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Analysis of obstacle factors in the collaborative governance of the ecological environment in the yellow river basin

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Collaborative governance (co-governance) is a crucial pathway and essential strategy for ensuring ecological security and high-quality development in the Yellow River Basin (YRB), which faces complex ecological challenges amid unbalanced regional development. This study employs a three-layer driving chain analytical framework to systematically investigate barriers to ecological co-governance in the YRB through a tiered approach. Firstly, spatial econometric methods are utilized to analyze spatial agglomeration, network strength, and spatial spillover effects, clarifying macro-level associations and driving mechanisms of ecological collaborative governance. Subsequently, tripartite evolutionary game analysis is conducted to explore the intrinsic dynamic logic of barrier factors emerging from micro-level interactions among key actors, supplemented by core driving layer theoretical analysis to investigate obstacles in the co-governance system. The results indicate that, (1) From a spatial measurement perspective, the effectiveness of ecological governance in the YRB exhibits significant spatial correlation, agglomeration, and interaction effects, with insufficient digital governance levels and structural flaws in the green industrial sector identified as key apparent-level barriers. (2) Under stable collaborative conditions, the vertical governance system operates efficiently; parameter sensitivity analysis and model robustness tests reveal that environmental protection costs in production, environmental regulation intensity, and supervision intensity are critical and sensitive parameters, significantly influencing the speed of strategic change and convergence, with the model demonstrating strong robustness. (3) Critically, divergent governance concepts and conflicting regional interests, rooted in disparities in core governance awareness and interests, constitute the most fundamental barriers to ecological co-governance.

KEYWORDS

collaborative governance, three-layer drive chain, spatiotemporal analysis, spatial lag model, evolutionary game model

1 Introduction

The YRB holds a key position in China's ecological security pattern and regional economic development map, and is an important pillar for maintaining national ecological stability and promoting coordinated regional development. At present, the governance of river basins still faces practical problems such as insufficient coordination between water conservation in the upper reaches and soil and water conservation in the middle and lower

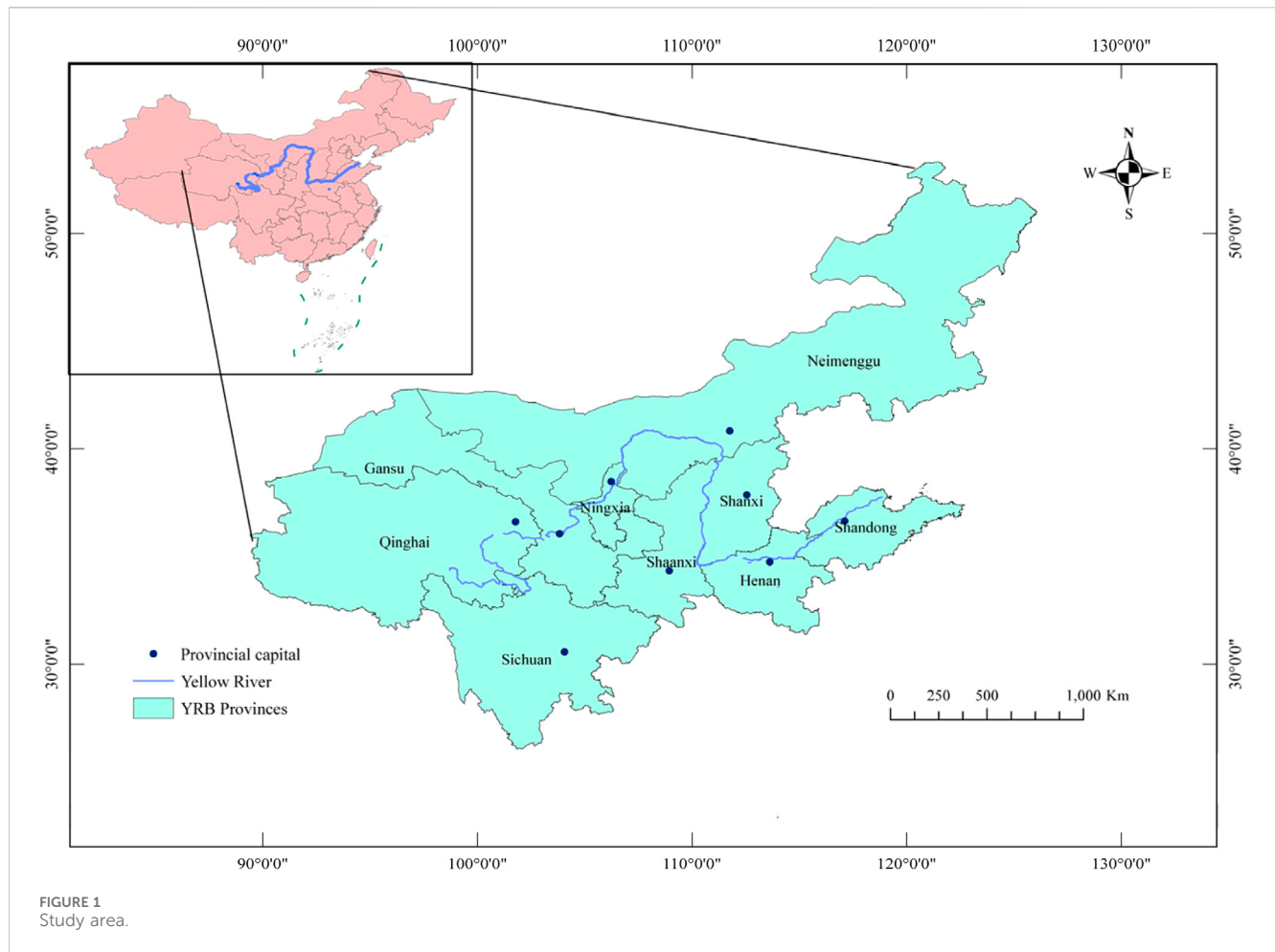
reaches, as well as poor cross-regional rights and responsibilities connection. It is urgent to break the “segmented governance” model and build a governance system that is coordinated throughout the region. On 20 January 2025, the Political Bureau of the Central Committee of the Communist Party of China held a meeting to review and approve the “Opinions on Comprehensively Promoting Ecological Protection and High-Quality Development in the Yellow River Basin”, clearly requiring continuous improvement of the large-scale ecological protection and coordination pattern in the YRB. This will be achieved by systematically enhancing the water conservation capacity in the upper reaches, strengthening soil and water conservation in the middle reaches, and promoting wetland protection and ecological governance in the lower reaches. Strengthen the integrity and correlation of ecological protection throughout the entire river basin; At the same time, it is emphasized that the Central Leading Group for Coordinated Regional Development needs to strengthen overall coordination and supervision and guidance, and relevant central departments should increase their support. The Party committees and governments at all levels in the provinces and regions along the Yellow River should earnestly fulfill their main responsibilities, forming a vertical governance system of “central coordination-departmental collaboration-local implementation”, which not only delineates the implementation path of cross-regional collaboration and hierarchical linkage for the governance of the river basin, It also provides a system framework for mobilizing multiple forces, including enterprises and social organizations, to participate in governance. Despite the high attention of the state and the active actions of various provinces, in the actual process of promoting co-governance, numerous obstructive factors have emerged one after another, significantly reducing the governance efficiency and hindering the improvement of the ecological environment in the YRB. A thorough understanding and analysis of these obstructive factors is precisely a key link in responding to the requirements of the above-mentioned meeting for “cross-regional coordination” and “hierarchical linkage”, and implementing the concept of multi-party participation in the Yellow River Protection Law. It has immeasurable practical significance for promoting the improvement of the ecological environment in the YRB and achieving a win-win development of ecology and economy.

Existing studies on the barriers to ecological co-governance in the YRB have adopted a single-dimensional analytical lens. Scholars have constructed multi-dimensional evaluation frameworks centered on ecological resilience, governance performance, environmental regulation efficiency, and industry-ecology synergy, leveraging spatial econometric models to decipher driving mechanisms. For instance, involved spatial analysis on four dimensions—ecological image, culture, institution, and vitality—using models such as the Theil index, modified gravity model, and multiscale geographically weighted regression (Yang et al., 2024). From the perspective of synergistic enhancement, it reveals the differentiation mechanism of four dimensions upgrading of provincial capital cities through ecological corridor construction and policy coordination to drive the development of the surrounding areas. Examined the impacts of technological innovation, opening-up, and industrial structure on ecological resilience using the Spatial Durbin Model (Wang et al., 2023). The DPSIRM framework is integrated with spatial autoregressive

models (SAR) to identify the “pollution haven” effect of interprovincial industrial transfers, and green technology diffusion and market entry restrictions are advocated for to enhance basin-wide collaborative emission reduction (Cai et al., 2022). Additionally, combined coupling coordination models with spatial econometric techniques to uncover the “east-high-west-low” spatial divergence in ecological-economic coordination across the YRB (Li et al., 2022). While these studies highlight the strengths of spatial econometric models in identifying cross-regional interactions and optimizing policy synergies, they often overlook the micro-level behavioral dynamics of governance actors.

In the realm of micro-level behavioral motivations for ecological collaboration, evolutionary game theory has emerged as a critical tool for analyzing strategic interactions among governments, enterprises, and the public. Early research focused on single-policy scenarios: The study developed a dual-level (interprovincial and intraprovincial) game model to assess the effectiveness of ecological compensation mechanisms, demonstrating that their success hinges on the synergistic enhancement of penalty intensity and information transparency (Dong et al., 2024). Constructed a central-local government game framework under China’s environmental inspection regime, revealing that inspection accountability pressures significantly curb local governments’ tendencies towards ‘passive collusion.’ Recent studies have innovatively incorporated extended variables such as reputation mechanisms and technology spillovers (Li et al., 2024). For example, Researchers (Cao et al., 2024) constructed a central-local government game framework under environmental inspection regime, revealing that inspection accountability pressures significantly curb local governments’ tendencies towards ‘passive collusion’. Absorptive capacity theory was integrated, proving that local governments’ ability to imitate neighboring governance practices acts as a key mediator in interprovincial ecological compensation coordination (Lu et al., 2022). Similarly, climate investment and finance and ecological value realization mechanisms were incorporated into a game-theoretic framework (Zhu et al., 2024). A tripartite evolutionary model involving governments, polluting firms, and third-party certifiers was designed, with simulations indicating that a 65% reduction in third-party certification costs effectively resolves “regulatory capture” dilemmas (Xu et al., 2018). These studies, along with several other research works (Lou et al., 2022; Peng et al., 2024; Zhang et al., 2024; Zhao et al., 2023) quantify the sensitivity of institutional parameters to equilibrium strategies through dynamic simulations, offering micro-level insights for precision policy design.

Existing studies have been able to clearly identify the key obstructive factors of co-governance from both macro and micro perspectives respectively. However, the determination of the levels and roles of these obstructive factors often lacks reasonable analytical support. Moreover, the failure to combine macro and micro factors has led to the entire co-governance system chain not being closed. For instance, macro spatial analysis is difficult to reveal the behavioral motives of governance subjects through apparent indicators (Chen M. et al., 2022; Jiang et al., 2023; Xu S. T. et al., 2024; Sun et al., 2023; Chen Y. et al., 2022). The micro-behavioral game model lacks the constraints of geographical heterogeneity on the choice of behavioral strategies, which easily makes it difficult for



policy recommendations to reach the root obstacles that hinder co-governance.

Therefore, this study takes the YRB comprehensive collaborative governance system as the research object, and based on the two-way perspectives of horizontal cross-regional collaboration and vertical multi-subject collaboration (central-local-enterprise interaction), conducts in-depth analysis using a three-layer driving chain structure. Firstly, after stratifying the obstacle factors, a spatial macroscopic analysis of the apparent driving layer is conducted to identify the spatial correlation and agglomeration characteristics of the basin's ecological governance, laying the foundation for clarifying the horizontal synergy effect. Secondly, construct a tripartite evolutionary model of stakeholders in the intermediate influence layer, explore the dynamic equilibrium of co-governance under the interaction of multi-agent strategies, and interpret the vertical collaboration mechanism. Finally, analyze the ideological obstacle factors of the core driving layer and address the root cause of the contradiction between horizontal collaboration and vertical collaboration. Overall, through the combination of spatial econometric model support, evolutionary game numerical simulation, and core factor theoretical analysis, systematically dissects the predicament of the YRB ecological co-governance system from the outside to the inside from a dual perspective, providing targeted analytical support for breaking the "fragmented governance" predicament.

2 Materials and methods

2.1 Study area

The Yellow River is the second longest river in China, with a total length of approximately 5,464 km, flowing through nine provinces and autonomous regions including Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan, and Shandong (Figure 1). There are significant regional differences in ecological quality and economic development within the YRB. Overall, the ecological environment of the YRB is relatively poor. The Yellow River accounts for only 2% of the country's total water resources, yet it must meet the water needs of 12% of the population and 17% of the cultivated land in the basin. In some areas of the basin, low vegetation coverage, concentrated precipitation, and frequent rainstorms lead to a large influx of sediment into the Yellow River, which raises the riverbed and increases flood control pressures. Moreover, as a key agricultural and industrial area in China, the economic development in the downstream provinces is significantly more advanced than that in the upstream regions. These issues are complex and challenging, spanning multiple regions, and severely restricting the sustainable development of the Yellow River economic belt. Therefore, it is imperative to conduct in-depth research on the barriers to ecological co-governance in the basin to promote high-quality development in the YRB.

TABLE 1 Specific obstacle factors.

Label	Obstacle factors
F ₁	Obstacles to corporate ecological collaboration
F ₂	Irrationality of the performance evaluation system
F ₃	Ambiguous definition of governance responsibilities
F ₄	Inadequate market regulation of environmental rights and interests
F ₅	High difficulty in the coordinated development of industries
F ₆	Lack of interest compensation and incentive mechanisms
F ₇	Defects in the green - development structure
F ₈	Considerable problems in the alignment between local policies and basin - wide policies
F ₉	Regional interest conflicts
F ₁₀	Institutional obstacles to judicial cooperation
F ₁₁	Insufficient vertical inter - government co-governance
F ₁₂	Weak correlation between network node characteristics and governance efficiency
F ₁₃	Differences in governance concepts
F ₁₄	Insufficient public participation and social coordination
F ₁₅	Facing challenges of innovative technologies
F ₁₆	Low level of digital governance

2.2 Data sources and factor acquisition

The study takes provincial administrative units as the research units. By systematically reviewing the relevant literatures in databases such as CNKI, Web of Science, and Ei Village, and combining with the policy documents released on the national official website, a systematic review and frequency statistics of the obstructive factors for ecological co-governance in the YRB mentioned in the literatures were conducted first. Then, based on the significance and frequency of the influence of the factors on governance practices, this study makes a preliminary selection. Subsequently, five experts who have been deeply engaged in the research field of the YRB for more than 3 years and hold at least the title of associate professor were invited to participate in the verification. These experts mainly come from the middle and lower reaches of the basin, and their research fields cover environmental governance, environmental policy analysis, sustainable development, environmental management science and engineering, etc. After expert verification and by eliminating some repetitive factors and combining those with strong correlations, 16 specific obstacle factors for the ecological co-governance of the YRB were finally determined through comprehensive screening (Table 1). The research data regarding the apparent layer and the ecological co-governance index are obtained from sources such as the National Data Network, China City Yearbook, China Statistical Yearbook, and China Urban Construction Yearbook. These data cover the nine provinces along the YRB from 2014 to 2023. Missing data are filled using the linear interpolation.

2.3 Research framework

2.3.1 Theoretical framework design and advantages

The three-layer driving chain framework is rooted in the co-governance theory proposed by Bodin (2017), which emphasizes that effective cooperation among different public and private actors as well as stakeholders is crucial when addressing complex environmental issues. Traditional co-governance research often suffers from narrow analytical perspectives and unclear hierarchical relationships when dealing with complex issues such as trans-regional river basin governance. Specifically, studies in the field often adopt fragmented perspectives, analyzing from macro, micro, and theoretical angles in isolation (Jiang and Zheng, 2024; Xu M. et al., 2024; Geng et al., 2022; Zhu et al., 2023; Nie et al., 2024), ignoring their connections and contradictions, and lacking a systematic transmission process, making it difficult to put forward constructive suggestions for the overall governance framework. To solve these problems, this study innovatively integrates and constructs a three-layer driving chain analytical framework, deeply integrating the co-governance theory, aiming to open up a new path for co-governance. Meanwhile, the analysis also conform to the processes and ideas of traditional methods, with credibility and reliability.

The framework transcends the flat and isolated analytical approaches of traditional research, establishing a three-dimensional hierarchical structure spanning the apparent driven layer, intermediate influence layer, and core driving layer. Progressing from shallow to deep, these layers jointly dissect ecological governance obstacles from diverse perspectives to enable efficient ecological co-governance: the apparent layer centers on the application effects of explicit tools, leveraging spatial econometrics to precisely identify characteristics like spatial agglomeration, network strength, and spillover of river basin governance outcomes; the intermediate layer focuses on subjects' behavioral strategies, integrating the "multi-subject collaborative interaction" concept of co-governance to analyze actors' behavioral choices during interest balancing and their impacts on the governance process; the core driving layer returns to the essence of "multi-subject consensus building" in co-governance, delving into ideological factors and their potential influences on governance directions, while incorporating insights from international governance frameworks. Compared to traditional co-governance research, this framework innovates and integrates at both theoretical and practical levels, overcoming the macro-micro disconnection dilemma: theoretically, it reconstructs a transmission chain for governance obstacles, tracing tool failures back to core-layer conceptual roots and revealing multi-perspective factor connections; practically, it bridges macro spatial spillover effects with micro subjects' strategy choices—addressing the fragmentation of existing studies (e.g., theoretical reviews, spatial econometrics, evolutionary games)—and by connecting macro governance spatial patterns with micro behavioral collaboration under core concepts, provides a holistic trans-regional co-governance solution from spatial pattern identification and behavioral strategy analysis to conceptual consensus building.

2.3.2 Technical route

Based on the three-layer driving chain analytical framework (Figure 2), this study first classifies 16 obstacle factors affecting the

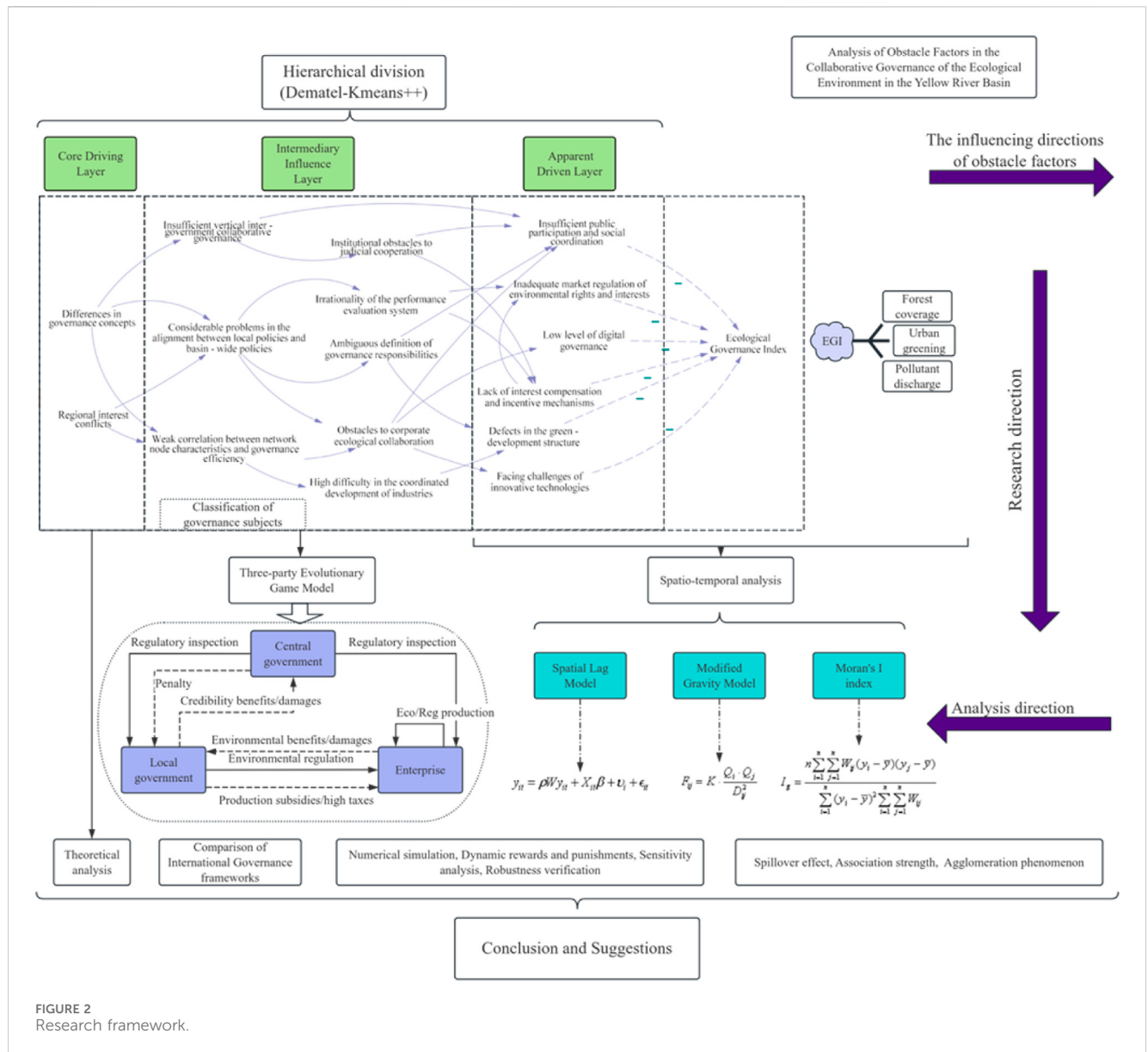


FIGURE 2
Research framework.

ecological co-governance of the YRB into the apparent driven layer, the intermediate influence layer, and the core driving layer using the DEMATEL method and K-means++ algorithm. Subsequently, in the horizontal perspective of the apparent layer, Ecological Governance Index (EGI) was constructed to analyze its spatiotemporal variations, and the global Moran's I index, modified gravity model and Spatial Lag Model (SLM), were utilized to analyze spatial correlations and spillover effects, thereby identifying the key epigenetic driving layer obstacles. From the vertical perspective of the intermediate influence layer, a tripartite evolutionary game model involving enterprises, local authorities and the central government was established. Through the analysis of equilibrium point stability, combined with numerical simulation, parameter sensitivity analysis and model robustness test, the interaction law of the subject strategy was clarified. At the core driving layer, core obstacles were analyzed, and experiences were extracted by comparing international governance frameworks. Finally, the research findings from the three layers were

integrated, and conclusions as well as targeted governance recommendations were proposed from both horizontal and vertical dimensions, to systematically reveal the obstacle mechanisms and solutions for ecological co-governance in the YRB.

2.4 Methods: quantification tools for the three-layer driving framework

2.4.1 Hierarchical classification of obstacle factors

The Decision-Making Trial and Evaluation Laboratory method (DEMATEL) constructs an influence relationship matrix to assist decision-makers in identifying the interactions among various obstacle factors in the ecological co-governance system of the YRB, thereby revealing the causal relationship structure within the system (Du and Li, 2022). The direct influence matrix is expressed as A after standardization. A comprehensive influence matrix T is equal to the direct impact A multiplied by the indirect

impact $(I - A)^{-1}$. The sum of each row element r_i represents the comprehensive influence of factor i on all other factors, the sum of each column element represents the degree to which factor j is affected by all other factors:

$$P_i = r_i + c_j \quad (2.1)$$

$$D_i = r_i - c_j \quad (2.2)$$

the values P_i and D_i respectively represent the sum of the degree of influence and influence by other factors, and the degree of influence on other factors as a cause factor.

The K-means++ algorithm first randomly selects a data point from the centrality and cause-degree values of each factor obtained by the DEMATEL as the first cluster center (Arthur and Vassilvitskii, 2006). For the i -th cluster center ($i > 1$), and for any data point x in the dataset, the distance $d(x, c_j)$ is the distance from each factor to the clustering centers. The probability $P(x)$ that the data point x is selected as the next cluster center is proportional to the square of the distance from it to the nearest selected cluster center:

$$P(x) = \frac{d^2(x, C)}{\sum_{y \in X} d^2(y, C)} \quad (2.3)$$

where X represents the entire dataset, $C = \{c_1, c_2, \dots, c_k\}$ is the set of k selected clustering centers. This avoids the problem of over-concentration of initial cluster centers, enabling more accurate clustering and hierarchical structuring of the obstacle factors in the co-governance of the ecological environment in the YRB.

2.4.2 Spatial agglomeration measurement

The EGI directly reflects the effectiveness of ecological environment governance. To study the coordinated development and spatial correlation within the YRB region, it is necessary to obtain the spatial autocorrelation index. Global spatial autocorrelation was used to analyze the distribution characteristics of the EGI and the spatial correlation across the basin (Dewinter et al., 2022). The calculation formula of the global Moran's I index is as follows:

$$I_g = \frac{n \sum_{i=1}^n \sum_{j=1}^n W_{ij} (y_i - \bar{y})(y_j - \bar{y})}{\sum_{i=1}^n (y_i - \bar{y})^2 \sum_{i=1}^n \sum_{j=1}^n W_{ij}} \quad (2.4)$$

among them, the value range of the Moran's I index (I_g) is $[-1, 1]$. Specifically, $I_g > 0$ indicates positive correlation, while $I_g < 0$ indicates negative correlation. Geographical proximity is used to construct the spatial weight matrix, which provides a prerequisite for spatial data analysis. By incorporating spatial structure characteristics, the results can better align with the actual spatial distribution.

2.4.3 Inter-provincial ecological collaboration linkage intensity measurement

In the process of ecological collaborative management in the YRB, the characteristics of close correlation and mutual influence among provinces and regions in the basin are extremely critical. The theoretical roots of the gravitational model can be traced back to Newton's law of universal gravitation. The improved model can depict the spatial connection strength between cities or regions through indicators such as GDP (Yang et al., 2024). By using the

modified gravity model, this study can accurately analyze the spatial linkage strength and its changes across temporal and spatial dimensions. The formula is as follows:

$$F_{ij} = K \cdot \frac{Q_i \cdot Q_j}{D_{ij}^2} \quad (2.5)$$

F_{ij} represents the intensity of the spatial connection between city i and city j , Q_i and Q_j represent the EGI of city i and city j respectively, D_{ij}^2 Represents the distance between two cities, where K is the proportionality constant, in this experiment, the value of it is 1.

2.4.4 Apparent driven obstacle spatial spillover effects measurement

Spatial panel models are econometric models that combine spatial correlation and the time dimension. They can effectively capture the spatial dependence and temporal trends among the ecological governance indices of various provinces. Specifically, the introduction of spatial weight matrices and spatial econometric models can reflect the mutual influence of ecological governance among provinces in a river basin and characterize the spatial dependence of ecological environment indices (Wang et al., 2023). After model verification, due to the weak spatial spillover effect of the independent variable, this study selects the SLM derived from the degradation of the Spatial Durbin model (SDM) to investigate the spatial spillover effect of the dependent variable. The EGI of each province is influenced not only by the obstacle-factor indicators within the province itself but also by the governance indices of neighboring provinces. The formula for the spatial panel lag model (random-effect) is:

$$y_{it} = \rho W y_{it} + X_{it} \beta + v_i + \epsilon_{it} \quad (2.6)$$

y_{it} is the variable value of unit i at time t . ρ is the spatial lag coefficient, which measures the degree of spatial dependence. X_{it} is the matrix of explanatory variables, which incorporates various factors that affect y_{it} . β denotes the degree of influence of the explanatory variables on the explained variable. v_i is the random-effect term, representing the random effect of the i -th unit and reflecting the unobservable heterogeneity of each unit. ϵ_{it} is the error term and satisfies specific distribution assumption. W is the spatial weight matrix, which describes the spatial or adjacency relationships across spatial units.

2.4.5 Intermediate influencing layer strategic interaction simulation

In the ecological co-governance system of the YRB, understanding the motives and strategies of the microscopic behaviors of the main bodies is of great importance. The high-, medium- and low-influence driving layers in the intermediate influence layer of this study can be attributed to three types of main bodies: the central government, local governments, and enterprises. These three subjects all belong the vertical cooperative governance system of the YRB, and there are game relations and differences in interest goals among them. A tripartite evolutionary game model is established for them to analyze the strategic choices and dynamic changes of the main bodies, find the stable equilibrium points of the strategies, and analyze the

optimization direction of the microscopic behavior mechanism of the co-governance main bodies.

Based on the actual conditions of the basin and the research design, the game relationships and specific interest orientations among various entities can be determined (Han et al., 2023). Subsequently, the spread and evolution of strategies among these entities can be simulated through the expected payoffs of each entity (for specific assumptions, see Section 2.5.3). Suppose the expected pay-off for subjects when choosing the “adopt” strategy is W_{11} , the expected pay-off when choosing the “do not adopt” strategy is W_{12} , and the average expected pay-off is W_1 :

$$W_1 = xW_{11} + (1-x)W_{12} \quad (2.7)$$

The dynamic replication equations of subjects (x , y , z) behavioral strategies and a Jacobian matrix J is constructed for stability analysis are obtained as follows (Only display $F(x)$):

$$F(x) = dx/dt = x(W_{11} - W_1) \quad (2.8)$$

$$J = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix} = \begin{bmatrix} \alpha_{11} & \alpha_{12} & \alpha_{13} \\ \alpha_{21} & \alpha_{22} & \alpha_{23} \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{bmatrix} \quad (2.9)$$

$\alpha_{12} = \frac{\partial F(x)}{\partial y}$ measures how y impact the evolutionary speed of strategies $F(x)$ (the same logic applies to others). Under the condition of Jacobian matrix stability, the system evolves toward an equilibrium state. Numerical simulation analysis can be employed to identify key parameters and the specific implementation path for co-governance.

2.5 Empirical design and parameter setting

2.5.1 Obstacle factor influence matrix

The construction of the Obstacle factor influence matrix was also determined by the majority voting principle of the above five experts. The scoring process follows the principle of majority voting: Only when 3 or more experts unanimously agree that there is an influence among the factors does the scoring stage commence. Subsequently, based on the intensity of the influence (strong, medium, or weak), the scoring is further refined through the principle of majority voting by the five experts. However, the number of experts, their regional distribution, the coverage of research fields, and the limitation that this scoring matrix cannot conduct reliability and validity statistics may have a potential impact on the universality of the research results. The direct influence matrix (Table 2) was derived and constructed after expert interviews and analysis of the obstacle factors for the co-governance of YRB collected from literature and materials. The score range is from 0 to 9, with 0 indicating almost no direct influence and 9 indicating strong direct influence.

2.5.2 Establishment of the indicator system

The EGI will select indicators from three dimensions: sewage discharge, urban greening, and forest coverage (Table 3). The standardized data are weighted using the critic weighting

method, and the comprehensive score is derived via a comprehensive evaluation approach. The six factors in the apparent driven layer are taken as explanatory variables (Table 4), and the EGI is taken as the explained variable to establish a spatial econometric model, aiming to explore the macro-level impact of obstacle factors on ecological co-governance. The data of obstacle factors in the driving layer, which have different measurement scales, were standardized, and collinearity diagnosis was performed. The VIF values were all less than 5, indicating no obvious multicollinearity among the explanatory variables.

2.5.3 Basic assumptions of the evolutionary game model

1. Game Subjects

The game involves three participant groups: enterprises, local governments, and the central government, all of which have bounded rationality.

2. Assumptions and meanings of relevant parameters in the evolutionary game model (Table 5)

3. Probabilities of adopting behavioral strategies

Suppose that in the initial state of the game among the three players, the probability that an enterprise chooses the “adopt environmentally friendly production” strategy is x , and the probability of choosing the “not adopt” strategy is $1-x$. (where $0 \leq x \leq 1, 0 \leq y \leq 1, 0 \leq z \leq 1$). In subsequent analysis, “taking environmentally friendly production actions” is denoted as 1 and “not taking environmentally friendly production actions” as 0, resulting in a total of eight strategy combinations.

3 Results and discussion

3.1 Hierarchical division analysis

In Figure 3, F_6 , F_7 , and F_{15} , as strong result factors, and F_4 , F_{14} , and F_{16} , as weak result factors, indicate that these six influencing factors are more likely to belong to the apparent-driven layer. F_9 and F_{13} , as strong cause factors, suggest that they are more likely to play the role of core drivers and influencers in the entire system. And F_1 , F_2 , F_3 , F_5 , F_8 , F_{10} , F_{11} , F_{12} may be at an intermediate level, both influencing the apparent factors and being influenced by the core factors.

Clustering is performed on the centrality and cause degree values, with the optimal number of clusters set between 3 and 6 (determined based on the number of influencing factors). Using the silhouette coefficient and clustering effect as criteria, it is found that the optimal number of clusters is 6 when the silhouette coefficient reaches 0.79 (Table 6). For further analysis, the core driving layer is retained; the high, medium, and low influence driving layers are merged into an intermediate influence layer; and all driven layers are merged into the apparent driven layer. Additionally, the EGI is incorporated as an indicator to characterize the direct impact of driven-layer indicators on the EGI. This facilitates analyzing the influence intensity and specific effects of factors in the apparent

TABLE 2 Obstacle factor direct influence matrix.

Obstacle	F ₁	F ₂	F ₃	F ₄	F ₅	F ₆	F ₇	F ₈	F ₉	F ₁₀	F ₁₁	F ₁₂	F ₁₃	F ₁₄	F ₁₅	F ₁₆
F ₁	0	1	1	4	0	6	5	0	0	1	0	0	0	4	5	4
F ₂	0	0	0	3	0	5	4	0	0	0	0	0	0	3	4	4
F ₃	0	0	0	3	0	5	4	0	0	0	0	0	0	3	3	3
F ₄	0	0	0	0	0	2	1	0	0	0	0	0	0	0	1	0
F ₅	0	1	1	4	0	6	5	0	0	1	0	0	0	4	5	4
F ₆	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F ₇	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
F ₈	1	2	2	4	1	6	5	0	0	2	0	0	0	4	5	4
F ₉	4	6	5	7	4	9	8	3	0	5	3	3	0	7	8	7
F ₁₀	0	1	0	3	0	5	4	0	0	0	0	0	0	3	3	3
F ₁₁	1	2	2	4	1	6	5	0	0	2	0	0	0	4	5	4
F ₁₂	1	2	2	4	1	6	5	0	0	2	0	0	0	4	5	4
F ₁₃	4	6	5	7	4	9	8	3	1	5	3	3	0	7	8	7
F ₁₄	0	0	0	0	0	2	1	0	0	0	0	0	0	0	1	0
F ₁₅	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
F ₁₆	0	0	0	0	0	2	1	0	0	0	0	0	0	0	1	0

TABLE 3 Index system for ecological governance.

First-level index	Second-level index	Unit	Impact
Pollutant discharge	Emissions of sulfur dioxide in wastewater	10 kilotons	-
	Emissions of nitrogen oxides in waste gas	10 kilotons	-
	Emissions of ammonia nitrogen in waste gas	10 kilotons	-
Urban greening	Urban green space area	10 kilo hectares	+
	Greening coverage rate in built-up areas	-	+
	Park Green Area	10 kilo hectares	+
Forest coverage	Forest coverage rate	-	+
	Forest area	10 kilo hectares	+
	Forest stock volume	100 M cubic meters	+

TABLE 4 Indicator system of explanatory variables.

Vars	Obstacle factors	Factor indexes	unit
X ₁	Inadequate market regulation of environmental rights and interests	Environmental protection penalty caseload	case
X ₂	Insufficient public participation and social coordination	Public Baidu Search Index	-
X ₃	Low level of digital governance	Number of users accessing the Internet	10 thousand households
X ₄	Lack of interest compensation and incentive mechanisms	Government's ecological investment funds	100 million yuan
X ₅	Defects in the green - development structure	Regional GDP/Energy consumption	10 million yuan/kt standard coal
X ₆	Facing challenges of innovative technologies	Transaction volume of the technology market	100 million yuan

TABLE 5 Main parameters and meanings.

Vars	Significance
E	The revenue obtained from enterprise production
t_1	The comprehensive tax rate for enterprises when paying income tax and ordinary environmental tax
t_2	The comprehensive tax rate for enterprises when paying income tax and high - level environmental tax
C_1	The cost incurred by enterprises when adopting an environment- first production mode
C_2	The cost incurred by enterprises when adopting a cost - first production mode
C_3	The additional cost incurred by local governments when strengthening environmental regulations
C_4	The additional cost incurred by the central government when strengthening supervision and inspection
C_5	The subsidy provided by local governments to enterprises for environmentally - friendly production
P	Penalties imposed by the central government on local for failing to strengthen environmental regulation
α	The proportion of tax revenue that local governments obtain from enterprises' tax payments
H_1	Environmental protection benefits gained by local governments from strengthening environmental regulations
H_2	The credibility gain or loss of the central government regarding whether to strengthen supervision and inspection

driven layer on ecological co-governance across spatiotemporal dimensions.

3.2 Analysis of apparent layer

3.2.1 Temporal and spatial changes analysis

The average EGI of the entire YRB has basically maintained an increasing trend year by year (Figure 4). The EGI witnessed a significant leap from 2015 to 2016 and has since remained at a relatively high level in recent years. The specific EGI performance of each province within the basin is shown in Figure 5, the provincial EGI performance within the basin exhibits distinct disparities: Qinghai and Gansu, despite starting with relatively high EGI in 2014, saw sluggish growth in subsequent years. While their ecological governance efforts have yielded modest results, significant room for improvement remains. Shanxi Province, Inner Mongolia Autonomous Region, and Ningxia Hui Autonomous Region fall into a medium EGI bracket, with similar growth trajectories, placing them in the second echelon. Since 2014, Sichuan, Shaanxi and Shandong Province have continuously demonstrated good EGI with rapid growth rates, showcasing strong ecological governance capabilities and achievements, thus belonging to the first echelon. Henan Province, which began with a low EGI in 2014, has surged through sustained efforts to join the first echelon.

Given the characteristics of China's YRB ecological governance, which features progressive deepening of policies and gradual release



TABLE 6 Stratification of obstacle factors.

Merged hierarchy	Stratification results	Obstacle factors
Appearance Driven Layer	Low - Influence Driven Layer	F ₄ , F ₁₄ , F ₁₆
	High - Influence Driven Layer	F ₆ , F ₇ , F ₁₅
Intermediate Influence Layer	Low - Influence Driving Layer	F ₂ , F ₃ , F ₁₀
	Medium - Influence Driving Layer	F ₁ , F ₅
	High - Influence Driving Layer	F ₈ , F ₁₁ , F ₁₂
Core Driving Layer	Core Driving Layer	F ₉ , F ₁₃

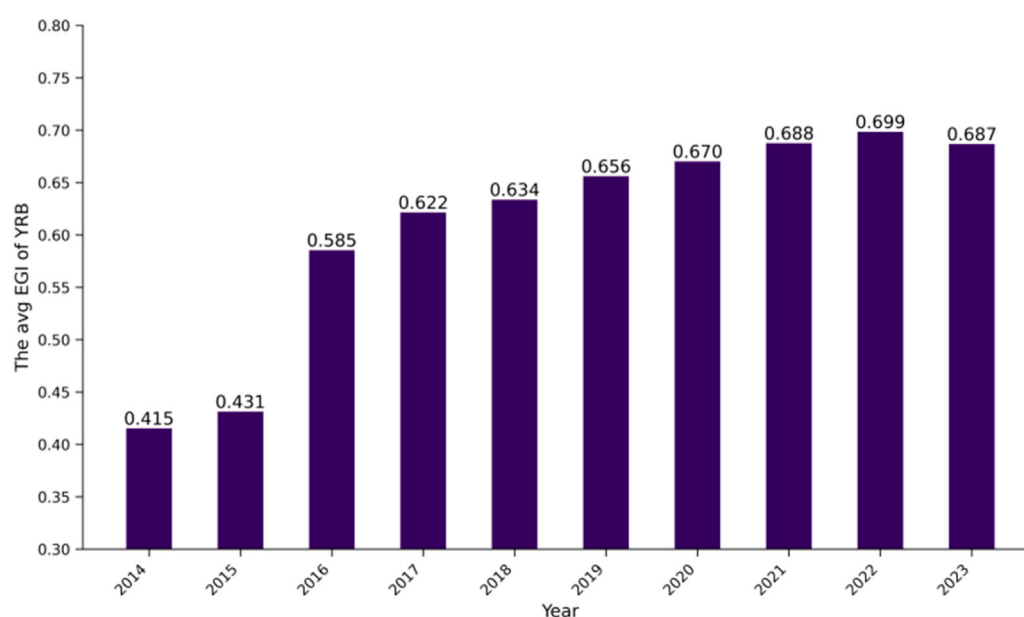


FIGURE 4
The annual average EGI of YRB.

of synergistic effects amid rapid development, the rapid growth of the EGI index is highly reasonable. However, this study observes relatively significant fluctuations in the EGI around 2016, potentially attributed to the immediate performance of relevant national policies promulgated that year to promote ecological governance. Meanwhile, the outbreak of the COVID-19 pandemic in 2020 may also have impacted the ecological governance process. Against this backdrop, this study aims to determine whether the fluctuations in the EGI index involve structural breaks caused by factors such as policy shocks or sudden events. The Mann-Kendall test (Table 7) on the EGI reveals a significant overall upward trend ($p = 0.0003$), and the ADF test further indicates that the original sequence is non-stationary. To avoid excessive interference from trend terms in the Quandt-Andrews test, first-order differencing is applied to obtain annual fluctuation terms, thereby stripping out the linear trend. The test results show that the most likely year for a structural break is 2017, with a corresponding F-statistic of 4.9928 ($p = 0.0606 > 0.05$), indicating no significant structural break at the 5% significance level.

This result preliminarily confirms that the improvement of ecological governance effectiveness is a gradual optimization

process driven by long-term trends. Notably, the absence of a structural break in 2020 aligns with practical logic: the construction of the EGI incorporates considerations of the continuity of existing governance achievements, and the strict control measures during the pandemic reduced human activities' interference with the ecosystem, objectively supporting the stable rise of the environmental index without disrupting the overall progressive trend. However, due to limited sample size (e.g., only 2 years of data before 2016), the potential impact of the 2016 policies and the 2020 pandemic on the data structure cannot be completely ruled out, requiring further verification with longer time series in subsequent studies.

3.2.2 Spatial agglomeration development

Based on the Moran's I index values (Table 8), the nine provinces along the Yellow River exhibited a weak spatial negative autocorrelation in 2014 ($I_g = -0.09$), indicating an interspersed distribution of provinces with low and high ecological governance levels. Throughout the ecological co-governance process, the spatial autocorrelation across the YRB

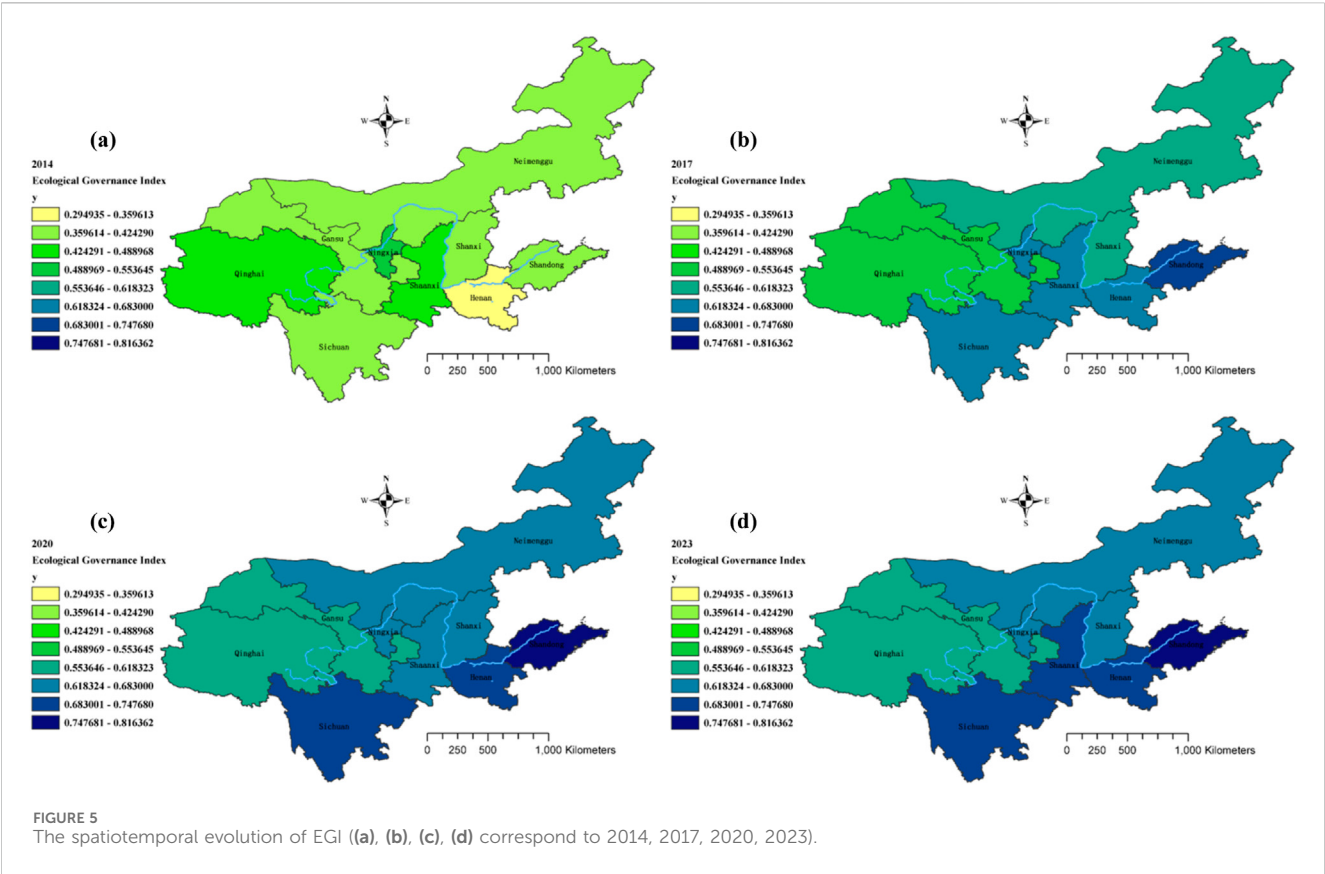


FIGURE 5 The spatiotemporal evolution of EGI ((a), (b), (c), (d) correspond to 2014, 2017, 2020, 2023).

TABLE 7 Temporal stability test.

Test method	Statistical quantity value	p-value
Mann-Kendall (S statistic,Z statistic)	3.5778	0.0003
KPSS(Lagrange Multiplier statistic)	0.3263	0.1000
Quandt-Andrews (F statistic)	4.9928	0.0606

consistently strengthened: by 2020, a statistically significant strong positive spatial autocorrelation emerged. Post-2020, while positive autocorrelation persisted, its intensity notably weakened—a trend potentially attributed to the COVID-19 pandemic, which may have undermined inter-provincial coordination and thus reduced spatial positive autocorrelation.

Furthermore, the overall Moran’s I index for ecological governance levels in the YRB remains relatively low. Observations of Moran scatter plots from 2014 to 2023 (Figure 6) further confirm that spatial agglomeration of governance levels is not pronounced. These results collectively indicate that the ecological co-governance effect among YRB provinces remains suboptimal, with insufficient spatial synergy and a need for enhanced inter-regional coordination mechanisms.

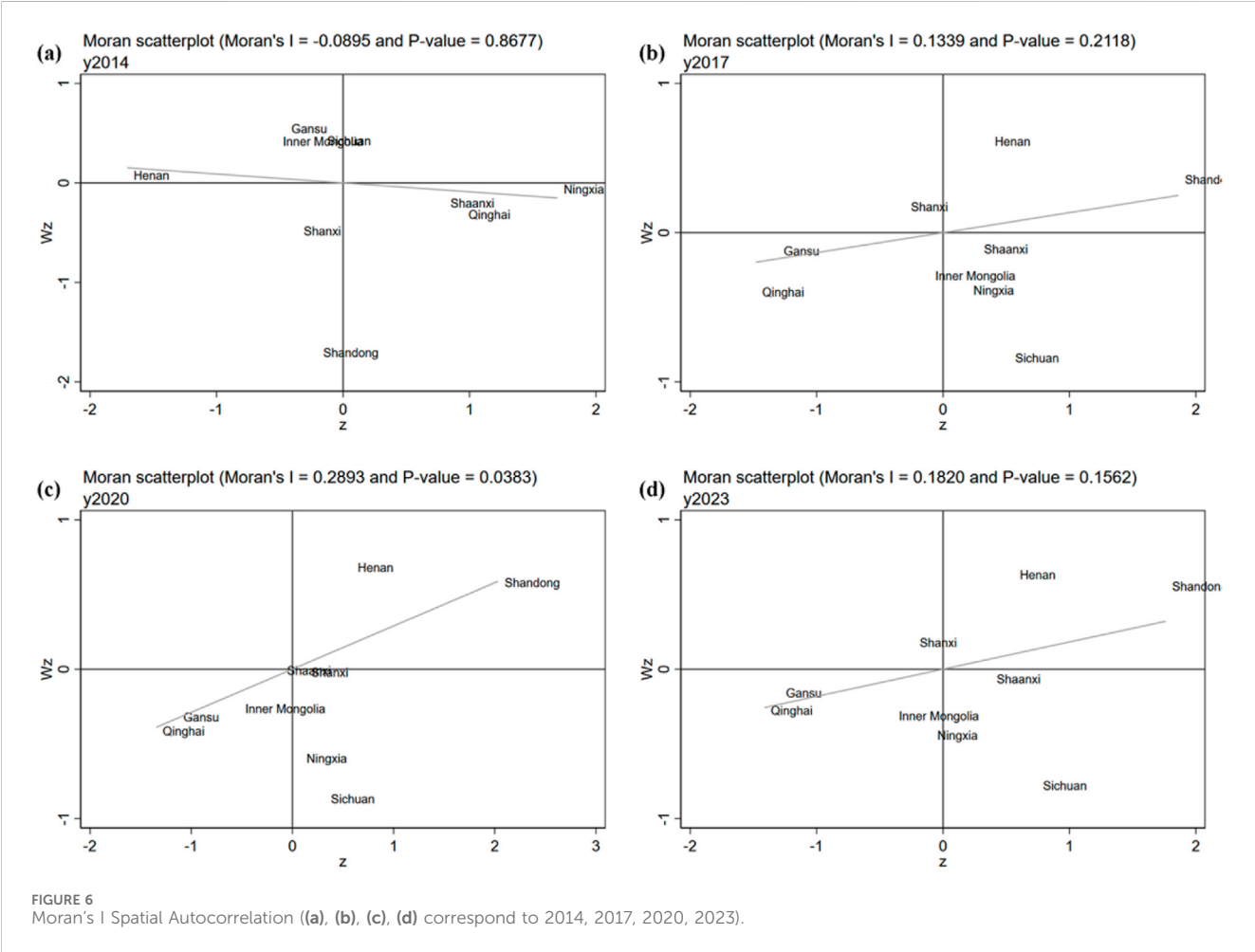
3.2.3 Spatial network strength

The study introduces a modified gravity model to deeply analyze the spatial network structure of the EGI in the YRB. Taking the provincial capitals as key nodes, the ecological gravitational values

between provinces are calculated to precisely analyze the linkage strength and mutual attraction degree among the provinces (Figure 7). The spatial network between provinces presents a multi-threaded overflow feature, and its influence has broken through the traditional geographical proximity restrictions. Even though Shandong is not adjacent to Sichuan, Inner Mongolia and Gansu, the spatial linkage between them remains close. Temporally, network strength showed a significant upward trend from 2014 to 2023, with all inter-provincial linkage strengths exceeding 4; notably, the 2023 ecological gravity value was substantially higher than that in 2014. These trends collectively indicate that the EGI spatial network is continuously strengthening, reflecting vibrant progress in ecological governance and robust cross-regional collaborative development capacity. Yang et al. (2024) found that the basin network presents a “Ji-shaped” pattern, which reflects the consistency between natural geography and ecosystems. This study selects the EGI as the quality variable, revealing that the network is in a ‘strong ecological attraction’ state. The difference between the findings and theirs may be attributed to the more refined research

TABLE 8 Global Moran's I.

Year	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
<i>I</i>	−0.090	−0.165	−0.045	0.134	0.171	0.211	0.289	0.184	0.09	0.182



perspective or the different setting of quality variables in their study. Meanwhile, this section finds that although the intensity of co-governance is constantly increasing, the degree of linkage is not close enough, which to some extent indicates that the network pattern identified by Yang et al. (2024) may be a favorable form for the subsequent development at the municipal scale.

3.2.4 SLM selection and regression outcomes

To select an appropriate spatial econometric model for this study, a series of diagnostic tests were performed (Table 9), including Lagrange Multiplier (LM) tests, Likelihood Ratio (LR) tests, Wald tests, and information criterion evaluations. First, both standard and robust LM tests were conducted to examine the presence of spatial lag or spatial error effects. Results indicated that the robust LM-error was not statistically significant. Notably, the information criteria (Table 10) and LR test results for the SEM were identical to those of the SLM, suggesting that the spatial autoregressive parameter λ in the SEM was effectively 0, thus

degenerating into the SLM. Further LR and Wald tests for model reduction confirmed that all coefficients of spatially lagged explanatory variables in the SDM were jointly insignificant, indicating that the SDM could be simplified to the more parsimonious SLM. Moreover, subsequent regression results revealed that several explanatory variables in both the SDM and SEM were individually insignificant, whereas the SLM exhibited better overall model fit, consistent with the information criterion rankings. So, the random-effects panel SLM was selected for further analysis.

The SLM has a quite good overall fitting effect with a goodness-of-fit of 0.8685 and all independent variables are statistically significant (Table 10; Figure 8). The coefficient ρ of the spatial lag term is 0.677, indicating significant spatial correlation in ecological governance effects among the nine YRB provinces. This strong positive spatial dependence among provinces underscores the necessity of ecological co-governance in the YRB, which is expected to yield better outcomes. Meanwhile, $\log \theta$

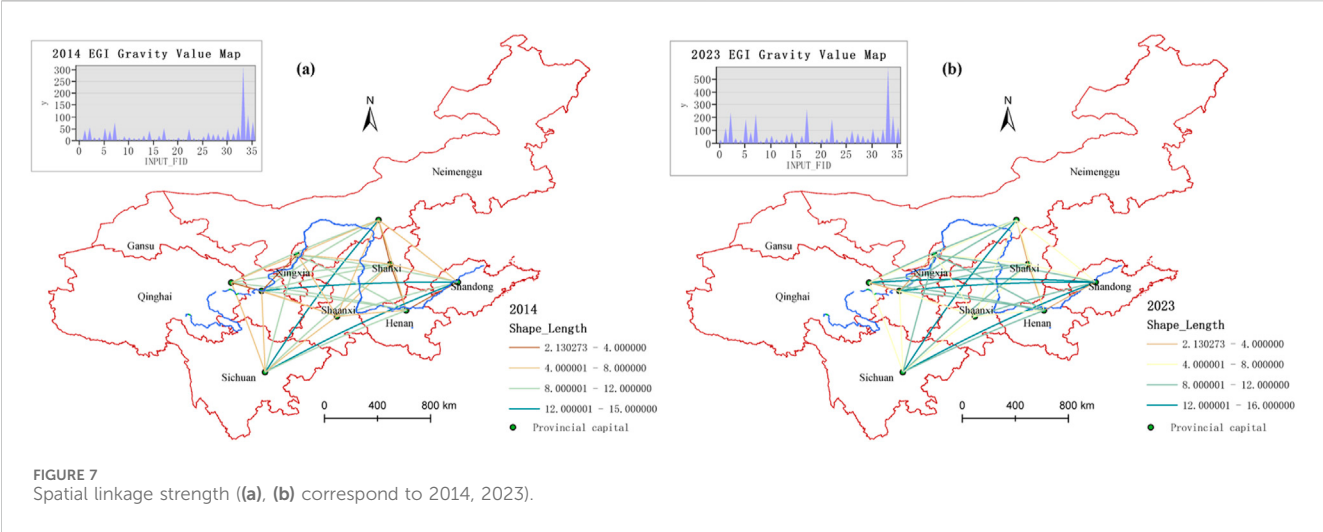


TABLE 9 Results of spatial Lagrange multiplier test.

Test names	χ^2 -value	p -value
LM-error Test	43.633	0.000
LM-lag Test	79.652	0.000
Robust LM-error Test	0.774	0.379
Robust LM-lag Test	14.934	0.000
LR (SDM-SLM)	11.25	0.081
Wald (SDM-SLM)	12.18	0.058

suggests that the spatial weight matrix has a relatively dispersed distribution; however, the significance of spatial dependence (as confirmed by the test) indicates the presence of a non-negligible spatial dependence relationship. The error variance σ_e^2 is small, reflecting sufficient explanatory power of the model with minimal errors. Overall, the SLM outperforms the other two models in terms of fitting effect.

Combining the coefficients of explanatory variables in the model with an analysis of the direct, indirect, and total effects of the SLM (Figure 8), although SDM performs poorly in some parameters and the model is relatively complex, the fitting effect is basically the same as that of SLM, once again confirming the authenticity of the results. X_3 and X_5 exert the strongest impacts on the ecological governance effects of the local province, neighboring provinces, and the overall basin. The impact degrees of X_1 and X_4 have relatively weak impacts. Notably, the coefficients of X_2 and X_6 exhibit negative coefficients, potentially due to a variable substitution effect that obscures their actual roles. In this context, two factors most directly affect the YRB's governance outcomes: the low level of digital governance and flaws in the green development structure. By comparison, factors such as insufficient public participation and social coordination, innovation bottlenecks, inadequate market regulation of environmental rights, and deficiencies in benefit compensation and incentive mechanisms have relatively weaker impacts. The obstacle factors identified by Shi et al. (2020) and Lu and Feng (2024) are basically consistent with those obtained in this study after factor stratification. They employed dynamic panel

regression with DIF-GMM/SYS-GMM and dynamic spatial Durbin causal analysis, respectively, to conduct in-depth discussions on the key factors for achieving high-quality development in the YRB. This section adopts a systematic perspective, focusing on the interaction intensity of inter-provincial co-governance and examining spatial-temporal relationships to explore the asymmetrically transmitted spatial spillover effects within the “core-periphery” structure. The findings of these studies are generally consistent with those of this section, key factors such as green technological innovation, industrial structure, and environmental regulation effectively promote high-quality development and co-governance, which also demonstrates the rationality of the factor hierarchy division adopted in this study.

3.3 Analysis of intermediate influence layer

3.3.1 Payoff matrix

To facilitate calculation and interpretation, an evolutionary game model involving tripartite entities is constructed with specific strategies and a payoff matrix (Table 11). The payoff matrix is ordered as follows: enterprises, local governments, and the central government.

3.3.2 Analysis of equilibrium point stability

Below, replicator dynamic equations for the behavioral strategies of enterprises, local governments, and the central government are constructed respectively (Figure 9). The dynamic replication equations of enterprise (x), local government (y) and central government (z) behavioral strategies are obtained as follows:

$$\begin{aligned} F(x) &= dx/dt = x(W_{11} - W_1) \\ &= x(1-x)[C_1 - C_2 + y(C_5 - A + B)] \end{aligned} \quad (2.10)$$

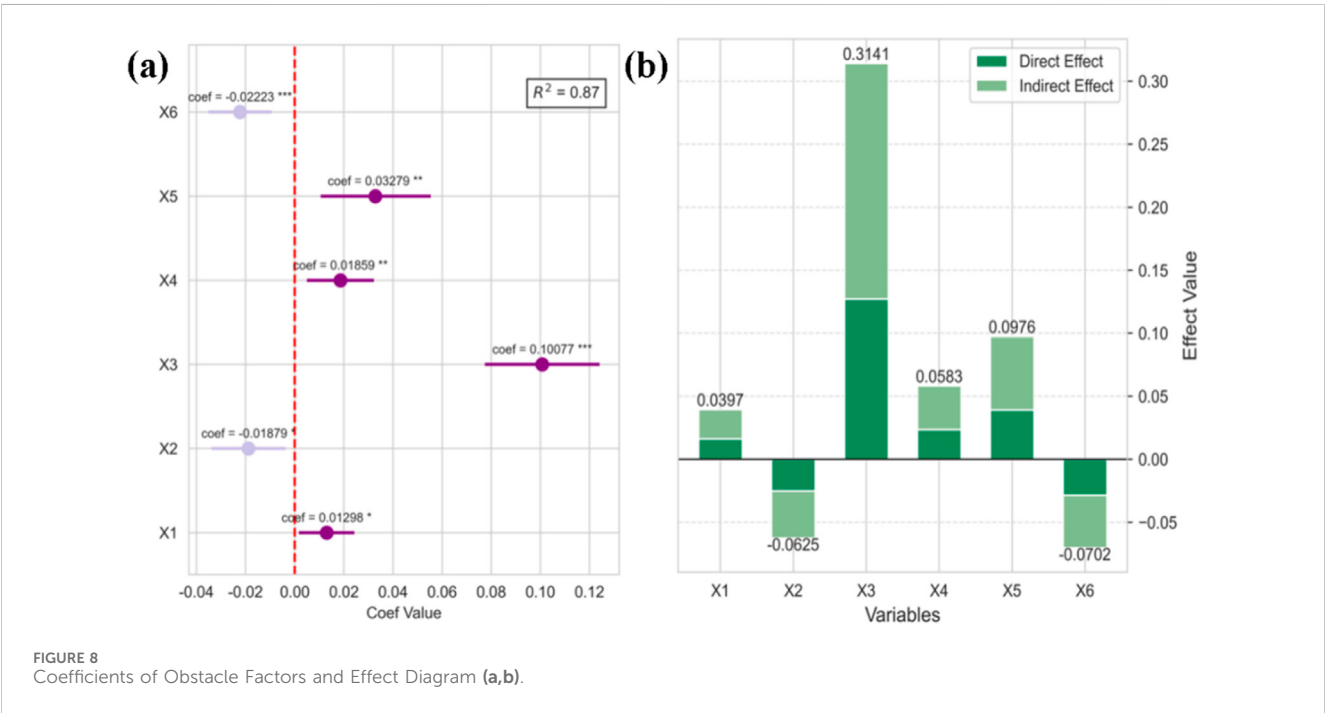
$$\begin{aligned} F(y) &= dy/dt = y(W_{21} - W_2) \\ &= y(1-y)[x(H_1 - C_5) + \alpha(1-x)(B - A) + zP - C_3] \end{aligned} \quad (2.11)$$

$$\begin{aligned} F(z) &= dz/dt = z(W_{31} - W_3) \\ &= z(1-z)[(1+xy-y)H_2 + (1-y)P - C_4] \end{aligned} \quad (2.12)$$

TABLE 10 Fitting results of the SLM.

Variables	SLM		SDM	SEM
	Main	Direct		
X_1	0.013**	0.016	0.010	0.011
X_2	-0.019**	-0.024	-0.029**	-0.016*
X_3	0.1***	0.127	0.107***	0.080**
X_4	0.019**	0.024	0.024**	0.023**
X_5	0.033**	0.039	0.037**	0.033**
X_6	-0.022**	-0.028	-0.033***	-0.022
ρ	0.677***		0.690***	
$\log \theta$	-1.760***		-1.981***	
σ_e^2	0.001***		0.001***	
Log-likelihood	173.054		178.677	173.054
AIC	-290.108		-289.355	-290.108
BIC	-220.113		-204.362	-220.113

***, **, *, **, *, ** means passing at the significance level of 1%, 5% and 10%, respectively Significance test.



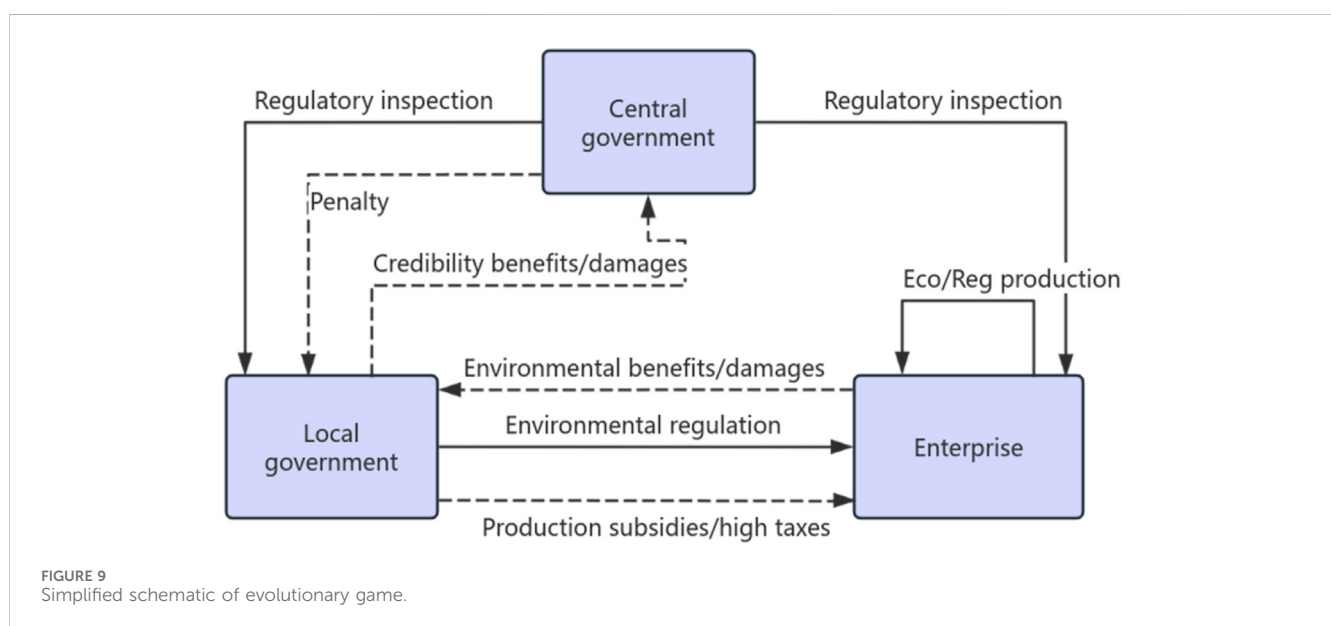
Setting $F(x) = F(y) = F(z) = 0$, all strategy combinations that may reach the system's steady state are as follows (0,0,0), (0,0,1), (0,1,0), (0,1,1), (1,0,0), (1,0,1), (1,1,0), (1,1,1) and a mixed-strategy equilibrium point (x^*, y^*, z^*) .

Table 12 shows the eigenvalues of the Jacobian matrix for each strategy combination. According to Lyapunov's stability theory, the local stability of the system at equilibrium points can be determined by the eigenvalues of the corresponding Jacobian matrix. An equilibrium point is an evolutionarily stable point if all its eigenvalues are less than 0. Substituting the equilibrium points

into the Jacobian matrix yields the eigenvalue expressions for each equilibrium point. In Table 13, $C_4 > 0$ holds consistently, meaning that (0,1,1) can only be an unstable point. Furthermore, since the cost of environmentally friendly production exceeds that of ordinary production ($C_1 < C_2$), (1,0,0) and (1,0,1) are also rendered unstable. In practical scenarios, the central government's credibility H_2 is far more critical than its cost of strengthening supervision C_4 , such that $H_2 > C_4$. This also makes the strategy points (0,0,0) and (1,1,0) unstable. After verification, the eigenvalues of the mixed-strategy equilibrium point (x^*, y^*, z^*) never satisfy the condition of

TABLE 11 The strategy and payoff matrix of the game players.

Game players			The central government	
			Strict supervision(z)	General supervision (1-z)
Enterprises Environmentally friendly production(x)	Local governments	Strengthening environmental regulations(y)	$E - A - C_2 + C_5$ $\alpha A + H_1 - C_3 - C_5(1 - \alpha)A + H_2 - C_4$	$E - A - C_2 + C_5$ $\alpha A + H_1 - C_3 - C_5(1 - \alpha)A$
		General environmental regulations (1-y)	$E - A - C_2$ $\alpha A - P(1 - \alpha)A + P - C_4$	$E - A - C_2$ $\alpha A(1 - \alpha)A - H_2$
Enterprises General production (1-x)	Local governments	Strengthening environmental regulations(y)	$E - B - C_1$ $\alpha B - C_3(1 - \alpha)B - C_4$	$E - B - C_1$ $\alpha B - C_3(1 - \alpha)B$
		General environmental regulations (1-y)	$E - A - C_1$ $\alpha A - P(1 - \alpha)A + P - C_4$	$E - A - C_1$ $\alpha A(1 - \alpha)A - H_2$



being simultaneously less than zero, confirming that this point is not an evolutionary stable point either. After excluding non-evolutionary stable points, the remaining points may be Evolutionarily Stable Strategies (ESS) under stability conditions (Table 13).

3.3.3 Numerical simulation of the tripartite evolutionary game

The simulation process focuses on simulating the three scenarios mentioned above that may reach evolutionary equilibrium points. Initial strategy probabilities are set as follows: for the two-dimensional evolution schematic, probabilities are set to $x = y = z = 0.5$; for the three-dimensional case, initial strategy probabilities range from 0.1 to 0.9. The strategic evolution of the equilibrium point (1, 1, 1): $C_4 - H_2 < 0$, $C_3 + C_5 - H_1 - P < 0$, $A - B - C_1 + C_2 - C_5 < 0$, $C_1 = 3$, $C_2 = 5$, $C_3 = 5$, $C_4 = 4$, $C_5 = 4$, $P = 6$, $E = 20$, $\alpha = 0.6$, $t_1 = 0.3$, $t_2 = 0.4$, $H_1 = 6$, $H_2 = 8$.

Currently, all three parties tend to adopt pro-environmental strategies, forming a virtuous cycle. When the central government strengthens supervision and inspection, the penalties imposed on local governments exceed the additional

costs incurred by local governments to enhance environmental supervision. For enterprises, adopting environmentally friendly production not only avoids high environmental taxes but also qualifies them for production subsidies from local governments; meanwhile, the environmental benefits gained by local governments outweigh the subsidies provided to enterprises. Key factors driving enterprises' strategic shifts include the costs of pro-environmental production and the intensity of local government supervision. For the central government, credibility considerations are critical, with its supervision intensity serving as the core factor guiding strategic directions. As illustrated in the three-dimensional evolution path diagram (Figure 10), the three parties gradually converge into a virtuous cycle and reach a stable state.

Furthermore, under the equilibrium parameter conditions, although varying the initial strategy probabilities of the three subjects (from 0.1 to 0.9, Figure 10b) alters the evolutionary simulation paths and speeds, the outcome remains consistent. This confirms that the stable behavioral strategy selection is significantly determined by parameter values: when parameters meet the evolutionary stability conditions, the initial strategy

TABLE 12 Eigenvalues of strategy points.

Strategic point	λ_1	λ_2	λ_3
(0,0,0)	$-C_3 - \alpha^*(A - B)$	$C_1 - C_2$	$H_2 - C_4 + P$
(0,0,1)	$C_1 - C_2$	$P - C_3 - \alpha^*(A - B)$	$C_4 - H_2 - P$
(0,1,0)	C_4	$C_3 + \alpha^*(A - B)$	$B - A + C_1 - C_2 + C_5$
(0,1,1)	C_4	$C_3 - P + \alpha^*(A - B)$	$B - A + C_1 - C_2 + C_5$
(1,0,0)	$C_2 - C_1$	$H_2 - C_4 + P$	$H_1 - C_5 - C_3$
(1,0,1)	$C_2 - C_1$	$C_4 - H_2 - P$	$H_1 - C_5 - C_3 + P$
(1,1,0)	$H_2 - C_4$	$C_3 + C_5 - H_1$	$A - B - C_1 + C_2 - C_5$
(1,1,1)	$C_4 - H_2$	$C_3 + C_5 - H_1 - P$	$A - B - C_1 + C_2 - C_5$
(x^*, y^*, z^*)	$\pm$	$\pm$	$\pm$

TABLE 13 ESS conditions.

Equilibrium point	Stability conditions
(0,0,1)	$P - C_3 - \alpha^*(A - B) < 0, C_4 - H_2 - P < 0$
(0,1,0)	$C_3 + \alpha^*(A - B) < 0, B - A + C_1 - C_2 + C_5 < 0$
(1,1,1)	$C_4 - H_2 < 0, C_3 + C_5 - H_1 - P < 0, A - B - C_1 + C_2 - C_5 < 0$

probabilities of subjects have a relatively minor impact on the evolutionary equilibrium of the vertical governance system.

3.3.4 Dynamic rewards and punishments analysis

Dynamic reward-punishment simulations were conducted by treating penalty P , high environmental protection tax B , and enterprise subsidy C_5 as dynamic parameters. Results show that under identical parameter conditions, dynamic reward-punishment measures exhibit slower convergence than static ones (Figure 11). This might be because the adoption of dynamic measures is related to the strategy probability of the subject, and the strategy probability reduces both rewards and punishments. Despite the slower convergence, the dynamic system demonstrates robust stability once equilibrium is achieved—indicating a resilient co-governance structure capable of adapting to changing strategic probabilities.

3.3.5 Parameter sensitivity analysis

This section conducts a sensitivity analysis of partial model parameters from the enterprise perspective. In practical research, some parameters lack practical significance after initial setting when adjusted, or their value ranges are restricted, making in-depth exploration difficult. Therefore, the analysis focuses on key parameters. As shown in Figure 12, the penalty intensity P , local government supervision cost C_3 , and subsidy expenditure C_5 have a moderate impact on the convergence of enterprises' strategy probabilities. In contrast, fluctuations in enterprises' own green production additional cost C_2 (i.e., environmental protection production cost) significantly affect strategy convergence. When C_2 fluctuates by $\pm 50\%$, a reduction in cost drives enterprises to converge rapidly to green production strategies; conversely, excessively high costs result in the

slowest convergence, lagging behind the optimal scenario by approximately 5 iterations.

Further observation on the impact of high environmental taxes reveals that when the environmental tax rate is at a low level, enterprises will persistently choose non-green production strategies (even when facing fines). Under other fluctuation scenarios, the interference pattern of tax rates on strategy convergence is like that of costs. In Figure 12, under fluctuation amplitudes of 5%, 25%, 35%, and 50%: negative fluctuations in B (tax revenue under high environmental tax rates) reduce the actual environmental tax payment of enterprises, delaying convergence to approximately 30 generations, which is significantly slower than other perturbation scenarios; the impact of positive fluctuations in C_2 is consistent with the previous analysis (convergence is significantly slowed); the remaining parameters have weak interference with enterprises' strategy convergence, with differences in convergence time generally controlled within 5 iterations.

3.3.6 Model robustness analysis

In the previous section, perturbations were added to the parameter range to verify parameter sensitivity. In this section, Gaussian white noise ($\sigma z(t)d\omega(t)$, where $d\omega(t)$ is the increment of the Wiener process, characterizing random disturbances; σ controls the noise intensity; and $z(t)$ is a coefficient term adapted to strategy evolution) is incorporated into the model structure to construct an alternative model, namely, a stochastic evolutionary game model, for verifying the robustness of the model. This operation aims to simulate the probability selection scenario under bounded rationality—in reality, the strategy choices of agents are not solely dominated by payoffs, and random disturbances can further incorporate the influences of complex factors such as policy ambiguity and market sentiment. Through evolutionary game simulation (Figure 13), under the impact of the same noise (with the noise intensity being 10%–30% of the parameter C_2), the strategy probabilities of local governments and the central government can quickly converge to the interval around 1 and remain fluctuating; however, the strategy probability of enterprises shows obvious jump characteristics, and when approaching the convergence interval subsequently, the degree of fluctuation is also significantly greater than that of the former two. The root cause is that enterprises are

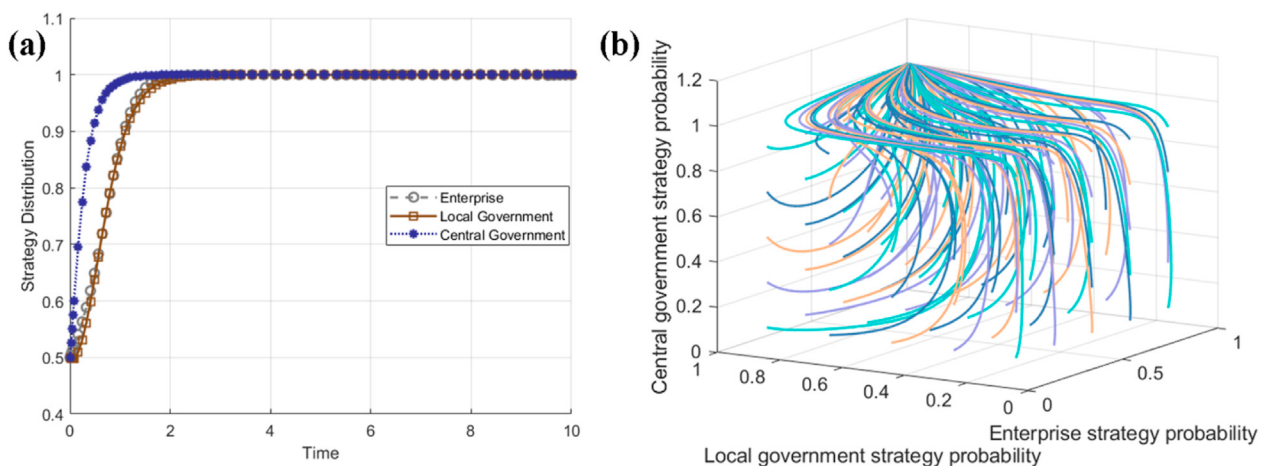


FIGURE 10
(1, 1, 1) Numerical simulation process ((a), (b) correspond to 2D, 3D graph).

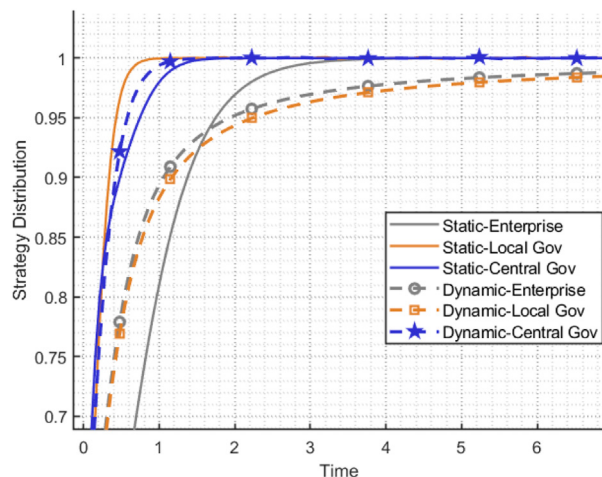


FIGURE 11
Dynamic rewards and punishments.

inherently at the center of complex payoff games, and the superposition of random noise further amplifies the interference of payoff uncertainty on strategy selection, resulting in the fluctuation amplitude of their strategies being much higher than that of government agents.

Meanwhile, a comparison of the average convergence times from 500 experiments under different noise levels was carried out. Considering that the stochastic evolutionary model only attains dynamic equilibrium within a certain range, a convergence threshold of 0.99 was set, and the model was deemed to have converged once this threshold was reached for the first time. By observing Figure 14a, it is evident that the average convergence time of enterprises is significantly longer than that of the other two subjects, which verifies the previous analysis results. However, it is observed that when the noise impact is relatively strong, the overall convergence is relatively faster. This phenomenon seems counterintuitive: Theoretically, strong noise will increase the

strategic fluctuations of subjects, requiring more time to explore optimal strategies and balance probabilities. Nevertheless, as the noise intensity in this study ranges from 10% to 30% of the green production cost C_2 of enterprises, strong noise, to a certain extent, conveys a signal of “a relative increase in environmental protection costs” to enterprises, indirectly facilitating the system to reach equilibrium more rapidly. From the observation of Figure 14b, it can be seen that as the noise increases, the terminal standard deviations of the three subjects all rise. The stability of enterprises is inferior to that of the other two subjects when noise initially exists, and their stability gradually deteriorates as the noise intensifies. The index value increases from 0.27 to 0.39, a rise of 44%. However, the terminal standard deviation of the central government shows a relatively large jump after experiencing different levels of noise (increasing from 0.15 to 0.39, a rise of 160%).

Comprehensively analyzing the overall stochastic evolutionary game model, along with the changes in convergence time and the fluctuation situation, it is concluded that the overall robustness of the model is favorable. The strategy evolution paths of the two government subjects are relatively stable, while the strategy probability of the enterprise subject is more significantly affected by the environment (such as noise and payoff), and its stability is somewhat poorer. If one intends to test the limit of the model's robustness, one can increase the noise intensity or switch to other perturbation methods.

3.3.7 Overall analysis of evolutionary game

Zhao et al. (2022) explored the evolution of the macro-level resource-economy-environment coupling system from a multi-dimensional perspective through simulation analysis, identifying macro critical factors such as resource and environmental carrying capacity and differentiated ecological constraint policies that influence ecological conservation and high-quality development of the composite system. Similarly, Cui et al. (2020) found that increasing pollution compensation and reducing regulatory costs can promote the development of a sustainable green financial system. From the perspective of vertical governance system, this

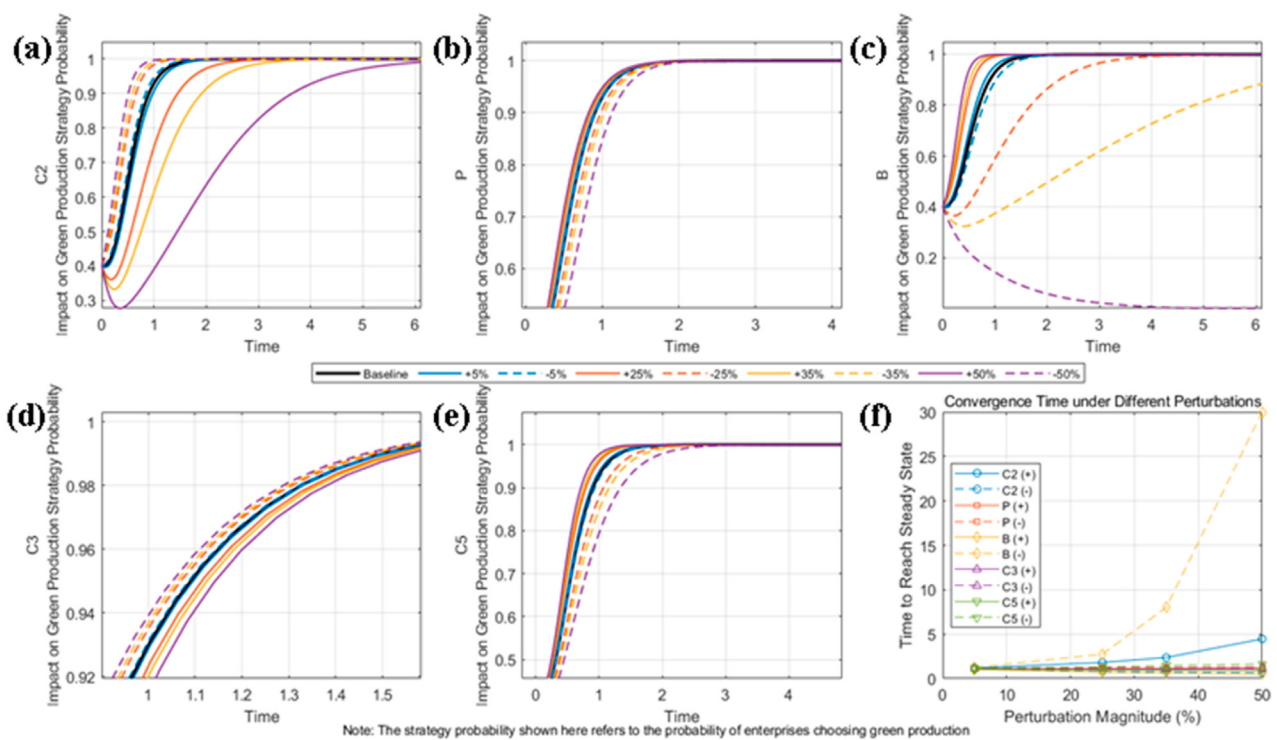


FIGURE 12

Multi - parameter sensitivity analysis. (a–e) show the sensitivity trends of different key factors on the impact of green production strategy probability over time; (f) presents the convergence time to reach a steady state under different perturbation magnitudes.

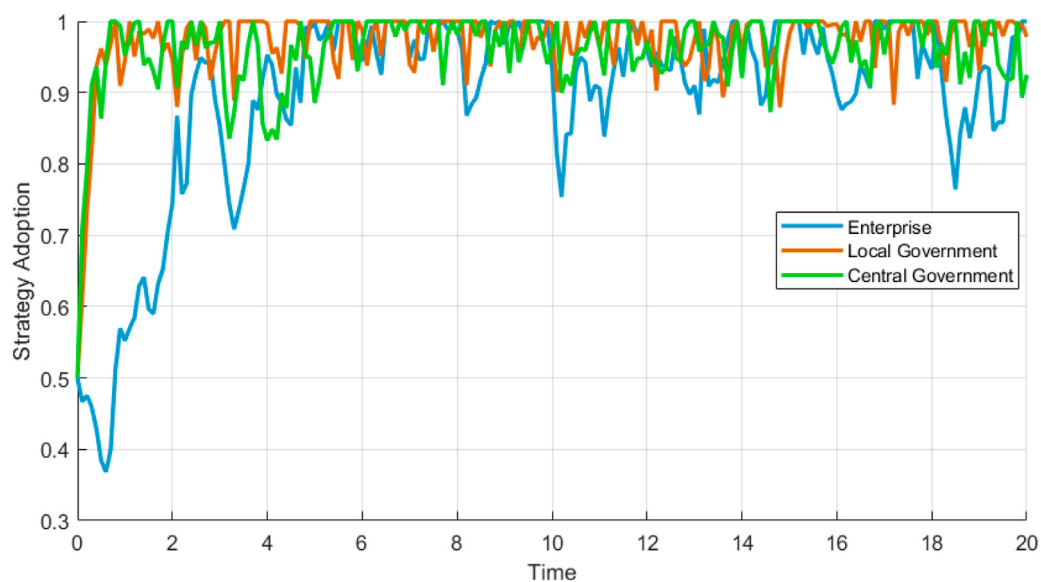


FIGURE 13

Stochastic evolutionary model.

section presents findings that align with the above studies while being more closely tailored to the context of vertical governance.

Among the three strategies that may reach the equilibrium point, only (1,1,1) can facilitate ecological co-governance, and

ensure the normal operation of the vertical co-governance system when parameters are satisfied. After comparing static and dynamic rewards and punishments, conducting a sensitivity analysis of parameter value fluctuations ranging from 5% to

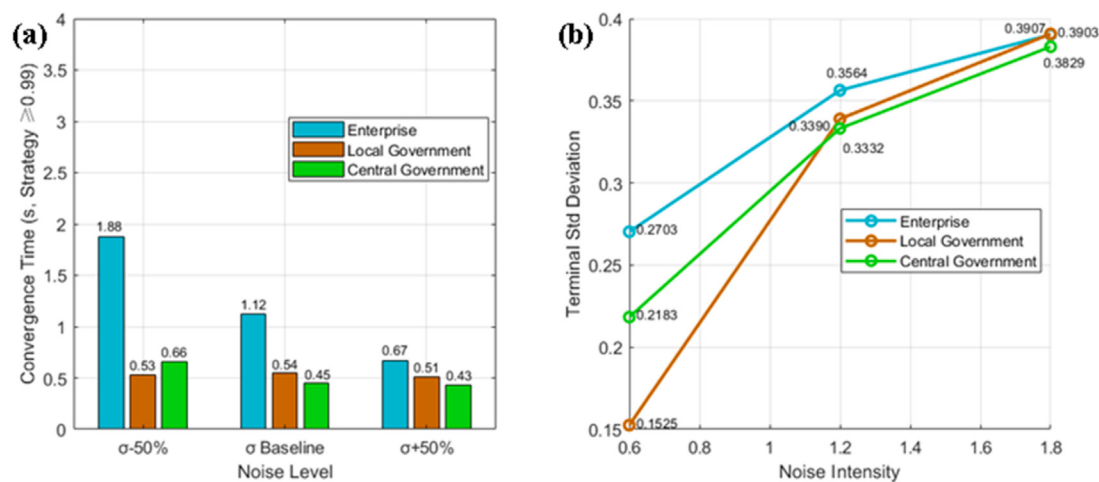


FIGURE 14
Convergence time and terminal standard deviation. (a) Convergence time under different noise levels; (b) Terminal standard deviation with varying noise intensity, both for enterprise, local government, and central government.

50%, and simulating a stochastic evolutionary game model with Gaussian white noise, it was found that among the three subjects, the enterprise is the one most affected by the environment and has the slowest convergence speed. This is consistent with the decision-making logic of enterprises in reality that takes profits and survival as the premise. Their strategies are prone to fluctuations due to external interference, and the key parameters C_2 , P , and B are all directly related to enterprise profits. They not only play an important role in the evolution of enterprise strategies but also have a profound impact in the dynamic reward and punishment mechanism. The above analysis not only clarified the key parameters driving the transformation of enterprise strategies, but also verified the robustness of the model in complex environments through random perturbation simulation.

To enhance the effectiveness of the YRB's vertical ecological governance system, the central government should appropriately increase penalties for local government inaction; local governments should raise the comprehensive tax rate (including environmental protection tax rates) and provide substantial subsidies to enterprises adopting environment-friendly production. These measures will promote the healthy development of the entire governance system and strengthen ecological co-governance effects.

3.4 Analysis of the core driving layer

The core driving layer contains two obstructive factors deeply rooted in the YRB context: divergent governance concepts and regional interest conflicts between its nine provinces. These factors operate at a foundational level, exerting cascading impacts on intermediate barriers such as policy misalignment and fragmented regulation across the basin. Whether at the national level or in the refined co-governance of the Yangtze River Basin and YRB, there exist deficiencies in trust, competitive mentality, and collective action dilemmas. These issues indirectly reflect the reality

of divergent governance concepts and regional interest conflicts as two parallel core obstacles (Liu and Ma, 2024; Xia et al., 2024).

Differences in governance concepts manifest starkly across the YRB's ecological and economic gradients. For instance, upstream provinces like Qinghai and Gansu—where fragile alpine ecosystems and headwater protection are paramount—prioritize strict ecological preservation, often advocating for restricted industrial development to safeguard water quality and biodiversity. In contrast, downstream regions such as Shandong and Henan, which host dense populations and industrial hubs (e.g., Zhengzhou's manufacturing sector and Shandong's coastal industries), tend to balance ecological goals with economic growth, emphasizing green industrial transition over absolute protection (Liu and Yuan, 2023; Li and Wu, 2022; Nie and Lee, 2023). This divide leads to inconsistent implementation of basin-wide policies: upstream provinces may resist infrastructure projects proposed by downstream regions, while downstream areas often delay investments in upstream ecological compensation.

Regional interest conflicts in the YRB are exacerbated by its uneven resource distribution and economic disparities. The basin's upstream regions control 60% of the Yellow River's water resources but contribute only 15% of the basin's GDP, creating a "protection-development paradox": upstream efforts to reduce pollution and conserve water directly benefit downstream regions but constrain local economic growth. These conflicts are further amplified by unequal negotiation power—economically stronger provinces like Shandong often secure favorable water quotas, leaving less developed regions like Gansu and Ningxia with unmet ecological protection needs.

The root causes of these core barriers are deeply embedded in the YRB's historical and economic fabric. Upstream provinces with large ethnic minority populations (e.g., Qinghai) have traditional livelihoods tied to pastoralism and low-impact agriculture, fostering a cultural emphasis on ecological harmony. In contrast, coal-rich regions like Shanxi and Shaanxi have long relied on resource extraction, shaping a governance culture focused on short-term

TABLE 14 Comparison of Key Dimensions of Ecological governance.

Governance dimension	EU WFD	MDB	YRB (this study)
Core Governance Goals	Ensure sustainable water use and achieve “good ecological status”	Balance water supply-demand and protect ecological flows to address frequent droughts	Synergize ecological protection and high-quality development
Collaboration Mechanism	Led by transnational river basin commissions, with member - state negotiations, public participation, “multi - level coordination”	Federal supervision + inter-state agreements, with “rigid constraints” centered on basin plans	Central coordination + provincial linkage, “flexible coordination” within a vertical governance system
Core Obstacle Factors	Transnational interest divergences, inconsistent standards, varying enforcement intensity	Conflicts over water allocation quotas, inefficient drought response, regional development imbalance	Divergences in governance concepts (F13), regional interest conflicts (F9)

economic gains. Addressing these core barriers requires YRB-specific solutions, such as establishing a trans-provincial ecological compensation fund (modeled on the Yangtze River’s pilot program but tailored to the Yellow River’s water scarcity) and creating a basin-wide coordination committee with rotating leadership to balance upstream and downstream voices. Additionally, aligning governance concepts could involve cross-provincial training programs, for example, pairing officials from Qinghai’s environmental agencies with their counterparts in Shandong to share best practices in balancing protection and development.

3.5 Comparative discussion on international governance frameworks

The core challenges in ecological co-governance of the YRB share significant commonalities (Table 14) with those addressed by the European Union Water Framework Directive (EU WFD) and Australia’s Murray-Darling Basin (MDB). Odume et al. (2022) identified ambiguous departmental responsibilities, prioritization of short-term economic agendas over long-term ecological goals, and overly centralized governance as key drivers of river ecosystem degradation; their proposed strategies—such as “strengthening science-policy-practice interactions and “promoting polycentric governance”, align closely with imperatives to break administrative barriers and improve cross-regional coordination mechanisms, mirroring the shared focus on “ecological primacy” within the EU WFD. Like the EU WFD (EC, 2000; EC, 2001), the YRB faces cross-administrative collaboration dilemmas, the former balancing interprovincial interests and the latter reconciling transnational ones—yet the approach of the EU WFD, which involves dynamic coordination through decennial “river basin management plans” and mandated stakeholder participation, offers direct insights for mitigating in the YRB; the polluter pays principle within the MDB, which internalizes ecological costs via economic levers, further informs optimization of benefit compensation mechanisms to resolve the upstream “protection-development paradox”.

Pressures of water scarcity and industrial-agricultural water conflicts in the YRB align more closely with the geographical context of the MDB—both are agricultural cores plagued by chronic drought and tensions between upstream protection and downstream development. The use of water rights trading by the MDB to clarify allocation quotas and market-based tools to reduce regional conflicts

provides critical lessons for alleviating “regional interest conflicts (F9)”; the drought emergency response mechanisms of the MDB, demonstrating robust coordination during crises, also serve as a model for addressing climate-induced water variability and enhancing dynamic coordination feasibility (MDBA, 2012a; MDBA, 2012b; Murray-Darling Basin Authority, 2012a; Murray-Darling Basin Authority, 2012b). This aligns with cross-basin comparative study (Bouckaert et al., 2022), which highlights the MDB focuses on biodiversity, the YRB emphasizes water demand and coordination. With insights from France and Brazil, it resonates with the three-layer driving chain framework of this study. While the core barrier of “divergent governance philosophies (F13)” is globally universal, the goal of the YRB to “synergize ecological protection and high-quality development” integrates developing-country transitional characteristics and national strategic imperatives, necessitating retention of centralized institutional strengths when adapting the periodic planning of the EU and the water rights trading experiences of the MDB.

The governance context of the YRB is uniquely irreplicable: as the world’s most sediment-laden river, its ecological restoration challenges far exceed those of basins under the EU WFD and the MDB; spanning China’s eastern, central, and western regions (with a fourfold gap in *per capita* GDP), developmental disparities exacerbate divergent governance philosophies; as a nationally strategic basin, it bears overlapping mandates of ecological, food, and energy security, rendering its governance complexity unparalleled globally. The three-layer driving chain identifies ideological consensus (core layer) as foundational, stakeholder behavioral synergy (intermediate layer) as critical, and tool implementation (apparent layer) as a safeguard, a framework that avoids the vicious cycle of ideological divergence-behavioral conflict-policy failure. Targeted policies for upstream (pollution control), midstream (industrial transformation), and downstream (ecological compensation) based on regional endowments further offer universal value for basins with “pronounced natural-economic gradients,” circumventing inefficiencies of one-size-fits-all policies (Gou and Liu, 2024; Zhou et al., 2024). Additionally, the integration by the framework of rigid administrative assessments and flexible ecological compensation outperforms the legal reliance of the EU WFD and the market-centric approach of the MDB in developing contexts. Administrative leverage can rapidly establish coordination foundations amid institutional and market immaturity, with gradual market integration providing transitional solutions for basins such as the Amazon, Mekong, Ganges, and Nile.

This three-layer driving chain theory and governance framework align closely with international best practices

(Table 14), comprehensively identifying governance barriers while acknowledging limitations, including its current theoretical rather than implementable status. The emphasis by the EU WFD on NGO roles, coupled with the findings of Baudoin and Gittins (2021) that enhanced NGO participation reduces point-source pollution, this highlights gaps in exploration of NGOs' specific functions; future research should deepen analysis of NGO engagement pathways in the YRB context and examine operational logics of the EU WFD and the MDB. In conclusion, the three-layer driving chain framework for the YRB both validates global basin governance commonalities and uniquely addresses “multi-objective synergy in complex contexts.” Its insights confirm no universally applicable governance model, but the principles of “hierarchical coordination”, “flexibility-rigidity integration”, and “contextual adaptation” offer cross-regional, cross-institutional references for global basin governance while informing localized progress through international experiences.

4 Conclusion and suggestions

4.1 Conclusion

This study adopts a three-layer driving chain framework and analyzes the obstacles to ecological co-governance in the YRB and their interactions by two systems: horizontal cross-regional collaborative governance and vertical multi-subject collaborative governance. Firstly, From 2014 to 2023, the average EGI showed an increasing trend year by year, and the ecological differences among regions gradually decreased. According to Moran's I index and the modified gravitational value, it can be found that from a weak negative correlation ($I = -0.09$) in 2014 to a significant positive correlation subsequently, The effect of inter-provincial governance has gradually shown spatial agglomeration characteristics from “high and low interlaced”, and the inter-provincial ecological collaborative linkage has gradually broken through the geographical proximity limitation, reflecting the enhancement of cross-regional co-governance capabilities. However, the overall Moran's I value remains relatively low (up to 0.289), indicating that the spatial linkage of co-governance within the basin still needs to be strengthened. In terms of spatial spillover, SLM is most suitable for analyzing the spatial spillover effect within the basin ($R^2 = 0.8685$, $\rho = 0.677$), and it has confirmed that there is a significant positive spatial spillover effect on the ecological governance effect of each province in the basin. The digital governance level X3 and the green development structure X5 have the strongest impact on the EGI of the local and neighboring provinces.

After constructing a tripartite evolutionary game model involving enterprises, local and the central government (the strategy combination includes 8 pure strategies and 1 hybrid strategy), and through the stability analysis of the equilibrium point, numerical simulation, comparison of static and dynamic rewards and punishments, sensitivity analysis of parameter fluctuations ranging from 5% to 50%, and random evolutionary game simulation introducing Gaussian white noise, it was found that When all three adopt active strategies (1,1,1), enterprises choose environmentally friendly production, local governments strengthen supervision, and the central government conducts strict inspections, the system can achieve ESS and meet the expectations of co-

governance. Currently, the core parameters need to satisfy $C4 < H2$, $C3 + C5 < H1 + P$, $A - B - C1 + C2 - C5 < 0$. Meanwhile, when the initial strategy probability varies within the range of 0.1–0.9, the result remains unchanged, indicating that the influence of parameter values on the evolution direction is much greater than that of the initial strategy. Further analysis indicates that among the three entities, enterprises are the ones most affected by the environment and have the slowest convergence speed. Their strategies are prone to fluctuations due to external disturbances. Key parameters such as environmental protection production cost $C2$, the penalty intensity P imposed by the central government on local authorities, and the high environmental tax B are directly related to enterprise profits and play a core role in the evolution of strategies - for instance, when $C2$ fluctuates by $\pm 50\%$, The convergence speed difference reaches 5 iteration cycles. When B fluctuates negatively by 50%, the convergence is delayed to the 30th generation. Although the dynamic reward and punishment mechanism converges more slowly than the static mechanism, it is more stable (due to the relatively smaller parameters caused by dynamic probability). After introducing the stochastic evolutionary game model, it is found that the government's main strategy can still converge rapidly, while the fluctuation range of the enterprise strategy reaches 44% (the terminal standard deviation rises from 0.27 to 0.39), but the overall model still remains robust. The overall evolutionary game analysis not only clarified the key parameters and threshold conditions that drive the synergy of the tripartite strategies, but also verified the reliability of the model in complex environments, providing a micro-behavioral basis for optimizing the vertical governance system.

In terms of theoretical analysis, the fundamental obstacles of the core driving layer focus on the differences in governance concepts and regional interest conflicts, which constitute the underlying constraints of ecological co-governance. The differences in governance concepts are reflected in the differentiation of the priority cognition of ecological protection and economic development within the basin, which directly affects the consistency of policy goals and the coordination of implementation. Regional interest conflicts stem from the imbalance between the resource allocation pattern and development demands, leading to the existence of interest games and mismatches of rights and responsibilities in cross-regional collaboration. These two factors, through hierarchical transmission, interact with the strategies of the middle-level subjects and the implementation effects of the apparent tools, becoming the deep-seated root cause that hinders co-governance.

The framework of this study shares commonalities with EU WFD and MDB in core governance goals such as cross-regional interest coordination and multi-subject collaboration, and all face the challenges of balancing protection and development and resolving regional differences. The dynamic programming mechanism and public participation system of the EU WFD, as well as the market-oriented water rights trading and emergency response system of the MDB, provide references for optimizing interest coordination and enhancing governance flexibility. The centralized governance advantages of the YRB and the systematic analysis framework of the “three-layer driving chain” also provide ideas for handling complex multi-objective collaborative issues in international river basin governance. The three parties need to learn

from each other in terms of the construction of consensus on concepts, the flexibility of mechanisms and the coordination of systems, to promote the optimization and popularization of the basin governance model.

4.2 Research limitations

This study has the following limitations:

1. At the research method level, the construction of the DEMATEL scoring matrix only relies on the discussion results of 5 experts and is limited by the initially designed scoring rules, making it impossible to conduct statistical verifications such as reliability and validity. This may have a potential impact on the objectivity of the research process and the universality of the conclusion.
2. The practical applicability of the theoretical framework remains to be tested. The three-layer driving chain research and governance framework proposed in this paper, although covering the complete content of ecosystem governance and logically capable of systematically analyzing the obstacle factors of ecological co-governance in the YRB, still remains at the theoretical deduction stage and has not yet been verified through practical application.
3. The depth of some research contents is still insufficient. Although the research has integrated macro and micro theories as well as various analytical methods, striving to comprehensively and systematically dissect governance obstacles, the exploration and model details in some specific fields are still relatively thin. For instance, the role positioning and participation paths of non-governmental organizations (NGOs) in ecological co-governance have not been fully analyzed, and the depth of research in related directions needs to be further strengthened.

4.3 Suggestions

Based on these findings, the study proposes the following recommendations:

1. Core Driving Layer Recommendations:

The central government should develop a unified ecological governance framework, clarify the rights and responsibilities of upstream, midstream, and downstream regions in ecological protection and development, and ensure consistent governance concepts across the basin. It is necessary to establish cross-regional coordination mechanisms and information-sharing platforms to enhance communication and trust among provinces, for instance, by regularly organizing joint conferences on basin governance to align strategic goals. Drawing on the EU Water Framework Directive's (EU WFD) experience of "decennial river basin management plans" and public participation mechanisms, it is necessary to establish cross-regional coordination committees with rotating leadership—comprising representatives from all nine

provinces—to balance upstream protection demands and downstream development needs through regular consultations. Additionally, learn from Australia's Murray-Darling Basin (MDB) water rights trading system to explore market-oriented tools such as ecological water quota trading, which can alleviate regional interest conflicts by quantifying the economic value of ecological protection. An inter-provincial ecological compensation fund should be established, with standards dynamically adjusted based on water resource contributions and pollution control efforts, ensuring that upstream regions' protection costs are reasonably compensated by downstream beneficiaries, thereby addressing the "protection-development paradox" at the root.

2. Intermediate Layer Recommendations-Vertical governance system

Strengthening the alignment between local policies and basin-wide strategies to maintain consistency in implementation—specifically, local governments should incorporate basin ecological goals into their development plans and establish a mechanism for regular assessment and adjustment of policy synergies. Clarify the vertical collaborative governance responsibilities between central and local governments: the central government could focus on formulating unified environmental standards and supervision mechanisms, while local governments implement targeted measures based on regional characteristics. Incorporate ecological governance outcomes, such as cross-border pollution reduction and water resource conservation, into local government performance evaluations, with incentives for provinces achieving collaborative goals and accountability for those failing to meet standards. For enterprises, local governments should improve the green production incentive system, such as increasing subsidies for environmentally friendly technologies and imposing differentiated environmental taxes based on pollution levels, to guide enterprises toward active participation in co-governance.

3. Apparent Layer Recommendations-Horizontal governance system

Accelerate the digital transformation of ecological governance in the YRB by building a unified big data platform integrating water quality monitoring, pollution sources, and resource allocation, to realize real-time data sharing and intelligent early warning among provinces. Promote the green transformation of industrial structures: upstream regions could develop eco-tourism and green agriculture, while midstream and downstream regions focus on upgrading high-pollution industries and fostering emerging green sectors, supported by preferential policies such as tax breaks for green enterprises and low-interest loans for technological upgrading. Enhance cross-regional policy coordination and improve interest compensation mechanisms—for example, using fiscal subsidies to support upstream ecological restoration and establishing a trans-provincial carbon trading market to internalize environmental costs. Strengthening public participation by expanding channels such as online supervision platforms and community environmental initiatives, and encourage social organizations to participate in governance through project funding. Increase investment in

scientific research to support green technology innovation, particularly in water-saving irrigation, sewage treatment, and renewable energy, while promoting regional cooperation in technology diffusion to bridge the innovation gap between upstream and downstream regions.

Data availability statement

The data analyzed in this study is subject to the following licenses/restrictions: Data may involve personal privacy, business secrets or legally binding confidentiality agreements. Disclosing such data may violate relevant laws or agreements. Requests to access these datasets should be directed to JH.

Author contributions

JL: Conceptualization, Software, Resources, Writing – review and editing, Formal Analysis. JH: Visualization, Validation, Software, Writing – original draft, Writing – review and editing. Data curation, Methodology. LS: Project administration, Funding acquisition, Formal Analysis, Supervision, Writing – review and editing. WH: Writing – original draft, Software, Investigation.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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