SYNERGY BETWEEN ECOLOGICAL ENVIRONMENT AND ECONOMIC DEVELOPMENT QUALITY BASED ON SPATIAL AUTOCORRELATION MODEL – TAKING CHINA AS AN EXAMPLE

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(Received 1st Sep 2025; accepted 21st Nov 2025)

Abstract. The ecological environment and the quality of economic development are the core pillars of regional sustainable development, with their synergistic relationship holding substantial importance for national macroeconomic regulation and the formulation of regional development strategies. This study aims to investigate the interactive characteristics and spatial synergy distribution patterns between the ecological environment and economic development quality. This study investigates the synergy between ecological environment and economic development quality in China, using a spatial autocorrelation model. The research spans the period from 2001 to 2021 and divides China into three regions: Eastern, Central, and Western. Data from national and regional statistical yearbooks and remote sensing datasets are used for analysis. The study constructs an integrated index system, incorporating ecosystem quality and economic development indicators, to evaluate regional development coordination. Results show that Eastern China generally exhibits a high degree of coordination, with Beijing and Shanghai having intermediate coordination levels. In contrast, Central and Western regions are primarily in a barely coordinated stage. The Moran's index indicates a significant positive spatial correlation between ecological and economic systems, highlighting regional agglomeration effects. The findings provide a basis for differentiated ecological governance and green economic strategies tailored to specific regions.
Keywords: *spatial autocorrelation, ecological governance, regional development, sustainability, economic-environmental synergy*

Introduction

The relationship between ecological protection and economic development (ED) has long been a core issue in regional development strategies. With the advancement of ecological civilization construction, the traditional development model of promoting economic expansion through resource consumption is facing enormous challenges, and regional development is gradually showing a trend of strengthening ecological constraints and increasing green demand. In the context of the "dual carbon" goal, balancing the stability of the ecosystem and the efficiency of the economic system has emerged as a key indicator for assessing the quality of sustainable development (SD). As the fundamental unit of natural resource supply and environmental regulation, the quality of ecosystems directly affects the ecological carrying capacity of regional development (Shakoor and Ahmed, 2023). In recent times, although notable advancements have been achieved in ecological governance in various parts of China, problems such as local ecological degradation, imbalanced land functions, and excessive resource development still exist, and the resilience and stability of ecosystems still face certain pressures. Additionally, the ED model is transitioning from factor driven to innovation driven, emphasizing the concept of high-caliber development that is green, inclusive, and coordinated. However, in some regions, problems such as a single industrial structure and lagging environmental

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_785805

governance have led to a counter effect of ED on the ecosystem, further exacerbating ecological pressure. Progress has been observed in ongoing studies exploring the interplay between ecology and the economy (Sui et al., 2023). Some scholars have explored the constraining effect of ecology on ED based on ecological footprint theory or green total factor productivity models, while others have attempted to quantify the interaction between the two from a system evolution perspective. Zhou et al. put forward the approach of constructing an evaluation index system and integrating multiple models for quantitative assessment with the aim of investigating the coordination of the water-energy-food ecosystem in Dalade Banner and its associated towns. The research findings revealed that the comprehensive index (CI) reflecting ecosystem coordination in Dalade Banner and its townships exhibited a gradual upward trend, characterized by a high degree of coupling yet low levels of coordination. Furthermore, the coordination among townships showed signs of improvement, with the ecological impact emerging as the most significant factor. In contrast, the ecosystem's coordination driving mechanism and its stability were discovered to be rather weak (Zhou et al., 2024). Wang et al. proposed a research method that combines indicator system, coupling coordination (CC) degree model, grey relational analysis, and system dynamics simulation model to clarify the relationship between water resources, economy, and ecosystem in Shanxi Province to support future SD. The research findings revealed that the comprehensive evaluation increased, the urban gap was obvious, and the economic subsystem had a significant impact (Wang et al., 2025a). However, current research commonly encounters issues such as the use of a limited range of indicators, inadequate analysis of the spatial dimension, and the absence of a unified framework for collaborative measurement. These limitations hinder the ability to conduct comparability analysis and devise regulatory strategies that are applicable across multiple regions at the national scale. Consequently, there exists a need to employ models that demonstrate strong systematicity and high regional adaptability for further exploration. To address these challenges, this study establishes a dual index system aimed at evaluating both ecosystem quality and ED quality, grounded in spatial autocorrelation models. It combines remote sensing monitoring, economic statistical data, and spatial analysis tools, utilizing CC degree models and Moran's index to assess the spatial synergy of ecological-economic systems across various provinces in China. The research endeavors to offer theoretical underpinning and empirical evidence to aid in the execution of ecological priority and green development strategies. The innovation of this study resides in the integrated modeling of the ecosystem CI alongside the five-dimensional quality indicators of ED, as well as the application of spatial autocorrelation methods to collaborative system research.

The objective of this study is to analyze the synergy between ecological environment quality and economic development quality in China. The research aims to assess the spatial and temporal distribution patterns of ecological-economic coordination across different regions of China, from 2001 to 2021, using a spatial autocorrelation model. This study also seeks to provide a framework for differentiated ecological governance strategies based on regional development characteristics.

Methods

Theoretical analysis

Ecological environment quality refers to the stability and functional health of the ecosystem structure in a region over a certain period of time, usually including

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_785805

indicators such as air, water, soil quality, biodiversity, and green space coverage. It not only reflects the carrying state of the natural environment, but also is a prerequisite for the sustainable operation of the ecosystem. The degradation of ecological environment will directly constrain the SD of regional economy, manifested as rising pollution costs, reduced resource supply, and increased public health risks (Huang et al., 2025; Wei et al., 2023). Therefore, dynamic monitoring and regulation of ecological quality in regional development have become an important foundation for ensuring ecological security.

The quality of ED is a key criterion for measuring whether regional ED is sustainable, inclusive, and green oriented. Its connotation not only includes the improvement of economic aggregate, but also should pay attention to multidimensional factors such as industrial structure optimization, innovation capability enhancement, employment and income equity, infrastructure improvement, and green growth (Chen et al., 2023). High quality ED emphasizes the unity of resource utilization efficiency, ecological cost control, and social welfare improvement, which is a key pathway for the modern economic system’s transformation and enhancement.

The collaborative theory emphasizes the dynamic coupling relationship formed between multiple systems through information exchange, energy transfer, and structural evolution. In the system of ecological environment and ED, the two can form a positive feedback mechanism under certain conditions. For example, a good ecological foundation provides resources and environmental support for ED, while high-quality ED can in turn promote ecological investment, green technology innovation, and environmental governance investment (Li et al., 2023; Yuan et al., 2023). Therefore, the two have structural interdependence and evolutionary coupling characteristics, and their level of synergy directly affects the overall efficiency of regional SD.

The theory of ecological carrying capacity originates from the analysis of ecosystem capacity, which refers to the intensity of human activities that a region’s ecosystem can support without damaging its structure and function. The basic assumption is that natural resources are limited and environmental capacity has a threshold, exceeding which will lead to system degradation or even collapse (Correia et al., 2023). In regional development, ecological carrying capacity not only constrains the scale of economic expansion, but also guides resource allocation and environmental capacity warning. Coupling analysis of ecological carrying capacity and ED process can scientifically identify development boundaries and environmental risks, and achieve spatial differentiation regulation.

The development process of ED theory has gradually evolved from traditional growth theory to a modern development paradigm that emphasizes quality and structure. In the early days, the Solow model emphasized capital and technology investment, but in recent years, it has focused more on green growth, inclusive development, and innovation driven development. Modern ED theory emphasizes the deep integration of the economy and the natural environment, proposing new indicator systems such as Gross Domestic Product (GDP), total factor productivity, and resource and environmental efficiency. Incorporating ecological factors into the ED assessment system can help break out of the development trap of “pollution first, treatment later” and promote the transformation of the economic system from resource dependence to sustainable structure.

Ecological environment quality assessment

Indicator system design

Ecological environment and regional economy, as important drivers of SD strategy, have been increasingly valued in national development strategies in recent years. However, while rapid economic expansion drives growth, it often leads to issues like excessive resource consumption, worsening environmental degradation, and overdrawn regional ecological carrying capacity (Zhu et al., 2025; Alsaleh et al., 2023). Therefore, how to scientifically and systematically evaluate the synergy between ecological environment and ED has become the basis for formulating regional development policies and ecological governance measures. The theory of SD emphasizes the coordination and unity of ED, ecological protection, and social welfare, advocating for the stability of ecosystems and the sustainable use of resources while promoting high-quality ED (Struwig et al., 2023). In this context, based on the concept of SD, a comprehensive evaluation system covering environmental quality and economic efficiency is constructed to represent the synergistic relationship between the two. The design of the indicator system follows four principles, striving to comprehensively reflect the ecological economic interaction mechanism in the process of regional development. In order to accurately assess the spatiotemporal variations in ecological environment quality and quantify the condition of natural ecosystems, remote sensing technology provides an effective, large-scale, and long-term monitoring solution. Given its advantages in wide-area observation and consistency across time, remote sensing-derived indicators such as vegetation productivity, land use, and water quality have become essential tools in evaluating ecological carrying capacity and environmental health. Within this study, remote sensing data are integrated to construct an ecosystem composite index (CI), which serves as a foundational component for measuring the coupling coordination degree between ecological and economic systems. To effectively reflect the ecological foundation of each region, this study constructs a dual-dimensional ecological evaluation system, incorporating both the ecosystem quality index and the ecosystem area index. The ecosystem quality index focuses on measuring the health status of different ecological land types such as farmland, forest, grassland, and water bodies. It is derived based on remote sensing indicators including net primary productivity (NPP), vegetation coverage, and water quality, which together reflect the vitality and stability of the ecosystem. Meanwhile, the ecosystem area index quantifies the spatial scale of each ecological type in a given region, based on the proportion of different ecological land areas within the total provincial territory. By integrating quality and area dimensions, this framework ensures a more comprehensive assessment of ecological conditions. The higher the ecosystem quality index and the larger the corresponding ecological area, the stronger the ecological carrying capacity and support function of the region. These two components are further synthesized into a unified ecosystem composite index (CI), which serves as the core ecological input in the coordinated development model. The indicators are shown in *Figure 1*.

The study integrates the ecosystem quality index with the ecosystem area index to construct an ecosystem CI for evaluating ecosystem quality. This index can comprehensively analyze the spatiotemporal dynamic changes of various ecosystems and achieve quantitative expression of ecosystem value. The CI of ecosystem can comprehensively evaluate the status of major ecological asset types such as arable land, forest land, and grassland, and intuitively reveal the trend of ecosystem evolution

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
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(Issahaku et al., 2024; Zhang et al., 2024). Its advantage lies in the ability to avoid heterogeneity in ecosystem quality and area between regions, thus enabling more effective cross regional comparisons of ecological environment quality. The higher the CI of the ecosystem, the better the quality and larger the scale of the ecosystem it represents. Given the complexity of ecological factors such as water bodies, the water quality classification in *Table 1* adopts a simplified five-level system (Class I-V) that aligns with the national environmental quality standards for surface water in China. While water quality is indeed influenced by a wide range of biotic and abiotic factors-including nutrient concentrations, biological oxygen demand, heavy metals, and microbial loads-the current classification is designed to provide a practical and consistent basis for large-scale regional comparisons. The ecological assets in the country are divided into four categories and classified into different quality levels according to standards, as presented in *Table 1*.

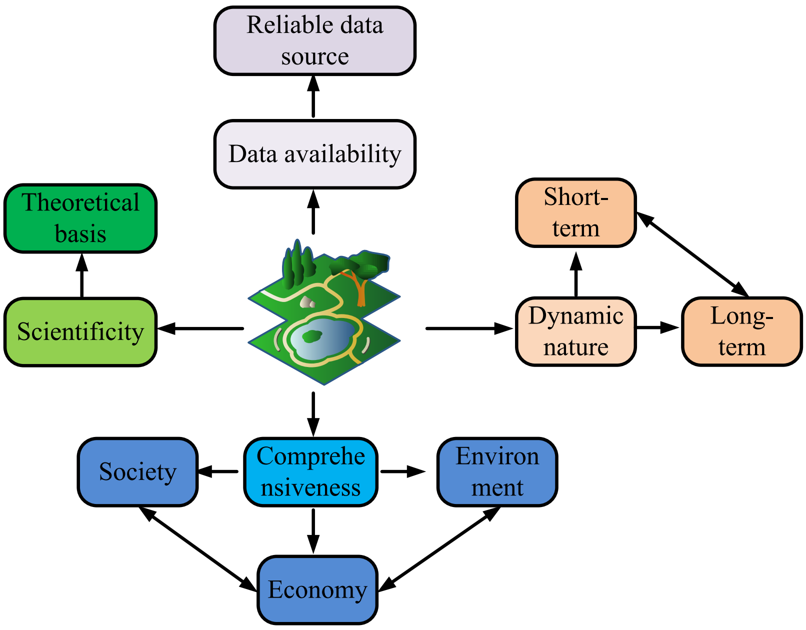

Figure 1. *Remote sensing ecological indicators*

Table 1. *Ecological system quality evaluation indicators and classification standards*

Ecosystem type	Evaluation indicator	Excellent (V)	Good (IV)	Moderate (III)	Poor (II)	Very poor (I)
Farmland	Relative NPP density	≥85%	70%–85%	50%–70%	25%–50%	<25%
Forest	Relative NPP density	≥85%	70%–85%	50%–70%	25%–50%	<25%
Grassland	Vegetation coverage rate	≥70%	50%–70%	35%–50%	20%–35%	<20%
Water area	Water quality	Class I	Class II	Class III	Class IV	Class V

In *Table 1,* the Net Primary Productivity (NPP) of vegetation quantifies the quantity of organic carbon that vegetation accumulates after harnessing solar energy through

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_785805

photosynthesis and transforming it into organic matter, while accounting for its own metabolic consumption. This metric serves as an indicator of the ecosystem's energy accumulation capacity and biological production potential. NPP is one of the key indicators of ecosystem carbon cycle, widely used to evaluate vegetation growth status, ecosystem health level, and ecological service functions. The higher the value, the more vigorous the vegetation growth and the better the ecological environment quality (Chen et al., 2024; Zhang et al., 2024). In the assessment of ecological environment quality, the NPP density under different ecological types serves as a core indicator, which can effectively reflect the production capacity and carrying potential of regional ecosystems, and serves as a crucial foundation for distinguishing the status and changing trends of ecological assets. This indicator can be obtained through remote sensing observation and climate data model inversion, and has the advantages of strong spatiotemporal continuity and wide applicability. It has been widely used in ecological monitoring and performance evaluation of ecological civilization construction. The expression for the quality status of ecological assets of cultivated land and forest land is shown in *Equation 1*.

$$RND_{ij}=\frac{B_{ij}}{CCN_j}\times 100\% \quad \text{(Eq.1)}$$

In *Equation 1*, RND_{ij} represents the relative NPP density of the *j*th plot in the class ecosystem, B_{ij} is the measured NPP value of the *i*th plot in the class ecosystem, and CCN_j represents the average NPP reference value of the class ecosystem (Saidi et al., 2023). The ecological asset quality of grassland is evaluated using vegetation coverage, as expressed in *Equation 2*.

$$F_c=\frac{NDVI-NDVI_{soil}}{NDVI_{veg}-NDVI_{soil}} \quad \text{(Eq.2)}$$

In *Equation 2*, F_c represents the proportion of plant coverage in a certain area of pixels, and $NDVI$ is the normalized vegetation index of the target area. $NDVI_{soil}$ denotes the NDVI value for pixels of purely bare soil, while $NDVI_{veg}$ signifies the NDVI value for pixels covered entirely by vegetation. It is acknowledged that grasslands encompass both natural and cultivated types, each differing significantly in ecological structure, vegetation composition, and management intensity. However, due to limitations in data availability and the need for consistency in national-scale assessment, this study applies a unified vegetation coverage indicator to all grassland types. This approach allows for cross-regional comparability while capturing the general status of vegetation growth. In future research, more refined classification systems can be established by integrating land use datasets, pasture management records, and remote sensing-based phenological indicators to differentiate natural and artificial grasslands, thereby improving the ecological accuracy of the index system.

Evaluation of ED quality

Steered by the innovative development approach, this study carries out a thorough analysis across five key dimensions: innovation, coordination, green development,

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openness, and sharing. It focuses on evaluating the quality of the ED process, reflecting the ED status of various provinces in China over different years. The study aims to minimize the influence of regional development stage disparities. As a result, an evaluation index system for the quality of ED has been constructed (Akinlo et al., 2024; Ha et al., 2024). *Table 2* displays the evaluation index system for assessing ED quality.

Table 2. *Evaluation index system for ED quality*

Primary indicator	Secondary indicator	Indicator description	Unit
Innovation development	Proportion of science & technology expenditure	S&T expenditure / total public expenditure	%
	R&D investment intensity	R&D expenditure of above-scale industrial enterprises / regional GDP	%
	Efficiency in investment	Incremental capital-output ratio (ICOR)	Ratio
Coordinated development	Degree of technology trade activity	Technology trade transaction amount	CNY (billion)
	Demand pulling capacity	Total social retail sales	CNY (billion)
	Urbanization structure	Level of urban development	%
	Composition of industries	Industrial structure rationalization index	Index (dimensionless)
	Burden of governmental debt	Government debt balance	CNY (billion)
Green development	Elasticity factor of energy consumption	Rate of increase in energy usage	%
	Wastewater discharge per unit output	Wastewater discharge	Tons / CNY million GDP
Open development	Waste gas discharge per unit output	Sulfur dioxide emissions	Tons / CNY million GDP
	Ratio of reliance on foreign trade	Total import and export volume	% of GDP
	Proportion of foreign investment utilization	Actually used foreign capital	CNY (billion)
	Marketization level	Regional marketization index	Index (dimensionless)
Shared development	Labor income share	Labor compensation	%
	Elasticity of resident income growth	Rate of increase in average disposable income per person / GDP growth rate	Ratio
	Disparity in consumption between urban and rural areas	Per capita consumption of urban residents/rural residents	Ratio
	Share of fiscal spending allocated to livelihood-related areas	Proportion of local fiscal education, medical care, housing, social security, and employment expenditures in total local budget	%

According to *Table 2,* the indicator system comprehensively evaluates high-quality ED from five dimensions: innovation, coordination, green, openness, and sharing. In terms of innovative development, the intensity of R&D investment reflects the degree of regional emphasis on technological innovation, while investment efficiency measures the ED effect brought by unit investment and is an important indicator for measuring resource allocation efficiency. In terms of coordinated development, the rationalization index of urbanization structure and industrial structure respectively reflects the coordination of population and industrial spatial distribution, while the government debt burden index reflects fiscal sustainability. In green development, the energy consumption elasticity coefficient measures the degree of dependence of ED on energy, and the smaller the value, the better the effectiveness of green transformation. Regarding open development, a region’s reliance on foreign trade and the share of foreign investment utilized serve as indicators of its degree of openness to the global

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market. In shared development, the elasticity of residents' income growth reflects whether their income is synchronized with ED, while the urban-rural consumption gap measures the balance of regional development (An et al., 2024; Zhong et al., 2024). To eliminate the influence effect of different indicators in the ED quality indicator system, the original data are standardized, and it is represented by *Equation 3*.

$$X_{mn} = \left| \frac{x_{mn} - \min(x_{mn})}{\max(x_{mn}) - \min(x_{mn})} \right| \tag{Eq.3}$$

In *Equation 3*, *m* represents the province, *n* is the measurement indicator, x_{mn} and X_{mn} are the values of *n* indicators of the original and standardized province *m*, respectively. The CI of ED quality is shown in *Equation 4*.

$$U_m = \sum_{n=1}^{c} W_n X_{mn} \tag{Eq.4}$$

In *Equation 4*, W_n represents the weight of each indicator and U_m represents the CI of ED quality.

Model establishment

The spatial autocorrelation model assesses the level of correlation among regional variables in the spatial context and serves as a key approach for examining the spatial distribution patterns and structure of geographical phenomena. Its core lies in determining whether a variable has similarities between geographically adjacent units, with different spatial patterns such as positive correlation, negative correlation, or random distribution (Yan et al., 2022; Mehdi et al., 2024). The global spatial autocorrelation index used in the study is Morans I, as presented in *Equation 5*.

$$I = \frac{g \sum_k \sum_l w_{kl} (x_k - \bar{x})(x_l - \bar{x})}{\sum_k (x_k - \bar{x})^2 \sum_k \sum_l w_{kl}} \tag{Eq.5}$$

In *Equation 5*, *I* represents the global spatial autocorrelation index, x_k and x_l are the observed values for regions *k* and *l* respectively, w_{kl} denotes the spatial weight between regions, and *g* is the total number of samples. If $I > 0$, it shows a positive spatial correlation, meaning that adjacent regions have similar characteristics. If $I < 0$, it implies negative spatial correlation, with significant differences in the eigenvalues. If $I \approx 0$, it implies a random spatial distribution. In the study of the synergy between ecological environment and ED, spatial autocorrelation models can effectively reveal the spatial dependence characteristics of variables, providing theoretical support and empirical basis for subsequent spatial regression modeling and identification of synergy mechanisms (Yin et al., 2024; Yang et al., 2022). The CC degree model is employed to characterize the interactive relationship and coordinated evolution level between the two subsystems of ecological environment and ED, emphasizing the correlation, synergy, and coordination degree between the systems. The basic idea is to first calculate the evaluation CI of each subsystem through standardized methods, and its expression is shown in *Equation 6*.

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$$C = \frac{2\sqrt{U_1 \times U_2}}{U_1 + U_2} \quad \text{(Eq.6)}$$

In *Equation 6*, U_1 represents the CI of the ecosystem, U_2 represents the CI of the economic system, and C represents the degree of coupling. The larger the coupling degree value, the closer the correlation between systems. However, strong coupling does not necessarily mean coordinated development, so the introduction of coordination degree characterizes its collaborative level, as expressed in *Equation 7*.

$$\begin{cases} D = \sqrt{C \times T} \\ T = \alpha U_1 + \beta U_2 \end{cases} \quad \text{(Eq.7)}$$

In *Equation 7*, *T* is the development CI of the system, *α* and *β* are the weights of each subsystem. The range of D's values spans from 0 to 1, with values nearer to 1 indicating a greater degree of coordination (Bhosle et al., 2023). The CC degree model can dynamically reflect the development process of ecological and economic systems from imbalance, low-level coordination to high coordination, providing quantitative basis for regional SD assessment and regulation strategy formulation. The study divides the CC degree into the following levels, as shown in *Figure 2*.

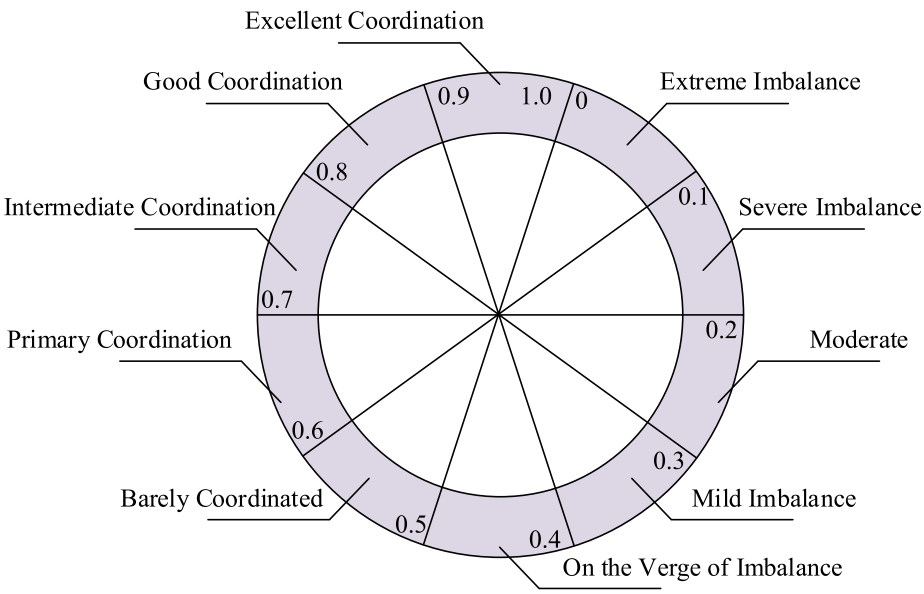

Figure 2. *Classification criteria for CC levels*

As depicted in *Figure 2,* the CC degree D spans a scale from 0 to 1, where values nearing 1 denote a higher level of system coordination. Based on different intervals of the D value, the degree of coordination is categorized into two main stages: the imbalance and the coordination. In the imbalance stage, when $0 < D \leq 0.1$, it signifies that the system is in an "extremely imbalanced" state, characterized by a severe disconnect between ecological and ED. The interval $0.1 < D \leq 0.2$ is deemed "severe imbalance", $0.2 < D \leq 0.3$ as "moderate imbalance", $0.3 < D \leq 0.4$ as "mild imbalance", and $0.4 < D \leq 0.5$ as "near imbalance". These intervals indicate that, although there

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exists some interaction between the systems, the synergy is notably weak. Upon entering the coordination stage, $0.5 < D \leq 0.6$ denotes “barely coordinated”, suggesting that the system has begun to establish a coordination mechanism. The interval $0.6 < D \leq 0.7$ is considered “primary coordination”, while $0.7 < D \leq 0.8$ is classified as “intermediate coordination”, reflecting a gradual strengthening of the collaborative relationship between systems. When the D value falls within $0.8 < D \leq 0.9$, the system has achieved “good coordination”. Finally, $0.9 < D < 1$ indicates “high-quality coordination”, signifying a high degree of integration between the ecological and economic systems, leading to development that is both sustainable and mutually advantageous.

Analysis of driving factors

In the study of the synergy between ecological environment and ED quality, examining the driving factors can uncover the intrinsic driving forces and key impact paths of system evolution. Grounded in the theoretical framework of ecological civilization construction and high-caliber development, a driving mechanism for the synergistic effect between ecological environment quality and ED quality has been studied and constructed, as shown in *Figure 3*. This mechanism model consists of three core modules: firstly, policy regulation and market development mechanisms are external driving forces. It mainly promotes the rational flow of resource elements and the development of green industries through environmental regulations, market development, and high-quality foreign investment, and enhances regional synergy. Secondly, the mechanism of economic operation and structural transformation is an internal driving force. Green finance, economic drivers, and advanced industrial structure play a key role in maintaining ED while reducing environmental pressure, achieving a shift in economic structure from resource intensive to green innovative. Thirdly, the mechanism of ecological civilization dissemination and technological innovation is the driving force for innovation. Talent elements, social promotion, technological support, and technological innovation constitute the core support system of knowledge and technology, providing long-term endogenous driving force for the synergy between ecological protection and ED. In summary, policies and market mechanisms provide external constraints and opportunities for coordinated development, economic structural transformation provides basic support for system linkage, and technological innovation and ecological civilization construction ensure sustainable and high-quality coordinated evolution of the system. This driving mechanism not only reveals the dynamic relationship between the ecological economic system, but also provides a foundational framework for the subsequent calculation of CC degree and policy optimization.

Data sources and regional division

The data used in this study were primarily sourced from national and regional statistical yearbooks, remote sensing data, and economic reports published by government agencies, including the China Statistical Yearbook, the Ministry of Ecology and Environment of the People’s Republic of China, and remote sensing datasets from MODIS and Landsat. The study period spans from 2001 to 2021, providing a comprehensive view of the temporal evolution of ecological and economic systems in China. For the purpose of analysis, China was divided into three major regions based on

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_785805

geographical and economic factors: Eastern China, Central China, and Western China. This regional classification aligns with commonly used divisions in national planning and development strategies. The Eastern region includes provinces such as Beijing, Shanghai, and Guangdong, while the Central region consists of provinces like Hunan, Henan, and Hubei. The Western region includes provinces such as Sichuan, Yunnan, and Tibet. This division allows for region-specific ecological and economic coordination analysis, accounting for the unique development dynamics and ecological characteristics of each region.

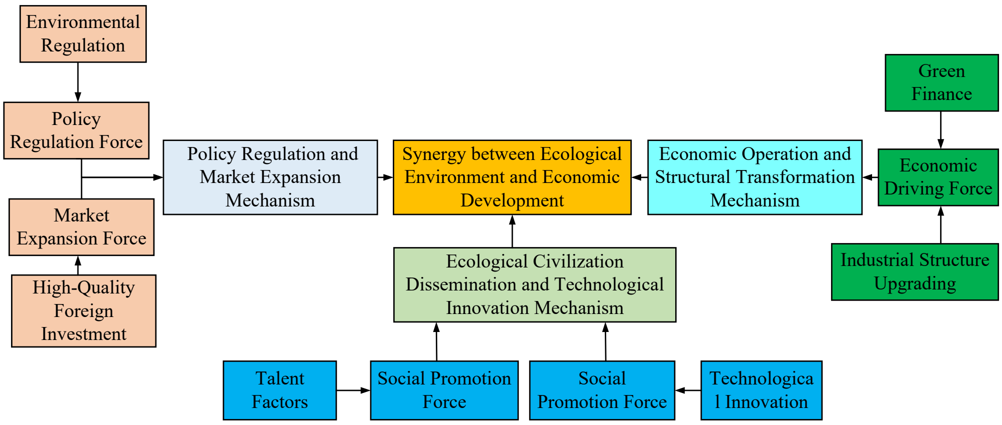

Figure 3. *Analysis of driving factors*

Results

Results of ecosystem assessment

Results of ecosystem assessment in the eastern region

To comprehensively evaluate the temporal evolution characteristics of ecosystem quality in the eastern region, the research was conducted grounded in five time nodes (quantifying the development level of ecosystems in each province and city, and calculating their mean level to reflect the overall trend of ecosystem quality changes, as presented in *Table 3*).

Table 3. *Ecological system assessment outcomes of various provinces in the eastern region (2001-2021)*

Province ($*10^{-1}$)	2001	2006	2011	2016	2021	Average
Beijing	4.344	4.209	4.293	4.126	3.927	4.180
Tianjin	4.288	4.157	4.299	4.053	3.984	4.156
Hebei	3.780	3.850	3.871	4.054	4.174	3.946
Shanghai	4.291	4.484	4.037	3.971	3.911	4.139
Jiangsu	4.532	4.320	4.182	3.904	4.085	4.205
Zhejiang	3.747	3.963	4.058	4.246	4.490	4.101
Fujian	4.089	4.191	4.158	4.210	4.312	4.192
Shandong	3.559	3.823	3.979	4.302	4.092	3.951
Guangdong	3.433	3.702	4.864	4.793	4.817	4.322
Hainan	3.635	4.012	5.101	4.503	4.518	4.354

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
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According to *Table 3,* the overall ecosystem quality in the eastern region showed a fluctuating upward trend, but there were significant differences among provinces. Among them, Guangdong and Hainan rapidly improved their ecosystem quality since 2011, with an average of 0.4322 and 0.4354 respectively in 2021, ranking among the top in the region, indicating outstanding achievements in ecological civilization construction and green development. In contrast, the average values of provinces such as Hebei and Shandong are relatively low, at 0.3946 and 0.3951 respectively, indicating a relatively slow improvement in their ecosystem quality, which might be constrained by factors such as industrial structure and energy structure. Overall, although the ecological system level of various provinces in the eastern region was good, there were still differences in ecological carrying capacity and uneven regional development.

Results of ecosystem assessment in the central and southern regions

To further reveal the evolutionary characteristics of ecosystem quality in the central region, this study measured the ecosystem evaluation values of six provinces in the central region at five time points from 2001 to 2021, and calculated the average level of each province to evaluate their ecological development status, as shown in *Table 4*.

Table 4. *Ecological system assessment outcomes of provinces in the central region (2001-2021)*

Province (*10^{-1})	2001	2006	2011	2016	2021	Average
Shanxi	3.318	3.566	3.750	3.884	3.736	3.651
Anhui	2.391	2.877	3.686	3.803	4.592	3.469
Jiangxi	3.636	3.900	4.036	4.297	4.411	4.056
Henan	2.628	3.207	3.473	3.728	3.978	3.403
Hubei	2.609	3.296	3.580	3.887	4.196	3.514
Hunan	3.271	3.592	4.030	3.913	4.211	3.803

According to *Table 4,* the overall ecological system quality of various provinces in the central region showed a steady improvement trend, with some provinces showing significant improvement during the 13th Five Year Plan period. Jiangxi performed relatively outstandingly, with an average of 0.4056, and was in a leading position in the region for multiple consecutive years, indicating that its ecological protection policies were effectively implemented. Hunan ranked second with an average value of 0.3803, showing a comparatively steady state of ecosystem health. In contrast, the average values of ecosystems in Anhui and Henan were relatively low, at 0.3469 and 0.3403 respectively, indicating that their ecosystems still faced certain pressures and there was significant room for improvement. Overall, the development of ecosystems in the central region was showing a trend of gradual optimization, but there were still certain gaps between provinces.

Results of ecosystem assessment in western regions

To systematically evaluate the development level of the ecosystem in the western region, this study selected an ecosystem evaluation value table for five time points from 2001 to 2021, and calculated the mean of each region to analyze its ecological quality evolution trend, as presented in *Table 5*.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_785805

Table 5. *Ecological system evaluation results of provinces in western China (2001-2021)*

Province (*10^{-1})	2001	2006	2011	2016	2021	Average
Inner Mongolia	3.713	3.921	4.046	4.254	4.362	4.059
Liaoning	4.496	4.584	4.675	4.844	4.877	4.695
Jilin	4.259	4.201	4.387	4.545	4.779	4.434
Heilongjiang	4.322	4.355	4.477	4.567	4.776	4.499
Guangxi	3.082	3.011	4.742	4.942	4.851	4.126
Chongqing	2.414	2.551	3.034	3.322	4.118	3.088
Sichuan	3.984	4.026	4.044	4.143	4.289	4.097
Guizhou	2.942	3.086	3.287	4.063	4.421	3.560
Yunnan	3.371	3.622	5.622	5.632	5.585	4.766
Tibet	4.261	4.701	4.511	4.537	4.534	4.509
Shaanxi	3.364	3.769	4.063	3.932	4.072	3.840
Gansu	3.557	3.626	3.930	4.045	4.214	3.874
Qinghai	4.372	4.376	4.542	4.606	4.319	4.443
Ningxia	4.210	4.320	4.425	4.554	4.275	4.357
Xinjiang	4.502	4.415	4.630	4.762	4.487	4.559

According to *Table 5,* the overall ecosystem quality in the western region showed an improving trend, but there were significant regional differences. The ecosystem evaluation values of Liaoning, Heilongjiang, Jilin, Qinghai, Xinjiang and other places always maintained a high level, with an average value exceeding 0.44, especially in Liaoning where it reached 0.4695, indicating significant ecological governance effectiveness. Although Yunnan had a low evaluation value in 2001, its ecosystem level rapidly increased after 2011, with an average of 0.4766, reflecting the good implementation effect of its ecological compensation and environmental governance policies. Relatively speaking, the average values of ecosystems in Chongqing, Guizhou, and Guangxi were still relatively low, at 0.3088, 0.3560, and 0.4126, respectively, indicating that their ecological environment foundation still needed further consolidation.

Evaluation of ED quality

Evaluation of ED quality in the eastern region

To further grasp the temporal evolution characteristics of regional ED level, this study analyzed 10 provincial-level administrative units in the eastern region, constructed a series of ED quality indicators for five key years from 2001 to 2021, and calculated the average level of each region, as presented in *Table 6*.

As shown in *Table 6,* the overall quality of ED in the eastern region continued to improve, exhibiting characteristics of “high-level growth and gradient convergence”. From the average perspective, regions such as Beijing, Tianjin, Jiangsu, Zhejiang, Shandong, and Shanghai maintained an average of 0.665 or above, indicating their sustained leading advantages in industrial upgrading, technological innovation, and urbanization processes. Beijing and Tianjin reached 0.665 and 0.666 respectively, indicating significant achievements in the integration of high-end service industry and modern manufacturing industry. Although Guangdong and Fujian started slightly lower, they have grown rapidly in recent years, with an average of over 0.664. The average

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_785805

quality of ED in Hainan was 0.673, and under the promotion of the free trade port policy, its growth potential and structural optimization effects were gradually emerging. Overall, in the context of high-caliber development, the eastern provinces showed a relatively balanced upward trend, but there was still pressure to transform from traditional industrial provinces to high-end service-oriented regions, and further improvement in development quality and sustainability was needed.

Table 6. *Evaluation results of ED quality in eastern provinces (2001-2021)*

Province (*10^{-1})	2001	2006	2011	2016	2021	Average
Beijing	4.88	5.90	6.87	7.61	8.00	6.65
Tianjin	5.04	5.88	6.86	7.44	8.09	6.66
Hebei	5.12	5.93	7.12	7.40	7.93	6.70
Shanghai	4.87	5.90	7.09	7.51	8.09	6.69
Jiangsu	4.86	6.09	7.07	7.56	7.98	6.71
Zhejiang	5.10	5.96	6.97	7.36	8.10	6.70
Fujian	4.98	6.11	6.88	7.37	7.86	6.64
Shandong	4.95	5.95	6.99	7.54	8.05	6.70
Guangdong	4.92	6.11	6.95	7.44	7.94	6.67
Hainan	5.15	5.88	6.98	7.57	8.06	6.73

The central evaluation of ED quality in the eastern region

To deeply analyze the stage characteristics of ED quality in the central region, the study selected six provinces in the central region as research objects, and constructed an evaluation sequence of ED quality in the central region based on indicator data from five time nodes from 2001 to 2021. The outcomes are presented in *Table 7*.

Table 7. *Evaluation results of ED quality in various provinces in the central region (2001-2021)*

Province (*10^{-1})	2001	2006	2011	2016	2021	Average
Shanxi	2.92	3.95	4.96	5.46	6.00	4.66
Anhui	2.97	4.01	4.96	5.56	5.90	4.68
Jiangxi	3.02	4.04	4.97	5.58	6.03	4.73
Henan	3.00	4.08	5.05	5.49	6.05	4.73
Hubei	2.96	4.01	4.96	5.45	6.04	4.68
Hunan	3.01	3.91	5.08	5.43	6.01	4.69

According to *Table 7,* the quality of ED in the central provinces showed a continuous improvement trend in the past two decades, especially during the 11th and 13th Five Year Plans, which showed significant leaps. Among them, the average values of Jiangxi and Henan both reached 0.473, ranking among the top in the region, reflecting their high degree of benefit in industrial transformation, infrastructure construction, and regional coordination policies. Although Shanxi started slightly lower, it benefited from energy structure adjustment and the introduction of high-end manufacturing, with an average of 0.466. Overall, the six central provinces gradually narrowed the gap with the developed eastern regions in the transition from traditional agricultural provinces to a

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_785805

new industrial and service economy system, and achieved phased results in the regional coordinated development strategy.

Results of ecosystem assessment in western regions

To comprehensively analyze the temporal evolution characteristics of ED quality in the western region, a five period ED quality evaluation index system from 2001 to 2021 was studied and constructed. The outcomes of the evaluation are presented in *Table 8*.

Table 8. *Evaluation results of ED quality in western regions (2001-2021)*

Province ($*10^{-1}$)	2001	2006	2011	2016	2021	Average
Inner Mongolia	2.09	3.04	4.11	4.43	4.99	3.73
Liaoning	1.87	3.09	4.04	4.39	4.86	3.65
Jilin	2.04	3.05	4.01	4.53	4.92	3.71
Heilongjiang	1.93	3.04	4.03	4.37	4.99	3.67
Guangxi	1.96	3.08	4.11	4.47	5.02	3.73
Chongqing	1.86	2.86	4.09	4.41	5.03	3.65
Sichuan	1.95	2.87	4.09	4.48	4.99	3.68
Guizhou	1.83	2.92	3.93	4.44	4.94	3.61
Yunnan	2.03	2.99	3.96	4.65	5.05	3.74
Tibet	1.94	2.99	4.01	4.46	4.89	3.66
Shaanxi	2.04	3.03	4.15	4.64	4.90	3.75
Gansu	2.12	2.85	3.92	4.36	5.08	3.67
Qinghai	2.07	3.06	4.08	4.41	5.04	3.73
Ningxia	1.95	3.10	3.93	4.39	4.97	3.67
Xinjiang	1.99	3.10	4.15	4.42	4.95	3.72

According to *Table 8,* although the overall ED quality level of western provinces still lagged behind that of the eastern and central regions, it showed a steady growth trend. Among them, provinces and regions such as Shaanxi, Yunnan, and Inner Mongolia showed swift expansion during the 13th Five Year Plan period, with an average value exceeding 0.37, reflecting substantial progress made in the region under the promotion of resource development, infrastructure investment, and regional synergy strategy. Additionally, the starting point of ED quality in Guizhou, Chongqing and other places was relatively low, but the growth rate was relatively stable, indicating that they had strong potential for latecomers under the drive of promoting industrial structure optimization and poverty alleviation policies. Overall, the western region was still in a critical period of transitioning from a resource dependent economy to a quality- and efficiency-based economy. It is essential to further strengthen the construction of scientific and technological innovation capabilities and the aggregation of high-end factors to achieve higher quality development goals.

Collaborative evaluation

Evaluation results of synergy in the eastern region

To investigate the evolving interplay between ecological environment and ED, empirical measurements were conducted on the CC degree of various provinces and

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_785805

cities in the eastern region. By constructing a coupled coordination model between ecosystem and ED quality, the development synergy of 10 eastern provinces from 2001 to 2021 was comprehensively evaluated. The specific calculation results and average coordination level for each year are presented in *Table 9*.

Table 9. *Calculation outcomes of ecological economic system coordinated development level in the eastern region (2001-2021)*

Province (*10^{-1})	2001	2006	2011	2016	2021	Average	Coordination level
Beijing	7.393	7.424	7.545	7.442	7.436	7.490	Intermediate coordination
Tianjin	6.538	6.641	6.845	6.964	7.099	6.757	Primary coordination
Hebei	5.150	5.352	5.428	5.658	5.830	5.415	Barely coordinated
Shanghai	6.980	7.255	7.125	7.252	7.192	7.198	Intermediate coordination
Jiangsu	6.352	6.463	6.671	6.992	7.224	6.791	Primary coordination
Zhejiang	6.122	6.457	6.693	6.912	7.132	6.735	Primary coordination
Fujian	6.041	6.252	6.445	6.681	6.733	6.433	Primary coordination
Shandong	5.976	6.247	6.566	6.825	7.072	6.569	Primary coordination
Guangdong	5.975	6.322	6.866	7.181	7.319	6.721	Primary coordination
Hainan	4.710	4.972	5.533	5.769	6.095	5.318	Barely coordinated

According to *Table 9,* the overall CC between ecology and economy in the eastern region was at a medium to high level, and showed a steady improvement trend over time. Among them, Beijing and Shanghai showed particularly outstanding performance, with an average coordination degree of over 0.71, at the intermediate coordination level, Suggesting a strong level of synergetic linkage between ecological and economic systems. Tianjin, Jiangsu, Zhejiang, Guangdong and other provinces and cities were all in a state of primary coordination, indicating the formation of a positive interaction mechanism between ecological protection and ED. In contrast, although Hebei and Hainan made significant progress in recent years, they were still at a barely coordinated level overall. It was necessary to further strengthen the green development policy orientation and ecological governance capabilities to promote high-quality coordinated regional development.

Results of collaborative evaluation in the central and southern regions

To further analyze the degree of coupling and coordination between the ecosystem and ED in the central region, a systematic calculation was conducted on the collaborative development level of six central provinces from 2001 to 2021. Based on the constructed CC model and combined with the national regional development strategy, the functional positioning of the central region is shown in *Table 10*.

According to *Table 10,* the central region as a whole was in a barely coordinated stage, indicating that the ecological environment system and ED system did not form a closely coordinated mechanism. Although Henan, Hunan, Hubei and other regions showed a clear upward trend in recent years, their average CC did not exceed the critical value of 0.6 due to weak early foundations, and did not reach the level of Primary Coordination. In the future, the region should strengthen the linkage of green development policies, accelerate the construction of an institutional guarantee system

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_785805

for the coordinated promotion of ecology and economy, to enhance the regional SD capacity and CC level.

Table 10. *Evaluation outcomes of ecological economic system coordinated development level in the central region (2001-2021)*

Province (*10^{-1})	2001	2006	2011	2016	2021	Average	Coordination level
Shanxi	5.382	5.207	5.943	5.283	5.891	5.373	Barely coordinated
Anhui	4.669	4.237	5.258	5.511	5.994	5.496	Barely coordinated
Jiangxi	4.849	5.150	5.596	5.978	5.828	5.615	Barely coordinated
Henan	5.356	5.643	5.317	6.829	6.869	5.961	Barely coordinated
Hubei	5.677	5.454	5.025	6.135	6.885	5.225	Barely coordinated
Hunan	5.595	5.715	5.128	6.999	6.191	5.109	Barely coordinated

Results of collaborative evaluation in western regions

To analyze the collaborative evolution relationship between the ecosystem and economic system in the western region, a coordination degree calculation model was used to systematically analyze the CC level of 11 western provinces from 2001 to 2021. The results are shown in *Table 11*.

Table 11. *Assessment results of ecological economic system coordinated development level in western regions (2001-2021)*

Province (*10^{-1})	2001	2006	2011	2016	2021	Average	Coordination level
Guangxi	4.496	4.714	5.461	5.982	6.389	5.304	Barely coordinated
Chongqing	4.080	5.199	5.022	5.934	6.658	5.538	Barely coordinated
Sichuan	5.418	5.746	5.866	5.674	6.471	5.705	Barely coordinated
Guizhou	4.555	4.983	4.726	5.647	5.437	4.732	On the verge of imbalance
Yunnan	4.597	5.279	5.592	5.375	6.146	5.903	Barely coordinated
Tibet	4.786	4.673	4.354	5.293	4.186	4.865	On the verge of imbalance
Shaanxi	5.134	5.537	5.462	5.672	5.736	5.809	Barely coordinated
Gansu	5.043	5.658	5.316	5.441	5.336	5.151	Barely coordinated
Qinghai	5.431	5.584	5.967	5.717	5.201	5.648	Barely coordinated
Ningxia	5.380	5.930	5.860	5.409	5.761	5.687	Barely coordinated
Xinjiang	5.843	5.666	5.009	5.429	5.207	5.347	Barely coordinated

From *Table 11,* the coordination level of ecological system and economic system in most western provinces and regions was still in a barely coordinated stage, and only Guizhou and Xizang approaching imbalance, indicating that the imbalance of development between regions was still significant. Although Sichuan, Shaanxi, Ningxia and other regions had relatively high levels of coordination, the overall level has not yet reached Primary Coordination or above. In the future, the western region needs to further promote ecological priority and green low-carbon development strategies, enhance the environmental carrying capacity of ED, and achieve coordinated progress between ecological protection and economic quality improvement.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_785805

Analysis of Moran's index results

To further analyze the spatial agglomeration characteristics of the coordinated development of regional ecological and economic systems in China from 2001 to 2021, the global Moran's index I was used to measure the spatial autocorrelation of each year, as shown in *Table 12*.

Table 12. *Global Moran index and significance test results of regional ecological economic system from 2001 to 2021*

Year	Global Morans I	p-Value	Year	Global Morans I	p-Value
2001	0.298	0.005	2012	0.235	0.023
2002	0.282	0.011	2013	0.243	0.021
2003	0.275	0.009	2014	0.307	0.004
2004	0.294	0.005	2015	0.329	0.003
2005	0.281	0.012	2016	0.313	0.005
2006	0.291	0.008	2017	0.312	0.003
2007	0.369	0.002	2018	0.309	0.003
2008	0.261	0.012	2019	0.295	0.003
2009	0.258	0.014	2020	0.325	0.003
2010	0.308	0.004	2021	0.315	0.003
2011	0.287	0.006	/	/	/

From *Table 12,* the global Moran's index for each year was positive, and the p-values for most years were less than 0.01, showing a notable and favorable association in the spatial development of China's regional ecological economic system, demonstrating a clear spatial agglomeration effect. In 2007 and 2021, the Moran index reached 0.369 and 0.315, respectively, indicating the most significant degree of spatial agglomeration. The indices for 2009 and 2008 were relatively low, at 0.258 and 0.261 respectively, indicating a significant difference in the level of regional collaborative development during this period. Overall, there was a significant synergistic interaction between regions, indicating spatial linkage between ecosystems and the quality of ED.

Conclusions

In response to the practical challenge of insufficient coordination between ecological environment and ED system, an evaluation system integrating ecosystem quality index and ED quality index was studied and constructed. The synergy between ecological and economic systems in 31 provinces of China from 2001 to 2021 was systematically measured and spatially analyzed. The experimental findings indicated that the overall coordination level in the eastern region was relatively high, with the average coordination degrees of Beijing and Shanghai reaching 0.7490 and 0.7198, respectively, which were at an intermediate level of coordination. The average coordination degree of provinces such as Jiangsu, Zhejiang, and Guangdong exceeded 0.67, ranking at the primary coordination level, reflecting strong green transformation capabilities. Although central regions such as Henan and Hunan showed rapid growth since 2016, the average coordination degree did not exceed 0.60 and was generally stuck in a barely coordinated stage. The western region lagged behind as a whole. Guizhou and Xizang

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_785805

are on the verge of imbalance, which reflected that ecosystem restoration and economic quality improvement were not promoted synchronously. The results of spatial autocorrelation analysis further revealed that a pronounced spatial clustering effect was observed in the harmonious advancement of regional eco-economic systems. The Moran’s index reached 0.369 in 2007 and remained at 0.315 in 2021, with p-values all less than 0.01, indicating that high synergy regions had a diffusion driving effect in space, while low synergy regions form potential ecological economic inefficient circles. Drawing on the aforementioned results, the following trio of policy suggestions are proposed: Firstly, the eastern region ought to further deepen the linkage between green technology innovation and ecological governance. It should enhance resource utilization efficiency to cement its advantages in high-quality collaboration. Secondly, the central region needs to speed up the construction of ecological infrastructure. It should drive the transformation and upgrading of polluting industries and set up an ecological compensation mechanism to ease environmental pressure. Thirdly, the western region should strengthen the coordination between ecological protection and targeted poverty alleviation policies. It should establish differentiated development indicators, guide resource-based regions to shift towards eco-friendly industries, and foster the healthy coupling of ecological and economic systems. In the future, it will be essential to incorporate multi-scale and multi-time-period data along with machine learning methods.

Conflict of interests. The authors declare that there is no conflict of interest.

Data availability statement. The datasets generated during and/or analyzed during this study will be available from the corresponding author upon request.

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