greening level (%)	+	0.0312 ^B
		Daily urban sewage treatment capacity (E_{32})	Measures urban sewage treatment infrastructure capacity and environmental management level (10,000 tons)	+	0.1859 ^B
		Local government environmental protection expenditure (E_{33})	Measures the intensity of local governments' support for ecological governance (billion yuan)	+	0.1028 ^B

The data were sourced from the following: the China Statistical Yearbook (labeled as A), provincial statistical yearbooks (labeled as B), the China Energy Statistical Yearbook (labeled as C), and calculations based on the IPCC (labeled as D).

3.3. Research Methodology

3.3.1. Entropy Weighting Method

The entropy weight method is an objective weighting approach widely applied in multi-indicator comprehensive evaluation systems. Its fundamental principle lies in measuring the variability of each indicator based on its information entropy value within the sample, thereby determining corresponding weights. Specifically, the more dispersed an indicator's values are, the lower its information entropy and the more pronounced its variability. This enhances its ability to distinguish system differences, resulting in a relatively higher assigned weight. Compared with subjective weighting methods, the entropy weight method is more suitable for comprehensive evaluation studies involving multiple indicator dimensions and significant regional differences. Given that this paper uses provincial panel data, the spatial variation among provinces compensates to some extent for the insufficient temporal variability of certain indicators. Additionally, through the design of the criterion layer structure, key indicators with relatively small fluctuations are ensured to be reasonably represented in the comprehensive evaluation. It should be further clarified that this paper adopts a comprehensive indicator evaluation method rather than DEA efficiency measurement due to differences in research objectives. The DEA model focuses on the input–output efficiency analysis of a single system, whereas this study is concerned with the comprehensive development levels and interactions among the three systems of low-carbon logistics, regional economy, and ecological environment. The connotation of low-carbon logistics encompasses multiple dimensions, including infrastructure conditions, industrial development foundations, operational capabilities, and green transformation characteristics, which exceed the scope of narrow efficiency analysis. Moreover, the coupling coordination degree model aligns methodologically with the comprehensive evaluation using the entropy weight method. In contrast, employing DEA to measure efficiencies separately before coupling could fragment the interconnections among systems and may not meet the quantitative requirements for decision-making units under multi-indicator conditions. Therefore, this paper utilizes the entropy weight method to construct a comprehensive evaluation indicator system for the LREES system. The specific calculation steps are as follows:

(1) Indicator Standardization

To eliminate differences in measurement units and magnitude among indicators, this paper employs range standardization to render the raw data dimensionless x_{itj} . Positive and negative indicators are standardized separately using Formula (1):

$$= Z_{itj} = \begin{cases} \frac{x_{itj} - \min_i x_{itj}}{\max_i x_{itj} - \min_i x_{itj}}, & \text{for positive indicators} \\ \frac{\max_i x_{itj} - x_{itj}}{\max_i x_{itj} - \min_i x_{itj}}, & \text{for negative indicators} \end{cases} \quad (1)$$

where x_{itj} and Z_{itj} represent the raw and standardized values of the j th indicator in the i th region for year t , respectively, $\max_i x_{itj}$ and $\min_i x_{itj}$ denote the maximum and minimum values of the j -th indicator across all samples, respectively. To enhance numerical stability in data processing and subsequent computational accuracy, this study shifts the standardized data by 0.0001 units after normalization, following relevant research methodologies. This prevents zero values from interfering with entropy calculations [17,18]. The shifted standardized values are denoted as Z'_{itj} .

(2) Determining indicator weights

Perform normalization on the standardized data [19], to calculate the weight of indicator j for region i in year t p_{itj} , using the following formula:

$$p_{itj} = \frac{Z'_{itj}}{\sum_{i=1}^n Z'_{itj}} \quad (2)$$

(3) Determining the Information Entropy Value of Indicators

Based on information entropy theory, calculate the information entropy for each indicator e_{tj} , using the following formula:

$$e_{tj} = -k \sum_{i=1}^n p_{itj} \ln(p_{itj}), \quad k = \frac{1}{\ln(n)} \quad (3)$$

(4) Determine redundancy and indicator weights

Based on the information entropy results, calculate the information redundancy of each indicator $d_{ij} = 1 - e_{tj}$, and subsequently determine the weight of the j -th indicator w_{tj} , as follows:

$$w_{tj} = \frac{d_{tj}}{\sum_{j=1}^m d_{tj}}, \quad \sum_{j=1}^m w_{tj} = 1 \quad (4)$$

where m is the total number of indicators, and w_{tj} reflects the contribution of the j -th indicator to the overall system evaluation. Through calculations using Equations (1)–(4), the weight results for each indicator in the comprehensive evaluation indicator system of the Yellow River Basin LREES system are obtained, as detailed in Table 1.

(5) Determining the comprehensive evaluation scores for the LREES system

Based on the weights and standardized values of each indicator, calculate the comprehensive evaluation score for each region in the low-carbon logistics, regional economy, and ecological environment subsystems for year i : U_{it} . This score serves as the basis for assessing the development level of each system in subsequent coupling coordination analysis, enabling further examination of their coupling relationships and coordination levels.

Using the corresponding annual indicator weights w_j , perform a weighted summation of the indicator scores Z_{itj} for each region i in year t , as follows:

$$U_{it} = \sum_{j=1}^m w_{tj} Z'_{itj} \quad (5)$$

3.3.2. Coupling Coordination Degree Model

Traditional coupling coordination degree models are often used to describe the relationship between two systems. In the context of multiple systems, they tend to dilute the differences among subsystems, thereby affecting the interpretability of coordination levels. To comprehensively evaluate the interactive relationships and coordinated development levels among the low-carbon logistics, regional economy, and ecological environment systems in the Yellow River Basin, this study introduces a modified three-system coupling coordination model. This model measures the synergistic evolution process and phased characteristics of these systems [20]. Based on the normalization of comprehensive evaluation scores for each subsystem, the model systematically assesses the interactive coupling relationships and coordinated evolution trends among the three systems.

Let U_L, U_R, U_E denote the comprehensive development scores for the low-carbon logistics, regional economy, and ecological environment subsystems within the LREES system of the Yellow River Basin, respectively. C represents the coupling degree (i.e., the strength of inter-system interconnections) among the three systems, ranging from $[0, 1]$. A value closer to 1 indicates a tighter coupling relationship. T is the comprehensive coordination index of the three systems, and D is the coordination level of their integrated development. Parameters α_1, α_2 , and α_3 represent the weight coefficients for the three subsystems, respectively. Their relationship is defined as follows:

$$C = \left[\frac{\prod_{i=1}^3 U_i}{\left(\frac{1}{3} \sum_{i=1}^3 U_i \right)^3} \right]^{\frac{1}{3}} = \sqrt[3]{\frac{U_L \times U_R \times U_E}{\left(\frac{U_L + U_R + U_E}{3} \right)^3}} = \frac{3\sqrt[3]{U_L \times U_R \times U_E}}{U_L + U_R + U_E} \quad (6)$$

$$T = \sum_{i=1}^3 \alpha_i \times U_i = \alpha_1 \times U_L + \alpha_2 \times U_R + \alpha_3 \times U_E \quad (7)$$

$$D = \sqrt{C \times T} \quad (8)$$

Given the intertwined and synergistic development of regional logistics and regional economy, while the ecological environment serves as a crucial foundation and fundamental safeguard for regional coordinated evolution, this paper assumes equal importance for the three subsystems when constructing the coupling coordination model. Therefore, when constructing the coupling coordination degree model in this paper, based on the principle of equal interaction status and balanced synergistic evolution among systems, and following common practices in relevant literature, equal weights are assigned to the three subsystems—low-carbon logistics, regional economy, and ecological environment. This approach aims to avoid interference from subjective human weighting on measurement results and enhance the objectivity and comparability of the model design, with the weight coefficient uniformly set at $\alpha_1 = \alpha_2 = \alpha_3 = 1/3$. To visually represent the coupling coordination level of the three systems, this study adopts the grading criteria proposed by scholars such as Ma HaiQiang. The coupling coordination index D is divided into ten levels, with classification determined by the stage characteristics of the coupling coordination relationship C . This approach characterizes the hierarchical features and dynamic evolution

of coordinated development across regions in the Yellow River Basin [21]. Here, a D value closer to 1 indicates a higher degree of coordinated development among systems; conversely, a lower D value reflects significant disparities and structural imbalances. The specific classification criteria are presented in Table 2.

Table 2. Classification criteria for coordination levels and degree of coordinated development.

Coupling Level Q	D Value Range	Coupling Coordination Level D
Q1	[0.000, 0.099)	Extremely Uncoordinated Type
Q2	[0.099, 0.199)	Severe Mismatch Type
Q3	[0.199, 0.299)	Moderate Dissonance Type
Q4	[0.299, 0.399)	Mildly Impaired Type
Q5	[0.399, 0.499)	Near-disharmonious type
Q6	[0.499, 0.599)	Barely Coupled Type
Q7	[0.599, 0.699)	Primary Coupling Type
Q8	[0.699, 0.799)	Moderate Coupling Type
Q9	[0.799, 0.899)	Well-coupled type
Q10	[0.899, 1.000]	High-quality coupling type

3.3.3. Spatial Autocorrelation Analysis

To investigate whether the level of coordinated development in the Yellow River region exhibits significant spatial correlation, this study employs both global and local Moran's I indices to measure the spatial distribution patterns of the three-system coordination levels [22,23]. The global Moran's I index characterizes the spatial clustering of coupling coordination levels across the entire study area, identifying typical spatial patterns such as "high-high" or "low-low." Its calculation formula is as follows:

$$I = \frac{n}{\sum_{i=1}^n \sum_{j=1}^n w_{ij}} \times \frac{\sum_{i=1}^n \sum_{j=1}^n w_{ij} (x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^n (x_i - \bar{x})^2} \quad (9)$$

Here, n denotes the number of study areas. x_i and x_j represent the variable values (coupling coordination degree in this paper) of spatial units i and j , respectively. $\bar{x}$ is the sample mean, while w_{ij} is the spatial weight matrix element, typically determined based on geographic adjacency or spatial distance. Moran's I ranges from -1 to 1 . When $I > 0$, it indicates positive spatial correlation among variables, meaning adjacent areas exhibit consistent coupling coordination levels, forming "high-high" or "low-low" spatial clustering patterns. When $I < 0$, the variable exhibits negative spatial correlation, manifesting as "high-low" or "low-high" heterogeneous clustering. When $I = 0$, indicates random spatial distribution with no significant spatial correlation. Building upon this, the local Moran's I index is further introduced to reveal the spatial clustering patterns and evolutionary trends of coupling coordination levels within local areas, identify spatial heterogeneity distribution patterns, and provide support for subsequent identification of regional coordination types and spatial regulation strategies.

3.3.4. Barrier Degree Model

To further identify key factors constraining the coordinated development of low-carbon logistics, regional economy, and ecological environment in the Yellow River Basin, this study introduces an obstacle degree model based on the coupling coordination index. Starting from the internal evaluation indicators of the LREES system, it comprehensively considers standardized scores and indicator weights to quantitatively assess the constraining effects of each indicator during system integration and identify primary obstacles in coordinated development. This approach helps reveal critical shortcomings in regional efforts to promote the coordinated development of the three systems, providing theoretic-

cal foundations and practical support for formulating differentiated regulatory strategies and path optimization plans tailored to local conditions. The calculation formula for the impedance model is as follows:

$$A_{ij} = \frac{(1 - Z_{ij}) \times F_{ij}}{\sum_{j=1}^m (1 - Z_{ij}) \times F_{ij}} \times 100\% \quad (10)$$

$$U_j = \sum_{i=1}^m A_{ij} \quad (11)$$

where $1 - Z_{ij}$ represents the deviation degree; F_{ij} denotes the product of the weight of the j -th indicator in the i -th criterion layer; A_{ij} indicates the obstacle degree of a single indicator in the indicator layer to the coupling coordination degree of low-carbon logistics, regional economy, and ecological environment; U_j represents the obstacle degree of the criterion layer to the coupling coordination degree of low-carbon logistics, regional economy, and ecological environment. A higher obstacle degree indicates a more significant constraint of that indicator on the coordinated development of the system. By comparing the composition of obstacle factors across different regions horizontally and tracking the evolution trends of obstacle degrees vertically, core bottlenecks affecting the coordinated evolution of the system can be identified. This provides empirical evidence for constructing green transition pathways and coordinated development policies tailored to regional characteristics.

4. Empirical Analysis

4.1. Analysis of Comprehensive Development Level

4.1.1. Overall System Development Trends

This study employs the entropy weighting method to assign weights to the constructed indicator evaluation system, calculating the comprehensive scores of the LREES system for the period 2010–2024. Dynamic trend charts depicting the mean, median, and growth rate are presented (see Figure 1). Overall, the collaborative level of the Yellow River Basin LREES system exhibits an evolutionary pattern characterized by “long-term improvement, phased fluctuations, and coexisting disparities.” The mean composite score increased from 0.1906 in 2010 to 0.3841 in 2024, with an average annual growth rate of approximately 4.5%, indicating a sustained improvement trend. From 2014 to 2019, the growth rate decreased to 3.1%, indicating a slowing trend. This periodic fluctuation is consistent with findings in existing studies. For instance, Dong et al. (2021) noted that the overall ecological efficiency of the logistics industry in the Yellow River Basin remained relatively low during this period, and the potential for green transformation had not yet been fully realized [7]. Similarly, in a comparative study of the Yangtze River Economic Belt, Liang et al. (2022) pointed out that industrial upgrading and adjustment, coupled with ecological governance constraints, were important factors restricting the synergistic development of systems within the basin [8]. The significant divergence between the 2019 mean and median reflects regional polarization. Since 2020, with the continuous advancement of the “dual carbon” goals and the 14th Five-Year Plan, green development momentum has strengthened, leading to a marked improvement in system integration levels. The median and mean trends generally converged, indicating a degree of coordination in inter-provincial synergistic development. However, the significant divergence in 2019 revealed that some provinces leveraged resource and policy advantages to achieve breakthroughs, elevating the overall level while also exposing internal regional disparities. Regarding growth rates, 2011 and 2021 recorded 10.21% and 9.26% respectively, demonstrating the dual-engine effect of

policy and technology. while the growth rates in 2015 and 2022 declined, reflecting that coordinated development still faces phased challenges in industrial restructuring and green transformation. Overall, the coordinated development of the three systems in the Yellow River Basin has progressed from an initial policy-driven phase to a stage of deepening integration and structural optimization. There is an urgent need to further enhance the coordination of interregional development and the level of system integration through differentiated policy guidance and technological innovation support.

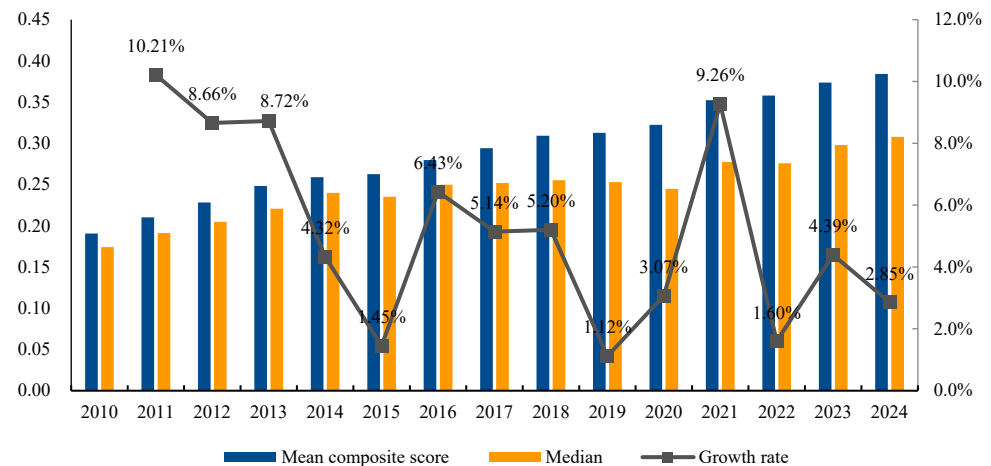


Figure 1. Trends in composite scores of the LREES system in the Yellow River Basin.

4.1.2. Developmental Disparities Among Subsystems

To further analyze the structural evolution characteristics of the LREES system within the Yellow River Basin, this study dynamically measured the development levels of the low-carbon logistics, regional economy, and ecological environment subsystems from 2010 to 2024. The results are presented in Figure 2. Overall, all three subsystems exhibited a continuous growth trend. The low-carbon logistics system maintained a leading position, reaching a score of 0.4432 in 2024. This finding is consistent with the study by Yang et al. (2023) on the low-carbon logistics–economy–environment system in Yunnan Province [9], which also observed that under a multi-system synergistic framework, the logistics subsystem tends to demonstrate a relatively faster pace of improvement. The regional economy subsystem showed strong growth momentum, with its score increasing from 0.1368 to 0.3413, reflecting the significant effectiveness of regional coordinated development strategies and industrial structure optimization. The ecological environment subsystem, driven by governance policies, maintained steady improvement, with its score rising from 0.2407 to 0.3876, indicating a continuous trend of ecological quality enhancement. The gaps among the three subsystems have gradually narrowed, and the trend toward integration has become increasingly pronounced. This convergence characteristic aligns with the empirical findings of Liu et al. (2025) on the interactive relationships among the three systems in Hebei Province, which concluded that during long-term evolution, the linkages among regional logistics, economy, and ecological environment progressively strengthen [11].

To further reveal the heterogeneous characteristics of the three subsystems across different regions in the Yellow River Basin, this study divides the basin into three parts based on geographical location: the upper reaches (Qinghai, Sichuan, Gansu, Ningxia), the middle reaches (Inner Mongolia, Shaanxi, Shanxi), and the lower reaches (Henan, Shandong). The average development levels of low-carbon logistics, regional economy, and ecological environment systems in each region from 2010 to 2024 are summarized (see Table 3). The three major subsystems in the Yellow River Basin exhibited an overall evolutionary

pattern of “sustained improvement with distinct gradients” during the 2010–2024 period, revealing significant developmental disparities among different river segments. In the low-carbon logistics system, the downstream region consistently maintained a significant lead, with its score rising from 0.4523 in 2010 to 0.8036 in 2024—a 77.6% increase. This reflects notable achievements in transportation hub construction and the upgrading of smart logistics infrastructure. In contrast, upstream regions have relatively weaker development foundations, with a 2024 score of only 0.299—approximately 37% of the downstream level. However, they have demonstrated rapid growth in recent years, indicating the gradual release of green logistics development potential. The regional economic system is evolving from an “East-strong, West-weak” pattern toward a “gradient-balanced” trend. Initially, the economic development gap between the middle and lower reaches was pronounced. However, with the continuous advancement of regional coordination strategies, the middle reaches have strengthened their development momentum. Their 2024 score rose to 0.2648, significantly narrowing the gap with the lower reaches. This indicates phased success in industrial transfer reception and development model transformation. The ecological environment system overall exhibits a relatively balanced development pattern. Notably, the upstream region has achieved remarkable ecological governance outcomes, with a score reaching 0.4181 in 2024, surpassing the downstream region. This fully demonstrates that, as a crucial water conservation belt for the Yellow River, it has made positive progress under the support of ecological protection and environmental restoration policies, with continuous improvement in ecosystem quality.

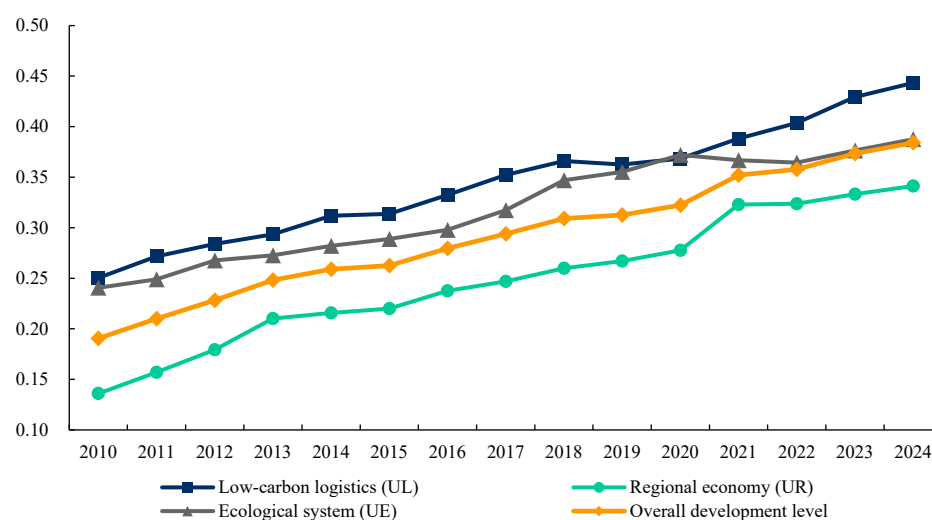


Figure 2. Temporal trends of low-carbon logistics, regional economy, ecological system, and overall development level (2010–2024).

Table 3. Regional development levels of the LREES system in the Yellow River Basin.

System	Time	Upper	Middle	Downstream	System	Time	Upper	Middle	Downstream	System	Time	Upper	Middle	Downstream
Low-Carbon Logistics	2010	0.1584	0.2386	0.4522	Regional Economy	2010	0.0982	0.1099	0.2511	Ecological Economy	2010	0.2675	0.2050	0.2405
	2011	0.1738	0.2612	0.4826		2011	0.1114	0.1229	0.2997		2011	0.2737	0.2183	0.2455
	2012	0.1807	0.2765	0.5017		2012	0.1253	0.1411	0.3444		2012	0.3020	0.2257	0.2618
	2013	0.1957	0.2818	0.5061		2013	0.1368	0.1859	0.3931		2013	0.2845	0.2565	0.2736
	2014	0.2068	0.3084	0.5271		2014	0.1507	0.1579	0.4325		2014	0.3037	0.2565	0.2773
	2015	0.2045	0.3083	0.5403		2015	0.1446	0.1652	0.4533		2015	0.2865	0.2767	0.3118
	2016	0.2188	0.3285	0.5655		2016	0.1636	0.1747	0.4799		2016	0.2972	0.2776	0.3297
	2017	0.2336	0.3367	0.6124		2017	0.1699	0.1903	0.4860		2017	0.3304	0.2747	0.3550
	2018	0.2367	0.3493	0.6494		2018	0.1854	0.1979	0.5015		2018	0.3676	0.2883	0.3934
	2019	0.2324	0.3423	0.6531		2019	0.1920	0.2069	0.5073		2019	0.3699	0.3053	0.4004
	2020	0.2374	0.3466	0.6628		2020	0.1993	0.2082	0.5380		2020	0.3949	0.3114	0.4172
	2021	0.2503	0.3596	0.7068		2021	0.2302	0.2472	0.6220		2021	0.3645	0.3373	0.4158
	2022	0.2625	0.3664	0.7413		2022	0.2322	0.2422	0.6286		2022	0.3670	0.3303	0.4100
	2023	0.2813	0.3856	0.7907		2023	0.2421	0.2522	0.6367		2023	0.3898	0.3369	0.4092
	2024	0.2989	0.3954	0.8036		2024	0.2386	0.2648	0.6617		2024	0.4181	0.3362	0.4037

4.2. Coupling Coordination Evolution Analysis

4.2.1. Analysis of Temporal Evolution Trends

To deeply reveal the temporal evolution characteristics of the coordinated development among the low-carbon logistics, regional economy, and ecological environment systems in the Yellow River Basin, this study measured the coupling coordination degree for each province (region) in the basin from 2010 to 2024 based on the coupling coordination degree model. The annual mean values for sub-regions and the entire basin were calculated, and the results are presented in Table 4. Overall, the mean coupling coordination degree of the Yellow River Basin steadily increased from 0.450 in 2010 to 0.623 in 2024, exhibiting a continuous optimization trend. This indicates that the synergistic linkage mechanism among the three systems has been continuously strengthened, and the effectiveness of coordinated governance and high-quality development has gradually emerged. This study further employed the kernel density estimation method to dynamically characterize the distribution patterns of the coupling coordination degree D at different periods (see Figure 3). The results reveal that the kernel density curves generally exhibit a characteristic of “peak shifting rightward and distribution widening,” reflecting an overall improvement in system synergy levels, while regional differences demonstrate dynamic changes across different stages. In 2010, the coupling coordination degree was mainly concentrated between 0.35 and 0.55, with a high peak and narrow bandwidth of the curve, indicating that most provinces were in the primary coordination stage with relatively concentrated development levels. Around 2015, the kernel density curve showed slight multi-peak characteristics, suggesting that the synergistic development paths of some provinces diverged during the green transformation process. After entering the “14th Five-Year Plan” period, especially from 2021 to 2024, the curve morphology tended toward a “single-peak with wide tail,” with the main peak shifting rightward to above 0.55. The proportion of provinces with high-level coordination increased, and the degree of system integration significantly enhanced. In 2024, the mean coupling coordination degree of the basin reached 0.623, which falls within a comparable range with research findings on other river basins using similar methods [24,25]. In summary, from 2010 to 2024, the coupling coordinated development of the three systems in the Yellow River Basin experienced a phase transition from “low-level agglomeration” to “high-quality synergy” in the temporal dimension. This evolutionary trend aligns with the research conclusions of Haiqiang Ma et al. (2023) on the spatiotemporal coupling of regional economy and carbon environment governance [21].

Table 4. Coupling coordination degree of the LREES system in the Yellow River Basin.

Region	Province	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Upper reaches	Qinghai	0.382	0.388	0.404	0.395	0.408	0.396	0.403	0.418	0.430	0.428	0.431	0.439	0.446	0.463	0.466
	Sichuan	0.493	0.519	0.547	0.571	0.594	0.582	0.612	0.641	0.664	0.668	0.687	0.707	0.713	0.734	0.750
	Gansu	0.345	0.363	0.375	0.390	0.405	0.407	0.419	0.417	0.432	0.439	0.444	0.452	0.456	0.466	0.471
	Ningxia	0.341	0.349	0.356	0.363	0.363	0.365	0.379	0.388	0.394	0.395	0.399	0.407	0.418	0.423	0.428
	Mean	0.390	0.405	0.420	0.430	0.443	0.438	0.453	0.466	0.480	0.482	0.490	0.501	0.508	0.522	0.529
Middle reaches	Inner Mongolia	0.428	0.446	0.464	0.487	0.499	0.498	0.508	0.507	0.513	0.513	0.508	0.539	0.535	0.552	0.559
	Shanxi	0.385	0.404	0.426	0.479	0.433	0.442	0.452	0.458	0.478	0.492	0.502	0.529	0.521	0.526	0.533
	Shaanxi	0.437	0.456	0.468	0.485	0.508	0.528	0.537	0.557	0.564	0.572	0.577	0.597	0.604	0.613	0.620
	Mean	0.417	0.436	0.453	0.484	0.480	0.489	0.499	0.507	0.518	0.526	0.529	0.555	0.553	0.564	0.571
	Mean	0.417	0.436	0.453	0.484	0.480	0.489	0.499	0.507	0.518	0.526	0.529	0.555	0.553	0.564	0.571
Lower reaches	Henan	0.483	0.505	0.529	0.543	0.566	0.594	0.614	0.637	0.669	0.675	0.680	0.700	0.703	0.716	0.714
	Shandong	0.604	0.631	0.654	0.678	0.687	0.702	0.718	0.733	0.747	0.750	0.771	0.800	0.808	0.814	0.823
	Mean	0.544	0.568	0.592	0.610	0.627	0.648	0.666	0.685	0.708	0.712	0.725	0.750	0.756	0.765	0.769

Table 4. Cont.

Region	Province	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Yellow River Basin	Mean	0.450	0.469	0.488	0.508	0.516	0.525	0.539	0.553	0.569	0.574	0.582	0.602	0.606	0.617	0.623

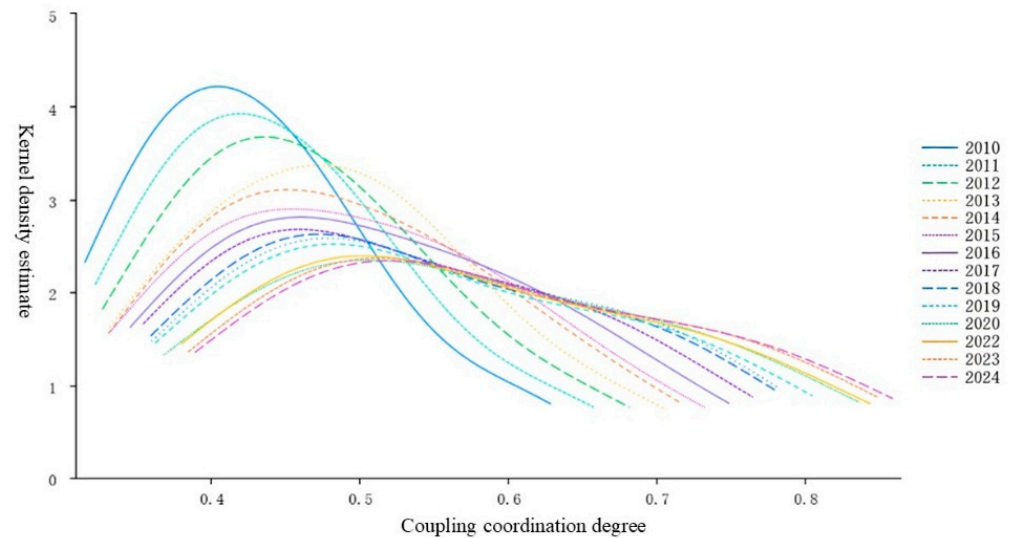


Figure 3. Kernel density evolution of the coupling coordination degree of LREES systems in the Yellow River Basin.

4.2.2. Spatial Distribution Pattern Analysis

This study selects four representative years—2010, 2015, 2019, and 2024—and uses ArcGIS (version 10.8, ESRI, Redlands, CA, USA) to generate classified maps of the coupling coordination degree for the nine provinces (regions) in the Yellow River Basin (see Figure 4), illustrating their spatial distribution and evolutionary trends. Overall, the Yellow River Basin exhibits a sustained upward trend in its overall coupling coordination level. Regional collaborative advancement capabilities continue to strengthen, spatial disparities gradually diminish, and the evolution follows a pattern of “overall improvement, gradient optimization, and enhanced coordination”.

Spatially, the basin’s coupling coordination degree has long exhibited a gradient pattern of “high in the lower reaches, moderate in the middle reaches, and low in the upper reaches,” with an overall east-to-west progression. Among these, Shandong Province in the downstream region has consistently led in coordination levels. Since 2010, it has maintained an intermediate coordination level, advancing to a well-coordinated level by 2024. Its coupling index rose from 0.6045 to 0.8229, demonstrating a stable state of high synergy. Henan Province also progressed from a barely coordinated level in 2010 to an intermediate coordination level, achieving a coordination index of 0.7141 by 2024 and establishing itself as a stable regional growth hub. The midstream regions exhibit a spatial evolution characterized by “overall improvement and convergence of disparities.” Shaanxi Province has seen its coordination level rise annually, reaching the upper limit of the primary coordination level by 2024, reflecting the positive effects of green transition policies and energy structure adjustments. Despite geographical and developmental constraints, the Inner Mongolia Autonomous Region achieved a leap from barely coordinated to primary coordination. Although Shanxi Province improved from near-imbalance to barely coordinated, its coordination level remained below 0.55 by 2024, indicating that its green development transformation requires sustained advancement. The upstream region exhibits weak foundations for coordinated development and significant inter-provincial disparities. Sichuan

Province has steadily improved since 2010, reaching a coordination level of 0.7505 in 2024 and entering the intermediate coordination category, creating a driving effect in the western region. In contrast, the coordination levels in Qinghai and Ningxia have improved slowly, remaining between low coordination and near imbalance as of 2024, making them key regions constraining the overall synergistic progress of the basin. This spatial differentiation pattern is consistent with the trend of “widening inter-provincial disparities” identified by Cheng Gongpeng (2023) [24] and the distribution law of “downstream outperforming upstream” observed by Chen Shuguang et al. (2024) [25]. Furthermore, when compared with the “east-high, west-low” gradient found in Liang et al.’s (2022) study on the Yangtze River Economic Belt [8], it can be observed that river-basin regions generally exhibit a gradient distribution characteristic during spatial evolution, progressively decreasing from areas with stronger economic foundations to those constrained by resources.

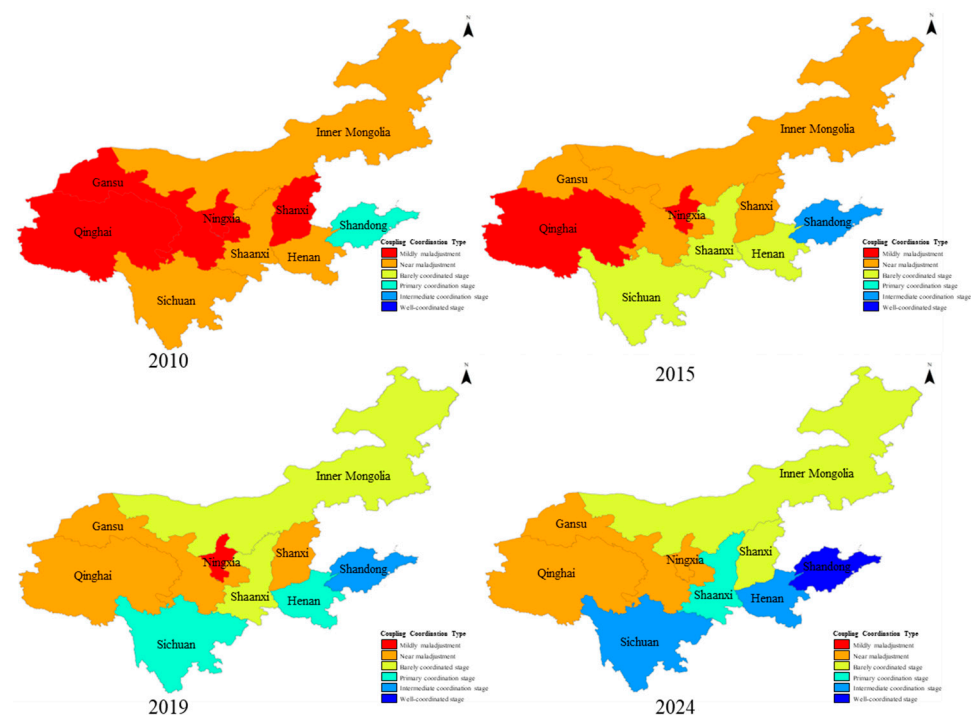


Figure 4. Spatial evolution of coupling coordination types of the LREES system in the Yellow River Basin during Typical Years.

4.3. Spatial Aggregation Analysis of Coupling Levels

4.3.1. Global Spatial Autocorrelation Analysis

This study utilizes panel data on the coupling coordination degree of the LREES system in the Yellow River Basin from 2014 to 2024. By constructing a spatial weight matrix with (version 10.8, ESRI, Redlands, CA, USA) software and performing 999 random replacements via the Monte Carlo method, we calculated the Global Moran’s I, standardized statistics (Z-values), and their significance levels (*p*-values). The relevant results are presented in Table 5. Overall, Moran’s I consistently remained positive, ranging from 0.1568 to 0.2674. This indicates a positive spatial correlation in the basin’s coupling coordination level, exhibiting a degree of agglomeration distribution—particularly pronounced in the low–low type. In most years, Z-values exceeded 1.28 and *p*-values were below 0.15, indicating spatial linkage in regional coupled coordination development. Temporally, Moran’s I steadily increased from 2014 to 2016, reflecting a gradual strengthening of synergistic clustering effects; and continued its upward trend from 2017 to 2019, peaking at 0.2674 in 2019, reflecting phased achievements in regional collaborative governance. Although

the Moran's I value experienced a slight decline after 2020, it remained at a relatively high level overall, indicating that the coupled and coordinated development of the Yellow River Basin still exhibits significant spatial dependency. This trend aligns with findings in existing research regarding the persistence of spatial correlations in regional synergistic development, further confirming that the coupled and coordinated development of the Yellow River Basin maintains a relatively stable spatial dependence.

Table 5. Global Moran's I values of the coupling coordination degree of the LREES system in the Yellow River Basin.

Year	Moran's I	Z	p
2010	0.216936	1.672071	0.09451
2011	0.209805	1.619336	0.105375
2012	0.217139	1.62656	0.103831
2013	0.198769	1.522784	0.127813
2014	0.156778	1.284567	0.198944
2015	0.234304	1.632052	0.102669
2016	0.220084	1.549243	0.121323
2017	0.229818	1.567598	0.116975
2018	0.259052	1.68491	0.092006
2019	0.267358	1.718648	0.085679
2020	0.263854	1.709982	0.087269
2021	0.257158	1.687293	0.091547
2022	0.255512	1.68033	0.092894
2023	0.23408	1.575851	0.11506
2024	0.208759	1.466645	0.142473

4.3.2. Identification of Local Spatial Aggregation Characteristics

Building upon global spatial autocorrelation analysis, this study employs the Local Moran's Index (Local Moran's I) to identify spatial clustering patterns in the LREES system's coordination within the Yellow River Basin using ArcGIS (version 10.8, ESRI, Redlands, CA, USA). LISA clustering maps were generated for four representative years: 2010, 2015, 2019, and 2024 (Figure 5). Results indicate that local spatial clustering predominantly exhibits "high-low," "low-high," and "low-low" patterns, with no occurrence of "high-high" clusters. This suggests significant disparities in coordination levels across different regions and pronounced spatial heterogeneity.

The absence of a "high-high" cluster area reflects, to some extent, that the synergistic development of the Yellow River Basin is still transitioning from a factor-driven to an efficiency-driven stage. In terms of spatial patterns, although Shandong and Henan provinces in the downstream region lead in coupling coordination levels, they are not geographically adjacent, with Hebei Province—a non-study area—lying between them. This geographical separation hinders the formation of a contiguous high-value zone. Between the midstream regions of Shaanxi and Shanxi provinces and the downstream areas, there exists a significant developmental gap. High-value areas often border low-value neighbors, resulting in synergistic effects that manifest more as "high-low" transitions rather than mutual reinforcement. Furthermore, while a few upstream provinces have achieved phased improvements driven by policy initiatives, their coordinated advancements rely primarily on intra-provincial adjustments. Due to resource and environmental constraints as well as infrastructural limitations, their capacity for cross-regional diffusion remains limited, making it insufficient to propel neighboring areas into a state of high coordination.

From the perspective of evolutionary trends, overall level of coordination and synergy within the province and its neighboring regions remained low, with systemic linkage effects yet to materialize. Most other provinces showed insignificant clustering, suggesting that regional coordinated development was still in its early stages. By 2015, Sichuan exhibited a "high-low" clustering pattern for the first time, indicating its relatively high coupling level contrasted with the overall weakness of surrounding provinces, signaling

emerging regional disparities. Provinces like Qinghai and Ningxia remained in a non-significant state, with spatial clustering characteristics still unclear. By 2019, Sichuan maintained its “high–low” pattern, while Qinghai, Gansu, and Ningxia clustered as “low–low,” reflecting weak collaborative development capacity in Northwest China and the initial emergence of regional differentiation. Shanxi and Shaanxi began transitioning to “low–high” clusters, demonstrating potential for collaborative advancement. By 2024, spatial clustering types further diversified. Sichuan maintained a stable “high–low” pattern, while Qinghai, Gansu, Ningxia, and Inner Mongolia remained in a persistent “low–low” cluster, showing no substantial breakthrough in their lagging development. Shanxi, Shaanxi, and Henan transitioned to “low–high,” exhibiting an evolutionary trend from weak to strong, converging toward high-coordination regions. Overall, the spatial dependency of the Yellow River Basin’s LREES system coupling coordination continues to strengthen, with spatial heterogeneity becoming increasingly pronounced. The spatial structure exhibits a dominant “high–low” pattern, an ascending “low–high” trend, and a solidified “low–low” configuration. This finding, when cross-referenced with the stage characteristic description of “overall transition—local differentiation” in regional economy and carbon environment governance by Haiqiang Ma et al. (2023) [21], reflects that the synergistic development in the Yellow River Basin exhibits strong spatial stickiness, with administrative barriers and geographical distance constraining the spillover effects from high-level regions.

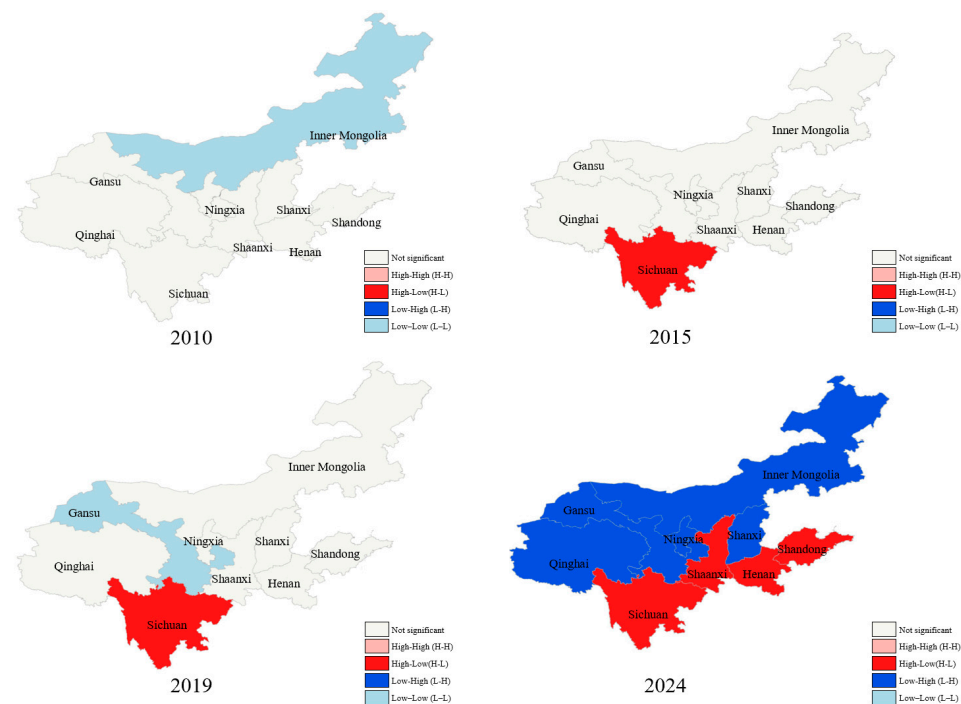


Figure 5. LISA cluster maps of the LREES system in the Yellow River Basin during typical years.

4.4. Identification of Coupling Coordination Barriers

Building upon the coupling coordination degree calculation, this paper introduces an impedance model. Based on the established indicator system (Table 1), it identifies key constraints affecting the coordinated development of the three major systems—low-carbon logistics, regional economy, and ecological environment—in the Yellow River Basin from both the criterion and indicator dimensions. The model systematically assesses the degree to which each indicator impedes the coupling coordination level, thereby revealing core shortcomings in the coordinated development of different regions.

4.4.1. Analysis of Constraints at the Guideline Level

Based on the results of the barrier degree model calculations, from a temporal perspective, the coupled and coordinated development of the LREES system in the Yellow River Basin from 2010 to 2024 exhibits typical structural constraints at the criterion level. Overall, it forms a barrier pattern characterized by “prominent dominant bottlenecks, interlinked secondary factors, and latent risks.” To more intuitively illustrate the long-term evolution trends of constraint factors at each criterion level, this paper presents annual variation charts and average annual change curves for primary constraint levels (Figure 6). The figure reveals that resource foundation and development scale consistently occupy high positions, collectively accounting for over 44% of the total, constituting the primary constraints on the coordinated evolution of the three systems. Their annual values exhibit a gradual upward trend, reflecting the persistence and stability of structural bottlenecks. The dual dominance of resources and scale reflects significant disparities within the basin regarding natural endowments, ecological carrying capacity, and economic scale. In some areas, extensive resource exploitation, fragile ecosystems, and water scarcity have resulted in weak foundations for green development. Simultaneously, regional economic imbalances have led to gaps in the operational efficiency of transportation, markets, and coordination mechanisms, becoming key factors constraining the enhancement of system synergy. Development levels, operational levels, and governance capabilities—all at moderate constraint levels—constitute secondary constraints at the current stage. Though their constraint levels are lower than those of resource and economic factors, they still exhibit strong systemic relevance in areas such as inadequate infrastructure, low system operational efficiency, and limited policy implementation capacity, particularly prominent in central and western provinces. In contrast, while the average constraint levels for green capacity and pollution levels are low, their ecological significance cannot be overlooked. Pollution levels, in particular, exhibit lagging and cumulative characteristics that render their potential risks hidden and irreversible. Phased governance achievements may mask systemic ecological hazards, necessitating vigilance and sustained attention. Overall, the LREES system in the Yellow River Basin exhibits a multi-level constraint pattern at the normative level: dominated by resource and economic factors, supported by foundational and governance factors, and constrained by latent ecological and environmental factors. This highlights the structural imbalances and functional constraints present in the current collaborative development process.

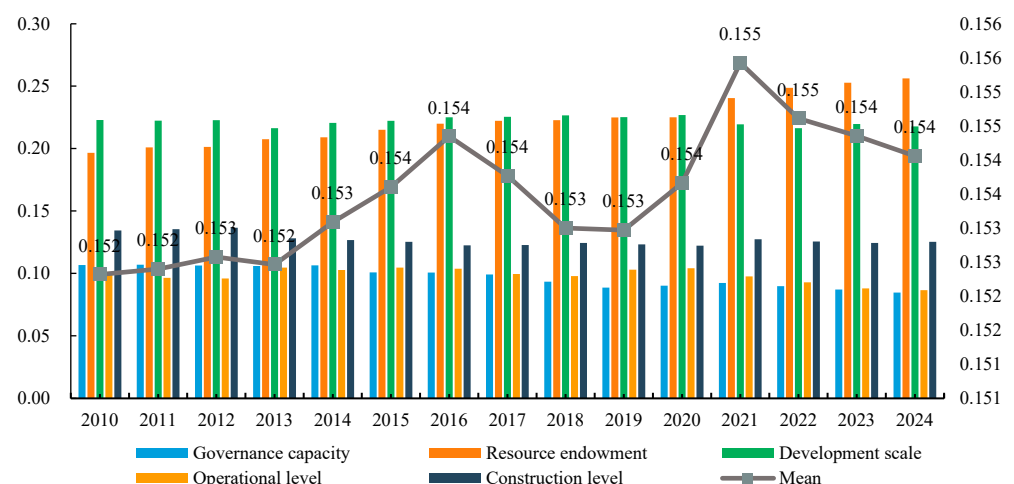


Figure 6. Temporal evolution of major barrier degrees at the criterion level of the LREES system in the Yellow River Basin.

4.4.2. Analysis of Barrier Factors at the Indicator Level

Given the broad coverage, large number, and complex diversity of factors at the indicator level, this study selected the top five indicators by barrier degree for each province across four representative years based on the barrier degree calculation results. Key indicators are listed in Table 6. Regarding the frequency of barrier factors, the total import and export volume (R14) appeared 35 times across the representative years, widely distributed across most provinces. This indicates that the level of openness to the outside world for most inland provinces within the basin still needs improvement, and the external connectivity of the regional economic system and the openness of industrial chains face certain constraints. Per capita water resources (E13) appeared 33 times, concentrated in Gansu, Inner Mongolia, Shanxi, Qinghai, Ningxia, Sichuan, Henan, and Shandong. This indicates significant rigid constraints from ecological endowments, where water scarcity continues to suppress the coordinated development of low-carbon logistics and ecosystems. Logistics industry value-added (L31) and logistics industry fixed-asset investment (L11) appear 32 and 26 times respectively, primarily distributed in the middle and upper reaches of river basins, such as Shanxi, Gansu, Qinghai, and Shaanxi. This indicates that the overall logistics system in river basins still shows deficiencies in construction investment, supporting capabilities, and industrial efficiency. The construction of a green logistics system needs to be strengthened, and the shortcomings in logistics infrastructure have become key bottlenecks hindering industrial synergy and regional interconnection. Urban sewage treatment capacity (E32) appeared 23 times, primarily in ecologically sensitive provinces like Ningxia, Qinghai, and Gansu, revealing persistent challenges in lagging green infrastructure development and inadequate governance capabilities. Additionally, indicators such as high-tech industrial value-added (R23), freight turnover (L23), and fixed-asset investment (R13) frequently rank among the top provincial barriers. This indicates persistent issues in certain regions, including insufficient technological innovation momentum, low transportation efficiency, and imbalanced investment structures, suggesting ongoing structural challenges in the green economic transition. Overall, the core barrier factors across provinces in the Yellow River Basin primarily cluster around three dimensions: ecological resources, infrastructure, and industrial structure. This pattern exhibits a structural barrier characteristic of “prominent resource constraints—insufficient facility support—lagging structural transformation,” constituting key constraints in the coordinated advancement of the three systems. This finding is generally consistent with existing research conclusions. For instance, Cheng Gongpeng (2023) pointed out that disparities in water resource distribution and economic development gradients constitute major contradictions in basin coordination [24]. Chen Shuguang et al. (2024) argued that the weak infrastructure and insufficient openness in the middle and upper reaches constrain green transformation [25]. The quantitative identification of high-frequency obstacle indicators—such as “per capita water resources,” “total import and export value,” and “urban sewage treatment capacity”—in this study provides an empirical supplement and refinement to the above conclusions from a multi-system coupling perspective.

Table 6. Major obstacle indicators at the indicator level of the LREES system in the Yellow River Basin for typical years.

Year	Qinghai	Sichuan	Gansu	Ningxia	Inner Mongolia	Shaanxi	Shanxi	Henan	Shandong
2010	R14 (8.87)	E13 (14.87)	E13 (14.85)	E13 (15.49)	E13 (15.34)	E13 (15.74)	E13 (16.03)	E13 (17.63)	E13 (21.45)
	L31 (7.97)	R14 (8.86)	R14 (8.00)	R14 (8.10)	R14 (8.64)	R14 (8.68)	R14 (8.26)	R14 (9.1)	L11 (7.92)
	E32 (7.62)	L31 (7.89)	L31 (7.07)	L31 (7.24)	L31 (7.09)	L31 (7.38)	L31 (6.99)	L11 (7.26)	L31 (7.17)
	L11 (7.48)	L23 (6.56)	L11 (6.81)	L11 (6.89)	E32 (6.89)	L11 (6.87)	E32 (6.49)	L31 (7.08)	R14 (6.92)
	R23 (6.84)	E32 (6.28)	E32 (6.59)	E32 (6.72)	R23 (6.58)	E32 (6.71)	R23 (6.47)	R23 (6.3)	L23 (5.00)

Table 6. Cont.

Year	Qinghai	Sichuan	Gansu	Ningxia	Inner Mongolia	Shaanxi	Shanxi	Henan	Shandong
2015	R14 (8.77)	E13 (17.49)	E13 (15.83)	E13 (15.78)	E13 (16.15)	E13 (17.29)	E13 (16.88)	E13 (21.04)	E13 (27.15)
	L31 (7.89)	R14 (9.68)	R14 (8.42)	R14 (8.22)	R14 (9.36)	R14 (9.32)	R14 (8.65)	R14 (9.45)	L11 (7.44)
	E32 (7.47)	L31 (8.21)	L31 (7.33)	L31 (7.31)	L31 (7.29)	L31 (7.76)	L31 (7.09)	L11 (6.97)	L31 (7.33)
	L11 (7.14)	L23 (7.15)	E32 (6.69)	L11 (7.09)	E32 (7.23)	L11 (6.82)	L11 (6.65)	L31 (6.46)	R14 (7.16)
	E13 (6.97)	R23 (6.85)	L11 (6.52)	E32 (6.84)	R23 (7.21)	E32 (6.77)	E32 (6.55)	E32 (5.63)	L23 (5.00)
2019	R14 (9.45)	E13 (19.87)	E13 (15.79)	E13 (16.18)	E13 (16.89)	E13 (19.13)	E13 (17.89)	E13 (25.08)	E13 (31.50)
	L31 (8.44)	R14 (10.19)	R14 (8.76)	R14 (8.45)	R14 (9.48)	R14 (9.47)	R14 (9.05)	R14 (10.94)	R14 (6.39)
	E32 (7.93)	L31 (8.59)	L31 (7.45)	L31 (7.52)	R23 (7.51)	L31 (7.74)	L11 (7.39)	R23 (6.60)	R23 (6.38)
	L11 (7.71)	L23 (8.28)	E32 (6.93)	L11 (7.09)	L11 (7.39)	E32 (6.85)	L31 (7.04)	L11 (6.05)	L31 (5.26)
	R23 (7.28)	R23 (6.09)	L11 (6.59)	E32 (6.90)	E32 (7.19)	L23 (6.35)	R23 (6.89)	L31 (5.48)	R13 (5.09)
2024	R14 (9.97)	E13 (26.79)	E13 (16.63)	E13 (16.73)	E13 (17.69)	E13 (20.76)	E13 (18.82)	E13 (28.64)	E13 (45.66)
	L31 (8.82)	R14 (11.22)	R14 (9.06)	R14 (8.72)	R14 (9.79)	R14 (9.89)	R14 (9.52)	R14 (11.51)	L11 (6.31)
	E32 (8.23)	L23 (9.84)	L31 (7.37)	L11 (7.30)	L11 (7.82)	L31 (7.63)	L11 (7.76)	R23 (8.37)	R13 (5.58)
	L11 (8.22)	L31 (7.86)	L11 (6.92)	L31 (7.20)	R23 (7.72)	L23 (6.27)	R23 (7.09)	R35 (5.01)	E33 (5.56)
	R23 (7.45)	R13 (6.27)	E32 (6.89)	E32 (6.96)	E32 (7.58)	L11 (6.03)	L31 (6.80)	E33 (4.05)	R23 (5.15)

Examining the relationship between obstacle factors and coupling coordination levels from regional and temporal dimensions reveals that the phased changes in constraint mechanisms across different regions align significantly with their respective regional development characteristics [26]. In the upstream region, the average coupling coordination degree at the beginning of the study period was 0.390, indicating a relatively low level. Obstacle factors such as per capita water resources and infrastructure conditions accounted for a high proportion, forming the primary constraints. The dual pressures of resource endowment limitations and inadequate supply capacity are consistent with the region's reality of prioritizing ecological functions while facing economic development constraints. Although coordination levels in this region improved with the implementation of relevant policies, the constraint of per capita water resources did not ease simultaneously. In later stages, the obstacle degree of this indicator remained high in some provinces within the basin, reflecting how the rigidity of ecological carrying capacity becomes more pronounced as development intensity increases. The system's coordination thus evolved from low-level coordination to phased improvement, only to tighten again under resource constraints. The midstream and downstream regions, however, exhibited differentiated pathways. In the midstream region, provinces such as Shanxi and Inner Mongolia maintained coupling coordination degrees below the basin average over the long term, with insufficient total import–export volume and openness hindering the positive interaction between logistics and the regional economy. In contrast, provinces like Shaanxi gradually alleviated structural constraints through innovation-driven approaches, demonstrating the growing role of high-tech industrial development in supporting systemic synergy. The downstream region, represented by provinces like Shandong and Henan, generally maintained high coordination levels. However, as economic activity intensified, the constraining effects of indicators related to ecological and environmental carrying capacity became increasingly prominent. To a certain extent, the phased transition of obstacle factors—from resource constraints to structural constraints and then to environmental constraints—corresponds to the gradient distribution of coupling coordination levels, revealing an evolutionary pattern in the green transformation of the Yellow River Basin: a shift from factor-driven development to quality-driven development.

5. Conclusions and Recommendations

5.1. Research Findings

Based on panel data from nine provinces (regions) in the Yellow River Basin covering 2010–2024, this study constructs an LREES system coupling coordination development index system encompassing low-carbon logistics, regional economy, and ecological environment. Employing entropy analysis, coupling coordination degree models, spatial autocorrelation analysis, and obstacle degree models, it systematically analyzes the developmental evolution characteristics, coupling dynamics, spatial agglomeration patterns, and primary constraints. The following conclusions are drawn:

- (1) The comprehensive development level has continuously improved, showing an overall coordinated trend but still exhibiting structural imbalances. From 2010 to 2024, the comprehensive scores of the low-carbon logistics, regional economy, and ecological environment systems in the Yellow River Basin all showed an upward trend, indicating the continuous improvement of the development levels of each system. Among them, the low-carbon logistics system scored the highest. The regional economy system demonstrated strong growth momentum but still faced constraints in terms of openness capacity and structural optimization. The ecological environment system showed the most significant improvement, reflecting the positive effects driven by green transformation policies.
- (2) Coupling coordination levels have generally improved, but regional disparities remain pronounced. Between 2010 and 2024, the coupling coordination of the LREES system in the Yellow River Basin followed an evolutionary trend of “fluctuating increase followed by enhanced synergy,” with the average D-value rising from 0.450 to 0.623, indicating steady progress in coordination levels. However, coordination levels varied significantly across regions, exhibiting a spatial gradient pattern where “downstream areas outperformed midstream areas, and midstream areas outperformed upstream areas,” indicating persistent regional development imbalances.
- (3) Spatial clustering characteristics are pronounced, with regional linkage mechanisms gradually emerging. The overall Moran’s I value remained stable between 0.1568 and 0.2674, consistently positive, indicating a significant positive spatial correlation in the coupling and coordination level of the LREES system. Local spatial analysis reveals that downstream regions (e.g., Shandong, Henan) exhibit pronounced “high-to-low” radiation patterns, while Qinghai, Gansu, and Ningxia persistently remain in “low-to-low” agglomeration zones. Meanwhile, “low-to-high” characteristics are gradually strengthening in areas like Shanxi, Shaanxi, and Henan, indicating emerging spatial synergy potential.
- (4) Development constraints are primarily driven by resource and economic factors, with pronounced structural limitations. Constraint analysis indicates that resource endowment and development scale remain persistently high, constituting the primary bottlenecks for the coordinated evolution of the three systems. Construction level, operational efficiency, and governance capacity represent secondary constraints. Although green capacity and pollution levels account for a relatively low proportion, ecological risks still warrant attention. At the indicator level, frequent occurrences of metrics like per capita water resources, total import–export volume, and urban sewage treatment capacity reflect prominent ecological constraints, insufficient openness, and weak green foundations. Overall, this presents an obstacle pattern dominated by resource limitations and structural lag.

5.2. Policy Recommendations

Based on the above research conclusions, and to comprehensively enhance the coupling coordination level among the low-carbon logistics, regional economy, and ecological environment systems in the Yellow River Basin—promoting the formation of a high-quality development pattern characterized by multi-system synergy, regional balance, and ecological priority—the following policy recommendations are proposed, taking into account the differentiated development characteristics of the upstream, midstream, and downstream regions:

- (1) Optimize logistics infrastructure layout to establish a tiered green logistics network. Addressing the basin's collaborative pattern of "strong downstream, developing midstream, and weak upstream," logistics infrastructure upgrades should be tailored to local conditions. Downstream regions should continuously enhance smart logistics hub development, improve trunk transportation and multimodal transport systems, and strengthen their radiating and driving effects on mid- and upstream areas. Midstream regions should deepen the integration of logistics and energy industries, promoting facilities for green coal transportation and emergency logistics storage and distribution. Upstream regions should focus on addressing shortcomings in cold chain logistics, urban-rural distribution, and green transportation to advance balanced regional logistics infrastructure development.
- (2) Promote the synergistic regulation of resources and the economy to alleviate structural development constraints. In response to the persistent structural bottleneck characterized by abundant resource reserves yet significant disparities in development scale, region-specific regulatory strategies should be implemented in areas with acute water scarcity and pronounced economic disparities. For upstream regions with insufficient resource endowments (e.g., Gansu, Ningxia, Qinghai), within the framework of total water resource control and water usage quota systems, high-water-consuming industries should be guided to phase out or transition in an orderly manner, with clear restrictions on the expansion of projects that are high in water consumption and emissions. Priority should be given to developing modern water-efficient agriculture, clean energy, and eco-service-oriented industries, accompanied by the promotion of efficient water-saving irrigation technologies and industrial water conservation measures to align industrial structure with water resource carrying capacity. For midstream regions with relatively weak economic foundations (e.g., western Inner Mongolia, southern Shanxi), fiscal transfer payments and industrial enclave cooperation should be leveraged to achieve complementary resource utilization and enable regional economic gradient development, thereby enhancing the endogenous growth capacity of the economic system. Downstream regions, on the other hand, should further leverage their industrial and market advantages to promote the efficient agglomeration of production factors and the optimization and upgrading of economic structures.
- (3) Focus on high-frequency constraint indicators and implement targeted governance actions. Differentiated governance plans should be implemented for indicators with high constraint rankings. For instance, in upstream regions where per capita water resource constraints are prominent, efforts should be accelerated to optimize water resource allocation projects and promote water-saving agricultural technologies such as drip irrigation. In midstream and inland provinces with low total import–export volumes, the construction of open-economy pilot zones should be advanced, encouraging the development of international logistics and cross-border e-commerce industries. For areas with weak urban sewage treatment capabilities, priority should be given to upgrading and expanding sewage treatment facilities, improving sewage collection pipeline networks, and enhancing the capacity of green infrastructure.

- (4) Strengthen regional collaborative governance mechanisms to enhance policy coordination efficiency. Establish and improve coordinated basin governance mechanisms that span upstream and downstream regions and enable horizontal linkage. Leveraging the national-level coordinated mechanism for high-quality development in the Yellow River Basin, promote cross-regional cooperation among provinces in areas such as green logistics standards, carbon trading mechanisms, and industrial chain coordination. Encourage pilot programs in mid-basin regions to establish a dual-drive mechanism combining “ecological compensation and industrial synergy.” By integrating fiscal guidance with market mechanisms, enhance institutional linkage effectiveness, overcome administrative boundary barriers, and elevate regional collaboration levels. Encourage the midstream region to pilot the establishment of a dual-driven mechanism combining “ecological compensation and industrial synergy.” By integrating fiscal guidance with market mechanisms, this approach aims to enhance institutional coordination effectiveness, break down administrative barriers, and elevate the overall synergistic development level of the basin.

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