Article

2025 3rd International Conference on the Sociology of the Global Economy, Education, Arts and Humanities (GEEAH 2025)

A Synergetic Assessment Framework Based on Composite System Coordination Metrics: Empirical Analysis of Ecological-Environmental Service Integration in the Jiaodong Economic Zone

Linjing Cui [1,*]

[1] School of Public Administration, Shandong Technology and Business University, Yantai, Shandong, China
* Correspondence: Linjing Cui, School of Public Administration, Shandong Technology and Business University, Yantai, Shandong, China

Abstract: Regional coordinated development demonstrates a robust interdependency with the integration of ecological-environmental services. This study establishes a multidimensional assessment framework for ecological-environmental service integration within the Jiaodong Economic Zone. Employing entropy weighting methodology, we conduct quantitative analysis of service provision levels spanning 2011-2023, with spatial heterogeneity characteristics elucidated through coefficient of variation and Gini coefficient computations. A composite system synergy model, augmented by system dynamics simulation, enables comprehensive evaluation of synergetic development efficiency across the economic zone. The findings reveal measurable progress in ecological service integration. However, they also identify persistent structural barriers, including interjurisdictional disparities in public goods allocation, organizational inertia within existing administrative structures, and suboptimal performance evaluation mechanisms. Policy recommendations emphasize incentive architecture optimization, collaborative governance institution building, and multidimensional assessment system design to catalyze regional synergy enhancement.

Keywords: Jiaodong economic zone; ecological-environmental services; composite system synergy metrics; collaborative governance

Received: 27 March 2025
Revised: 05 April 2025
Accepted: 14 April 2025
Published: 29 May 2025

1. Introduction

Regional coordinated development has become an important mechanism supporting sustainable and balanced economic growth, particularly in the context of evolving spatial economic strategies. The city cluster-oriented coordination strategy, as a national-level spatial governance model, has been systematically refined through continuous policy experimentation. Within this context, The Jiaodong Economic Circle Synergistic Development Medium-to-Long-Term Plan, introduced by Shandong Province, outlines a polycentric regional network anchored by Qingdao's core hub functionality and synergized with nodal cities including Yantai, Weihai, Weifang, and Rizhao. This blueprint prioritizes the restructuring of institutional supply mechanisms and factor marketization frameworks, while advancing spatial organization innovation and cross-administrative collaborative governance models to amplify synergistic momentum within the peninsula's urban agglomeration. Hermann Haken's synergetics theory posits that subsystem competition-cooperation dynamics under specific parameters spontaneously engender ordered structures through functional optimization [1]. The Jiaodong Economic Zone, serving as Shandong's primary economic growth engine, highlights the importance of ecological-environmental service synergy as a key institutional support for achieving sustainable development. Under the Dual Carbon Strategy (peaking carbon emissions and achieving carbon neutrality), the transformation of industrial structures and the increasing complexity of environmental management impose unprecedented demands for institutional innovation within regional ecological governance systems [2]. Contemporary scholarship has produced multifaceted empirical investigations into this domain. Xiang and Jiang developed a multidimensional synergy measurement framework through comparative analysis of Beijing-Tianjin-Hebei, Yangtze River Delta, and Pearl River Delta metropolitan clusters, integrating technological innovation and ecological system panel data to formulate policy optimization pathways. Complementing this approach, Xiang and Jiang devised a composite evaluation index system encompassing five dimensions of regional coordination, establishing a novel analytical paradigm through social network analysis of Yangtze River Delta integration dynamics [3,4]. Building upon this theoretical foundation, our study constructs a composite system synergy model calibrated to the Jiaodong Economic Zone's ecological carrying capacity and integration imperatives. Through quantitative assessment of five municipalities' ecological service coordination levels, we identify critical constraints and institutional bottlenecks, ultimately proposing an innovative governance framework for regional ecological synergy optimization.

2. Data Sources and Methodological Framework

2.1. Data Acquisition and Indicator System Development

The empirical foundation derives from provincial statistical yearbooks and municipal socioeconomic development reports encompassing five Jiaodong cities. Core datasets include: Shandong Statistical Yearbook (compiled by Shandong Provincial Bureau of Statistics) and Statistical Communiqués on National Economic and Social Development published by individual municipalities. Missing values in yearbooks were addressed through linear interpolation, with reliability verification based on temporal consistency checks and cross-source comparison, ensuring maximal data integrity.

Drawing upon established policy frameworks — notably Shandong Peninsula Urban Agglomeration Development Plan and National Basic Public Service Standards (2021 Edition) — this study synthesizes theoretical advancements from Li Jinchang's seminal work on high-quality development evaluation systems. Through systematic indicator screening adhering to feasibility and representativeness criteria, we formulate an ecological-environmental governance evaluation framework comprising six categorical dimensions: Environmental Protection Fiscal Intensity (percentage of general public budget expenditure) [5,6]. Per Capita Urban Green Space (square meters per capita), Municipal Utility Workforce Density (personnel per square kilometer). Industrial Pollution Emission Intensity (tonnes per 10,000 RMB GDP), with tripartite monitoring metrics covering wastewater, SO_2, and particulate emissions. Standardization procedures and entropy-based weighting mechanisms underpin the integrated evaluation model, enabling systematic assessment of economic-environmental coordination.

The Jiaodong Economic Zone has institutionalized collaborative environmental governance through landmark policy innovations. The 2021 Regulations on Marine Pasture Management in Qingdao City — the region's first cross-jurisdictional legislative initiative — mandates intercity consultation mechanisms for marine projects with transboundary ecological impacts. This regulatory paradigm demonstrates systemic coordination through unified policies spanning marine industry integration, ecological redline enforcement, and cross-border environmental law enforcement protocols established via the 2021 Joint Prevention and Control Agreement on Jiaodong Peninsula Ecological Conservation.

During the 14th Five-Year Plan implementation phase, 2023 marked the operationalization of regional ecological governance mechanisms through the Framework Agreement on Coordinated Environmental Governance and standardized intergovernmental coordination protocols, emphasizing holistic pollution control systems and critical infrastructure upgrades targeting marine restoration, air quality improvement, and water purification.

2.2. Analytical Methodology

The Composite System Synergy Model (CSSM) operationalizes holistic system theory through multidimensional dynamic regulation frameworks, enabling panoramic monitoring and optimization of inter-subsystem element flows, functional coupling, and evolutionary trajectories. Within complex systems comprising functionally distinct yet interdependent subsystems, lack of synergy among subsystems may limit the overall efficiency and coordination capacity of the system.

2.2.1. Calculation of Subsystem Orderliness

In this study, the ecological and environmental service system of the Jiaodong Peninsula Economic Circle is modeled as a composite system S, which contains five prefectural-level city subsystems denoted as; (i = 1 = Qingdao, i = 2 = Yantai, i = 3 = Weifang, i = 4 = Weihai, i = 5 = Rizhao). The operation state of each subsystem is characterized by n vectors of ordinal parametric indicators, denoted as ordinal parameter. $X_i = (X_{i1}, X_{i2}, X_{i3}, \dots, X_{in})$ n is the number of ordinal parameters affecting the operation of the system and ≥ 1. There are two types of ordinal parameters: positive and negative indicators. For positive indicators, an increase in the value will improve the order of the subsystems; on the contrary, an increase in the value of the negative indicators will reduce the order of the system. In the study, the first step is to normalize the data to eliminate the quantiles, the specific steps are as follows:

$$y_{ij} = \begin{cases} \dfrac{x_{ij} - \alpha_{ij}}{\beta_{ij} - \alpha_{ij}} (x_{ij} \text{is positive indicators}) \\ \dfrac{\beta_{ij} - x_{ij}}{\beta_{ij} - \alpha_{ij}} (x_{ij} \text{is negative indicators}) \end{cases}$$

$y_{ij} \in (0,1]$, α_{ij} and β_{ij} are the maximum and minimum of the order parameter components on the stabilization threshold of the subsystem, $\alpha_{ij} \le x_{ij} \le \beta_{ij}$, $(j = 1,2,3,\dots,n)$, respectively, to avoid the situation of 0 or 1 during the calculation of the order parameter, β_{ij} is taken as 110% of the maximum value as the upper limit value, and α_{ij} is taken as 90% of the minimum value as the lower limit value. By integrating the orderliness of the indicators through the linear weighting method, the subsystem orderliness can be obtained:

$$Y_j = \sum_{j}^{n} \lambda_j \bullet y_{ij}$$

$$\lambda_j \in [0,1], \sum_{j}^{n} \lambda_j = 1$$

Where, $Y_j \in [0,1]$, denote the order parameter of subsystem i, where a higher Y_j value corresponds to enhanced system coordination. The weighting coefficient λ_j, quantifying the relative significance of parameter y_{ij} in system evolution dynamics, is algorithmically derived through entropy-based optimization procedures.

The specific calculation process of entropy value method:

1) Dimensionless processing of positive indicators.

$$X_{\mathrm{ij}} = \frac{x_{ij} - m_j}{M_j - m_j}$$

Where M_j is the maximum value of x_{ij} and and m_j is the minimum value of X_{ij}; X_{ij} and denotes the value of the jth evaluation indicator in the ith year.

2) Dimensionless processing of inverse indicators.

$$X_{\mathrm{ij}} = \frac{M_j - x_{ij}}{M_j - m_j}$$

3) Calculate the characteristic weight or contribution of year i under the jth indicator.

$$P_{\mathrm{ij}} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}}$$

4) Entropy value calculation for the jth indicator.

$$e_j = -\frac{1}{\ln \mathrm{n}} \sum_{i=1}^{n} p_{ij} \ln（p_{ij}），\ 0 \leq e_{\mathrm{ij}} \leq 1$$

5) Difference coefficient calculation.

$$g_j = 1 - e_j$$

6) Determine the weight of evaluation indicators.

$$W_j = \frac{g_j}{\sum_{i=1}^{m} g_j}, j = 1,2,3,\ldots,m$$

7) Apply the weights of the evaluation indicators W_j, and multiply them with the dimensionless data X_{ij}, to obtain a composite score for the level of basic public services in each city (Table 1).

Table 1. Evaluation Indicator System for the Level of Public Service Provision in the Jiaodong Economic Circle.

Primary Dimension	Secondary Indicators	Operationalization & Measurement	Polarity
Environmental Governance Metrics	X20 Fiscal Intensity of Environmental Protection Services (%)	(Environmental protection expenditure / General public budget expenditure) × 100%	Positive (+)
	X21 Per Capita Green Space Coverage in Built-up Areas (m²)	Average green space per resident in urbanized zones	Positive (+)
	X22 Workforce Allocation in Environmental Utilities (%)	(Employees in water/environment/public facilities management ÷ Urban workforce) × 100%	Positive (+)
	X23 Industrial Wastewater Intensity per 10k RMB Secondary Sector Output (10k tonnes)	Total industrial wastewater discharge ÷ Secondary industry GDP	Negative (-)
	X24 Industrial SO_2 Emission Intensity per 10k RMB Secondary Sector Output (tonnes)	Total SO_2 emissions ÷ Secondary industry GDP	Negative (-)
	X25 Industrial Particulate Emission Intensity per 10k RMB Secondary Sector Output (tonnes)	Total particulate emissions ÷ Secondary industry GDP	Negative (-)

2.2.2. Composite System Synergy Calculation

Assuming that $Y_i^0, i \in [1, k]$ is the degree of ordering of subsystem i at moment t_0 and $Y_i^1, i \in [1, k]$ is the degree of ordering of subsystem i at moment t_1, then the degree of synergy C of the composite system at moment $t_0 \sim t_1$ is:

$$C = \theta^{k}\sqrt{\left|\prod_{i=1}^{k}[Y_i^1 - Y_i^0]\right|}$$

Where,$\theta = \frac{\min[Y_i^1 - Y_i^0]}{|\min[Y_i^1 - Y_i^0]|}$, Reflects the direction of the subsystem's effect on the composite system synergy, i.e., at $Y_i^1 - Y_i^0 > 0$, the composite system synergy, C is positive, otherwise it is negative, $C \in [0, 1]$. The larger C is, the higher the synergy of the system is, and vice versa, the lower it is, the composite system synergy takes the value corresponding to the synergy status level is as follows (Table 2):

Table 2. Composite System Synergies and Their Corresponding Synergy Status Levels.

C	(-1,0]	[0,0.333]	[0.333,0.666]	[0.666,0.999]	1
Synergy Status	No synergy	Mild synergy	Medium synergy	High synergy	Full synergy

3. Results

3.1. Allocation of Ecological and Environmental Resources

3.1.1. Level of Service Supply of Ecological and Environmental Services

In terms of ecological environmental service provision scores, Weihai City consistently achieved relatively high values between 2011 and 2023, supported by sustained ecological investment and policy backing. Qingdao demonstrated a generally upward yet fluctuating trajectory, with a notable peak occurring in 2020. All five cities in the Jiaodong Economic Circle have progressively improved ecological protection mechanisms, implemented pollution control measures, and enhanced institutional support for sustainable development. Shifts in the strategic focus of municipal governments, including the increasing prioritization of green development, have further influenced environmental governance performance. As a result, the level of eco-environmental service supply across the region exhibits considerable annual variation (Table 3).

Table 3. Comprehensive Score of Eco-Environmental Service Provision Levels in the Jiaodong Economic Circle.

Score	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Qingdao	0.220	0.207	0.305	0.195	0.174	0.273	0.258	0.248	0.249	0.318	0.252	0.307	0.295
Yantai	0.371	0.357	0.377	0.312	0.329	0.330	0.311	0.310	0.305	0.276	0.272	0.274	0.276
Weifang	0.349	0.328	0.350	0.422	0.480	0.420	0.460	0.593	0.506	0.499	0.348	0.331	0.279
Weihai	0.552	0.756	0.522	0.463	0.511	0.467	0.507	0.461	0.477	0.443	0.397	0.388	0.388
Rizhao	0.268	0.268	0.226	0.292	0.301	0.295	0.382	0.337	0.271	0.292	0.270	0.258	0.216

3.1.2. Differences in the Supply of Ecosystem Services

Ecological environment is an important aspect in evaluating urban development. As people's attention to the living environment increases, the supply of urban ecological and environmental protection services has also become an important part of urban public service supply. From Figure 1, the coefficient of variation and the Gini coefficient of the level of environmental protection service supply in Jiaodong Economic Circle show the same trend of change, with local fluctuations but the overall view of the coefficient of variation and the Gini coefficient have decreased. Specifically, from 2011 to 2023, the coefficient of variation of the supply level of environmental protection services in the Jiaodong Economic Circle decreases from 0.362 to 0.214, and its Gini coefficient decreases from 0.111 to 0.056, both of which are slightly decreased. The difference in the supply level of environmental protection services within the Jiaodong Economic Circle has slightly decreased, and the integration level of ecological and environmental services has improved. The coefficient of variation showed significant fluctuation over the 13-year period. From a long-term urban development perspective, government investment in environmental protection typically does not yield immediate or visible economic returns. Therefore, as environmental protection cooperation programs typically aim to mitigate risks rather than generate direct economic returns.

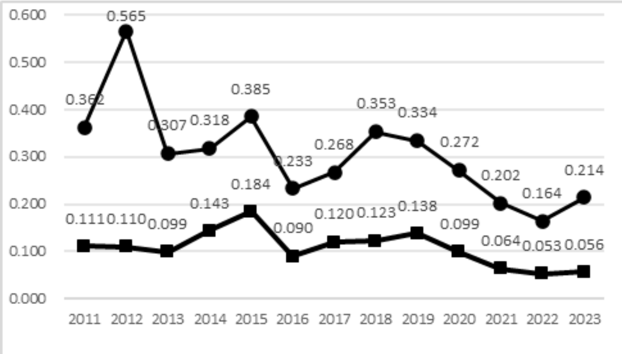

Figure 1. Gini Coefficient and Coefficient of Variation of Ecological and Environmental Service Provision Levels in the Jiaodong Economic Circle.

3.2. Synergistic Development of Ecosystem Services

The degree of orderliness can objectively measure the level of coordinated development of the elements within the subsystem and jointly promote the synergistic and orderly development of the system. Figure 2 shows the mean value of the degree of orderliness of the ecological and environmental systems in the five cities and the results of the calculation of the degree of synergy of the composite system. The average value of the degree of orderliness of ecological and environmental services of the five cities shows a stepped growth trend, and the gap in orderliness is significantly narrowed, indicating that the level of coordination of the five cities in ecological and environmental protection has been improved, and no city has been in the lead or lagging behind, and that inter-governmental cooperation to promote ecological and environmental protection has achieved significant improvement.

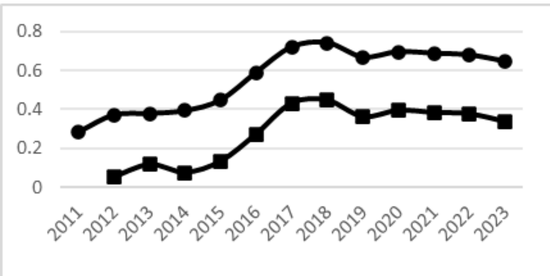

Figure 2. Mean Value of the Degree of Orderliness of Ecological and Environmental Services in the Jiaodong Economic Circle and the Degree of Synergy of the Composite System.

In terms of the synergy of the composite system of ecological and environmental services, the change in synergy is relatively satisfactory, from 2012 to 2016, the regional ecological environment orderliness steadily increased from 0.0509 to 0.2728, marking the transition of ecological governance from disorder to the primary synergy stage; in 2017, the synergy level broke through the threshold to reach 0.4312, and entered the medium synergy development zone; as of 2023, the synergy index has increased 5.6 times from the base period, indicating that the regional ecological service system has formed a stable self-organizing mechanism. It can be seen that the five cities in Jiaodong have continued to promote the ecological environment in the ecological environment of the joint protection and joint governance, together with the ecological environment of the joint law enforcement, and actively promote the management of atmospheric and water pollution joint prevention and control, and has yielded notable improvements in joint pollution prevention and environmental enforcement.

Public goods are non-competitive and non-exclusive. The gap in the synergy of ecological and environmental services can largely be attributed to the varying levels of involvement by local governments. While benefiting from regional integration and development, these governments often face challenges in fully coordinating the collective responsibility of providing public goods, which affects the management of regional interests. As a result, discrepancies in public service provision among cities persist, slowing the integration of public services within the Jiaodong Economic Circle. Therefore, the integration of public services in the Jiaodong Economic Circle has been progressing at a gradual pace.

3.3. Deficiencies in Performance Assessment Frameworks

The government performance evaluation system centered on the level of economic development determines the development momentum of local governments, and a single evaluation system cannot promote the improvement of the cooperation momentum of public services in the economic circle. The input strength of ecological and environmental services reflects the quality of urban functions, directly affecting the convenience for residents' daily lives. However, there is no unified index to measure the level of cooperation among local governments. The frequency of public service cooperation can reflect local governments' enthusiasm for participating in integrated ecological development. Therefore, the degree of cooperation in public services should also be included in the performance evaluation of local governments.

4. Conclusion

1) Institutionalizing Incentive-Compatible Governance Mechanisms

Stimulating the market's role in supplying ecological and environmental services is crucial. This can enhance the dynamics of ecological service supply, alongside improving and implementing a benefit compensation mechanism. During the integration of ecological environmental services, interest differences may arise between cities and regions. To address this, it is crucial to establish and refine the benefit compensation mechanism, ensuring fairness and reasonableness in balancing the interests of all parties. The benefit compensation mechanism promotes cooperation among cities and regions and realizes the rational allocation and sharing of ecological environmental service resources.

2) Restructuring Intergovernmental Coordination Architecture

Establishing an overarching organization, such as the Coordination Committee for Ecological Environment of the Jiaodong Economic Circle, is key to promoting regional integration. Building on the overall promotional organization, establish the Jiaodong Economic Circle Coordination Committee as a permanent body to resolve inter-governmental conflicts and foster cooperation in ecological and environmental services. Promote the transformation of government functions. Focus on improving the efficiency and quality of ecological and environmental services, enhancing accessibility and convenience through decentralization and process optimization; at the same time, the government should strengthen the supervision of the supply of ecological and environmental services to ensure the fairness and universality of ecological and environmental services.

3) Advanced Performance Evaluation System Design

To promote the integration of regional ecological environment management, it is essential to establish a scientific and systematic evaluation mechanism for the effectiveness of ecological services. The evaluation system should include three core modules: a multi-dimensional indicator framework, differentiated evaluation methods, and a dynamic feedback loop. Among them, the indicator system needs to systematically integrate the three dimensions of ecological product supply scale, environmental quality improvement degree, and service performance level, and comprehensively characterize the degree of realization of regional ecological service functions through the combination of quantitative indicators and qualitative assessment, and Assessment indicators should address the quantity, quality, and efficiency of ecological service supply to comprehensively reflect its performance. For example, quantitative indicators can include the number and coverage of ecological environment service facilities, qualitative indicators can include satisfaction with ecological environment services, service standards, etc., and efficiency indicators can include the cost-effectiveness of ecological environment service provision, resource utilization rate, etc.

References

1. W. Hong, Y. Li, X. Yang, R. Guo, M. Liang, and X. Li, "Identification of intercity ecological synergy regions and measurement of the corresponding policy network structure: A network analysis perspective," *Landsc. Urban Plan.*, vol. 245, p. 105008, 2024, doi: 10.1016/j.landurbplan.2024.105008.
2. Z. Deng, Y. Chen, F. Jiang, Y. Zhang, Z. Xie, Y. Zhang, and L. Zhao, "Spatio-temporal study on coupling coordination between urbanization and eco-resilience in the Erhai Lake Basin," *All Earth*, vol. 36, no. 1, pp. 1–20, 2024, doi: 10.1080/27669645.2024.2317053.
3. S. Xiang and W. Zhou, "Challenges and countermeasures of marine ecological and environmental governance in the Guangdong-Hong Kong-Macao Greater Bay Area—Based on the perspective of multi-level governance," *SSRN Electron. J.*, 2023, doi: 10.2139/ssrn.5184857.
4. J. Jiang, X. Wang, G. Xu, S. Jiang, J. Gu, and J. Zhang, "Exploring the coupling coordination and spatial correlation of logistics industry and regional economy in the context of sustainable development: Evidence from the Yangtze River Delta region," *Sustainability*, vol. 15, no. 2, p. 992, 2023, doi: 10.3390/su15020992.
5. D. Li and W. Yang, "The regional difference, dynamic evolution, and multidimensional inequality of China's ecological environment quality from the concept of ecological resilience," *Environ. Sci. Pollut. Res.*, vol. 30, no. 12, pp. 34793–34813, 2023, doi: 10.1007/s11356-022-24696-w.
6. Y. Wang, C. Wu, B. Wu, J. Zhao, and H. Wang, "Evaluation of spatial structure resilience in coastal traditional villages using complex network analysis: Case study of Rongcheng City, Shandong Province," *Land*, vol. 14, no. 3, p. 505, 2025, doi: 10.3390/land14030505.