SPATIOTEMPORAL EVOLUTION OF THE COUPLED AND COORDINATED DEVELOPMENT OF THE LOW-CARBON ECONOMY, GREEN FINANCE, AND ECOLOGICAL ENVIRONMENTAL QUALITY: EVIDENCE FROM CHINA

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Abstract. This study conducts a comprehensive analysis of the spatiotemporal dynamics of the coupled and coordinated development levels among China’s low-carbon economy, green finance, and ecological environmental quality. By optimizing the traditional coupling coordination degree (CCD) model and utilizing various analytical tools, this research reveals the spatiotemporal evolution patterns, development trends, and regional differences in the coordinated development of these three aspects—namely, low-carbon economy, green finance, and ecological environment quality. The research findings indicate that significant progress has been made in the coordinated development of these areas in China, which have now attained a primary coordination state. However, clustering algorithms, the Dagum Gini coefficient, and kernel density estimation reveal an increasing imbalance in regional coordinated development. The coupled and coordinated development level in the eastern regions is relatively high and stable, while the central and western regions, though improving, still lag behind. Notably, the eastern coastal regions exhibit a high degree of spatial agglomeration effects, whereas certain areas in the central and western regions demonstrate lower development levels and spatial agglomeration. Furthermore, the spatial Markov chain analysis results indicate that regions with strong coupled and coordinated development remain stable, whereas regions with low levels exhibit greater fluidity and potential for improvement.

Keywords: *low-carbon economy, green finance, ecological environmental quality, coupling coordination degree, spatial analysis*

Introduction

In recent years, global concern over climate change and environmental degradation has intensified. Rapid industrialization and urbanization have increased greenhouse gas emissions, leading to rising temperatures, glacier melting, sea level rise, and extreme weather events (Chen et al., 2022). The UNFCCC reports that global temperatures could rise by 1.5 to 2 degrees Celsius by 2100 (Hausfather and Peters, 2020), threatening ecosystems and sustainable development (Capon et al., 2021). Against this backdrop, green finance and a low-carbon economy have become vital for sustainable development. Green finance provides financial support for environmental initiatives (Grafström et al., 2023), while a low-carbon economy seeks to reduce carbon emissions through innovation and policy measures (Zhang, 2021). Both are essential for environmental protection and resource conservation. The green bond market supports environmental projects (Gabr and Elbannan, 2023). Renewable energy adoption reduces emissions and improves efficiency. Environmental quality impacts human health and ecosystem stability, making the study of green finance, a low-carbon economy, and environmental quality crucial.

Green finance promotes environmental protection and sustainable development through financial means, showing significant results in recent years (Hu and Gan,

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2025). It has driven economic development, facilitated the transition to a low-carbon economy, and improved environmental quality by reducing carbon emissions, optimizing capital allocation, and promoting green innovation (Cui et al., 2025; Zhang et al., 2024). The core of a low-carbon economy is decoupling growth from carbon emissions via innovation and restructuring, with green finance playing a key role. This is evident in the Yangtze River Basin, where green finance has effectively supported the low-carbon transition and enhanced environmental quality (Peng et al., 2025). Furthermore, the mechanisms of green finance have effectively propelled the development of a low-carbon economy, demonstrating a symbiotic and mutually reinforcing relationship (Yang and Wang, 2023). Green finance not only reduces pollution but also supports low-carbon energy systems and investments, aiding emerging Asian economies in their energy transitions (Shi and Yang, 2025). This process highlights the comprehensive role of green finance in driving technological innovation, optimizing industrial structures, and enhancing environmental quality. To understand the dynamic coupling relationships among green finance, the transition to a low-carbon economy, and environmental quality, this study aims to analyze the spatiotemporal evolution characteristics of their coupled and coordinated development. Specifically, it seeks to address these key questions: What is the current status of green finance, the low-carbon economy, and environmental quality? Is there a dynamic coupling relationship among them? Are there significant differences in the levels of coupled and coordinated development across regions? Does the coupled and coordinated development exhibit spatial agglomeration or divergence?

To address these issues, this study constructs a theoretical framework for the coupled and coordinated development of green finance, the low-carbon economy, and environmental quality using provincial data from 2013 to 2022. It examines the intrinsic mechanisms and interactions among these three systems. Compared to existing research, this paper makes three main contributions: (1) optimizing the traditional TOPSIS-entropy weight model and the coupling coordination degree (CCD) model to more accurately assess the coupled and coordinated development levels of the three systems across different regions and periods; (2) applying unsupervised learning algorithms and spatial analysis models to investigate the spatiotemporal evolution characteristics of their coupled and coordinated development, providing theoretical and practical guidance for enhancing coordination levels; (3) integrating theoretical analysis with empirical findings to propose policy recommendations for promoting the coordinated development of green finance, the low-carbon economy, and environmental quality. These policy innovations offer references and pathways for achieving the dual goals of economic development and environmental protection.

The remainder of this paper is structured as follows: The second section presents a literature review. The third section establishes the indicator evaluation system for green finance, the low-carbon economy, and environmental quality. The fourth section details the model and methodology. The fifth section provides empirical analysis and discussion. The sixth section concludes the study and offers policy recommendations

Literature review

The concept and development of green finance

Green finance supports environmental protection and sustainable development through instruments like green banks, green bonds, and green investment funds, guiding the global economy towards sustainability (Berensmann and Lindenberg, 2016). Its core is financial support for environmental projects, promoting clean energy, technological innovation, and industrial upgrades (Zhu, 2024). Since the late 20th century, green finance has become vital for environmental and sustainability goals, growing rapidly due to improved policies, financial services, and environmental support (Freeman et al., 2020; Zhao et al., 2022). The Paris Climate Agreement and stronger environmental policies have advanced green finance, prompting eco-friendly reforms and green financial tools (Bhandary et al., 2021). Key instruments include green bonds, which finance green projects and prevent “greenwashing” (Corapi, 2023). The green bond market has expanded rapidly in recent years, becoming a vital source of funding for green projects. Green banking provides loans and other financial services for environmentally friendly projects, such as renewable energy and energy efficiency retrofits, which have significant environmental benefits (Cunha et al., 2021). Green investment funds focus on projects with environmental and social benefits, helping enterprises secure necessary funding for sustainable development (Bellucci et al., 2023). The diverse forms of green finance and its evolving market mechanisms are crucial for achieving global sustainable development goals (Zheng et al., 2021). Key factors in developing the green finance market include policy improvements (Huang and Zhang, 2021), enhanced financial services (Rasoulinezhad, 2022), and optimized environmental support (Zhou et al., 2022b).

Green finance research has progressed through three stages: establishment, system optimization, and a current focus on Sustainable Development Goals (SDGs) and Environmental, Social, and Governance (ESG) criteria. Studies have addressed policy, market operations, and climate risk management, supporting a green, low-carbon transition. Recent research emphasizes green finance’s role in SDGs, exploring products, financing challenges, and government roles. Notably, Hou et al. (2023) and Chien (Lee and Du, 2024) have further explored its impacts on ecological quality, providing new insights into the regional disparities. In developing countries, green finance is vital for sustainable development, reducing greenhouse gas emissions, and promoting corporate ESG performance (Liu et al., 2024a; Jawadi et al., 2025). Overall, green finance is key to global sustainable development, enhancing economic transitions, environmental resilience, and social equity.

The concept and development of a low-carbon economy (LCE)

A Low-Carbon Economy (LCE) aims to achieve economic development while reducing greenhouse gas emissions. Since 2003, it has become a global trend in response to rising energy consumption and pollution (Xie, 2009). A low-carbon economy is characterized by “three lows and three highs”: low energy consumption, low pollution, low emissions, high efficiency, high benefits, and high utility (Dang et al., 2022). It aims to achieve these goals by improving energy efficiency, developing clean energy, optimizing the energy structure, and pursuing green GDP (He et al., 2020). Recent research on LCE covers three main areas: policies and institutions, technological innovation, and industrial transformation and impacts.

Firstly, regarding policies and institutions for a low-carbon economy, governments have implemented carbon emissions trading systems (ETS), carbon taxes, renewable energy subsidies, and energy efficiency standards. ETS has been effective in the EU (Flues and Van Dender, 2020), and carbon taxes have reduced emissions in OECD countries (Cuervo and Ved, 1998). Additionally, renewable energy subsidies and energy efficiency standards promote green technologies (Azhgaliyeva and Rahut, 2022). However, policy design must balance economic costs and social equity (Boyce et al., 2023). Secondly, technological innovation is crucial for achieving the goals of a low-carbon economy (Zhao et al., 2023). This includes renewable energy technologies, energy storage technologies, smart grids, and carbon capture and storage (CCS) technologies. Advances in these technologies have reduced costs and improved efficiency (Elia et al., 2021; Colak et al., 2020; Belu, 2019). CCS technology is crucial for the industrial sector but requires further research on feasibility (Dziejarski et al., 2023; Bassano et al., 2020). Thirdly, achieving a low-carbon economy necessitates transforming and upgrading various industries. The energy, transportation, construction, and manufacturing sectors, as major carbon emitters, require structural adjustments and technological innovations. The energy sector should promote renewable energy and cleaner fossil fuels (Chen and Jin, 2023). The transportation sector can adopt electric vehicles and optimize public transportation (Ribeiro et al., 2024). The construction industry can enhance energy efficiency and use low-carbon materials (Xi and Cao, 2022). Manufacturing should adopt cleaner production and circular economy models (Fobbe and Hilletofth, 2023). Moreover, the impacts of a LCE on the economy and environment are multifaceted. LCE policies and technologies can promote green employment, economic growth, improve air quality, and reduce health risks (Khan and Khan, 2023). However, the transition also involves economic costs and social challenges (Geels, 2022).

The interrelationship among green finance, low-carbon economy, and environmental quality

The interplay between green finance, a low-carbon economy, and environmental quality is a current hot topic, with complex interactions among these elements. Scholars primarily study the mutual influence between green finance and a low-carbon economy, the impact of green finance on environmental quality, and the influence of a low-carbon economy on environmental quality. However, the dynamic coupling relationship among all three systems remains unexplored. Research shows that green finance and a low-carbon economy have complementary roles in sustainable development and environmental protection. For example, De Haas and Popov (2022) demonstrate a mutually beneficial relationship, where green finance drives economic growth and environmental protection, and a low-carbon economy enhances green finance mechanisms. This creates a virtuous cycle for both the economy and the environment (Wu et al., 2024; Xu, 2022). In China, green finance promotes high-quality economic development and carbon emission reduction (Zeng et al., 2023). As an important transmission mechanism, green finance helps achieve coordinated economic growth and environmental protection.

Regarding the impact of green finance on environmental quality, scholars have found that their coupled and coordinated development plays a significant role in promoting sustainable development. Firstly, studies indicate that green finance effectively enhances environmental quality. For example, Zhang and Zhao (2023) used a traditional CCD model to explore the coupling relationship between environmental quality and the green financial economy, finding a significant positive correlation. Similarly, Zhou et al. (2022a) observed an improving coupling and coordination between green finance and the ecological environment, demonstrating that green finance development contributes to ecological enhancement. Yang et al.

(2024) found that a high degree of coupling coordination between green finance and environmental regulation boosts corporate innovation capabilities. This conclusion is supported by an analysis of digital finance development and regional green innovation coupling coordination in the Yangtze River Economic Belt, which observed an overall positive trend in coordinated development despite spatial imbalances among provinces (Yu and Peng, 2023). Additional studies have measured and analyzed the coupling and coordinated development of green finance and environmental governance in China from both temporal and spatial dimensions, revealing a gradual improvement in coordination (Peng et al., 2023). Furthermore, the contribution of green finance policies to high-quality economic development has been confirmed. Xu and Dong (2023) found that green finance acts as an intermediary in promoting high-quality economic development through advanced and rational industrial structures, with environmental regulation playing a positive moderating role.

Regarding the impact of a low-carbon economy on environmental quality, researches indicate that the coupled and coordinated development of a low-carbon economy and environmental quality exhibits complex interactions across different regions and policy contexts. Recent studies have explored the interaction between low-carbon policies and environmental governance at various regional and administrative levels, revealing that policies and regional characteristics significantly influence coupling coordination. For instance, Liu et al. (2021) found varying effects of low-carbon policies on different pollutants in Chinese cities. Jing (Jing, 2022) highlighted improved regional economic resilience and environmental quality in Northeast China due to effective policy implementation. Additionally, Chen et al. (2020) noted an overall trend towards equilibrium in the coordination between carbon emissions and the ecological environment in China, despite regional imbalances. Huang et al. (2021) found that carbon trading policies help mitigate the conflict between economic development and environmental pollution, especially in socioeconomically developed cities.

Research gaps

Despite the valuable insights provided by existing research on the interactions between green finance, the low-carbon economy, and environmental quality, there are still several notable gaps. Firstly, much of the current research focuses on either individual aspects or the relationships between two of these sectors, lacking a systematic exploration of the coupled and coordinated pathways for their combined development. Secondly, most existing studies emphasize static or cross-sectional analyses, resulting in a limited understanding of the spatiotemporal evolution of these interactions. There is a relative dearth of dynamic studies examining how green finance, low-carbon policies, and environmental quality influence each other over time. Additionally, most research has concentrated on specific regions, with a lack of comparative studies across different areas, limiting our understanding of how regional policies and economic environments differently impact the coupled and coordinated development of green finance, the low-carbon economy, and environmental quality. Lastly, quantitative studies on the coupled and coordinated development of these three aspects remain limited. Although some studies have employed traditional coupling coordination models, these models often fall short in capturing the complexity and diversity of real-world scenarios.

Materials and methods

Data sources

The time period analyzed in this study spans from 2013 to 2022. The data sources primarily include the CSMAR database, the China Statistical Yearbook, and the statistical yearbooks of various provinces. Due to data availability, the study focuses on 30 provinces of China, excluding Hong Kong, Macau, Taiwan, and Tibet. Missing data are supplemented using interpolation methods. This time period was chosen to comprehensively reflect the spatiotemporal evolution of China’s low-carbon economy, green finance, and environmental quality, and to examine the coupling and coordinated development of these three aspects over the past decade. In this study, Python was utilized for data processing, computational tasks, and the creation of visual representations.

Construction of the indicator system

The data for this study come from multiple sources: the CSMAR database, various China Statistical Yearbooks, and provincial yearbooks. Specifically, financial and economic indicators were obtained from the CSMAR database; demographic, economic, and social statistics from the China Statistical Yearbook; energy consumption data from the China Energy Statistical Yearbook; industrial statistics from the China Industrial Yearbook; and environmental statistics from the China Environmental Statistical Yearbook. Additionally, regional-specific data were collected from provincial yearbooks. The sample includes 30 provincial-level administrative regions in China, excluding Tibet, Hong Kong, Macau, and Taiwan. To address any missing data, we used the Newton interpolation method to fill in the gaps, ensuring a complete and robust dataset for analysis.

This study constructs an indicator system tailored to China’s low-carbon economy, based on the principles of scientific feasibility, comprehensive representativeness, and dynamic comparability. Drawing on the research findings of Niu et al. (2022), Ye et al. (2022) and Zhongyu and Zhongxiang (2021) regarding system construction and indicator selection, we have developed an indicator system that reflects the specific circumstances of China’s low-carbon economic development. The system is divided into three dimensions: low-carbon development, low-carbon innovation, and low-carbon society, encompassing a total of 18 indicators, as shown in *Table 1*. Descriptive statistics for these 18 indicators are presented in *Table 2*. These statistics include the mean, standard deviation, minimum, and maximum values, providing an overview of the central tendency and variability of the indicators.

There is currently no unified standard for assessing green finance. Jiang et al. (2020) proposed a green finance evaluation framework encompassing three dimensions: economy, finance, and society. Yu and J (2021) designed a maturity measurement system that covers green credit, green bonds, green investment, and carbon finance. Feng et al. (2022) categorized green finance into green credit, green securities, green insurance, green investment, and carbon finance, establishing assessment standards for each category. Zheng and Ye (2022) developed an evaluation system from a macro perspective based on environmental, financial, and social factors. Zeng et al. (2022) used indicators such as carbon intensity to evaluate the performance of green supply chains, accurately reflecting the progress in environmental sustainability. Based on the methodologies of these scholars and considering data availability, this study selected evaluation indicators across five dimensions—green credit, green securities, green insurance, green investment, and carbon markets—to construct our assessment system, as detailed in *Table 3*. Descriptive statistics for these 13 indicators are presented in *Table 4*. These statistics include the mean, standard deviation, minimum, and maximum values, providing an overview of the central tendency and variability of the indicators of green finance development.

Table 1. *Evaluation indicators of low-carbon economy development in 30 provinces of China from 2013 to 2022*

Objective layer	Criterion layer	Variables	Indicator name	Attribute	Units
Low-carbon economy development (U_1)	Low-carbon development	X1	Carbon productivity	+	10^4/ton
		X2	Per capita carbon emissions	-	ton/person
		X3	Total carbon emissions/GDP	-	tons/10^4
		X4	CO_2 emission intensity	-	tons/10^4
		X5	General industrial solid waste generation/GDP	-	ton/10^4
		X6	Urban environmental infrastructure construction investment/GDP	-	% of GDP
		X7	Industrial pollution control investment completed amount/GDP	+	% of GDP
		X8	Total energy consumption/GDP	+	ton/10^4
		X9	Proportion of renewable energy consumption	-	%
	Low-carbon innovation	X10	Market share of technology	+	%
		X11	Per capita number of green invention patents	+	Patents/10^4
		X12	Green utility model patents per capita	+	Patents/10^4
		X13	Intensity of R&D investment	+	% of GDP
	Low-carbon society	X14	Engel coefficient of residents	-	%
		X15	Per capita disposable income of residents	+	CNY/person
		X16	Number of public transportation vehicles per 10,000 people	+	Vehicles/10^4
		X17	Education expenditure/GDP	+	% of GDP
		X18	Urban population using natural gas	+	%

Table 2. *Descriptive statistics values of low-carbon economy development in 30 provinces of China from 2013 to 2022*

Variables	Mean	Standard deviation	Min	Max
X1	0.0115	0.0025	0.0051	0.0213
X2	10.0658	7.4947	1.3124	44.7002
X3	2.0343	1.6461	0.2390	0.9428
X4	1.99E-04	1.64E-04	2.39E-05	8.29E-04
X5	7.74E-05	1.10E-04	4.82E-07	7.19E-04
X6	0.0079	0.0046	0.0010	0.0260
X7	0.0010	0.0010	0.0000	0.0099
X8	7.28E-05	4.17E-05	1.75E-05	2.05E-04
X9	0.0012	0.0001	0.0001	0.0003
X10	0.0041	0.0012	0.0025	0.0067
X11	6.90E-04	2.20E-05	3.80E-04	7.10E-04
X12	1.52E-03	5.00E-05	1.12E-03	1.68E-03
X13	0.0228	0.0017	0.0202	0.0256
X14	0.3283	0.0210	0.2787	0.3609
X15	24837.7362	16480.3362	33195.1362	5547.3735
X16	4017.8571	535.7143	3214.2857	4821.4286
X17	0.0427	0.0005	0.0414	0.0434
X18	0.4827	0.0628	0.5739	0.3879

Table 3. *Evaluation indicators of green finance development in 30 provinces of China from 2013 to 2022*

Objective layer	Criterion layer	Variables	Indicator name	Attribute	Units
Green finance development (U_2)	Green credit	X1	Proportion of green credit	+	%
		X2	Interest expense ratio of high energy-consuming industries	-	%
	Green securities	X3	Share of green bonds	+	%
		X4	interest share in high energy-consuming industries	-	%
		X5	Market capitalization ratio of high energy-consuming industries	-	%
	Green insurance	X6	Coverage ratio of agricultural insurance	+	%
		X7	Agricultural insurance payout ratio	+	%
	Green investment	X8	Investment share in environmental pollution control	+	%
		X9	Proportion of public spending on energy Conservation and environmental protection	+	%
		X10	Share of foreign direct investment in energy conservation and environmental protection industries	+	%
		X11	Proportion of venture capital in energy conservation and environmental protection industries	+	%
	Carbon market	X12	Carbon intensity	-	ton/10^4
		X13	CDM project transaction volume ratio	+	%

Table 4. *Descriptive statistics values of green finance development in 30 provinces of China from 2013 to 2022*

Variables	Mean	Standard deviation	Min	Max
X1	0.1199	0.0234	0.0867	0.1553
X2	0.0564	0.0072	0.0463	0.0669
X3	0.0135	0.0087	0.0011	0.0256
X4	0.0737	0.0107	0.0563	0.0873
X5	0.4135	0.0782	0.3628	0.5769
X6	0.5613	0.1521	0.3620	0.7724
X7	0.6529	0.0474	0.5853	0.7408
X8	0.0126	0.0025	0.0071	0.0127
X9	0.0329	0.0055	0.0254	0.0405
X10	0.0154	0.0062	0.0053	0.0330
X11	0.0497	0.0082	0.0343	0.0642
X12	1.5119	0.2157	1.1357	1.7593
X13	0.0151	0.0022	0.0114	0.0176

Constructing ecological environment quality evaluation indicators is a crucial step in regional ecological environment monitoring and management. The core objective is to comprehensively and systematically reflect the health status and changing trends of ecosystems. Based on the research by Fang et al. (2023) and Lv and Zhou (2023), this paper constructs indicators from three dimensions: ecological environment pressure, state, and response. Ecological environment pressure primarily reflects the various impacts of human activities on the ecosystem; ecological environment state describes the current condition of the ecosystem and its changing trends; ecological environment response focuses on the feedback and countermeasures from society to the changes in the ecological environment. For specific indicator details, please refer to *Table 5*. Descriptive statistics for these 18 indicators are presented in *Table 6*. These statistics include the mean, standard deviation, minimum, and maximum values, providing an overview of the central tendency and variability of the indicators of ecological environment quality.

Table 5. *Evaluation indicators of ecological environment quality in 30 provinces of China from 2013 to 2022*

Objective layer	Criterion layer	Variables	Indicator name	Attribute	Units
Ecological environment quality (U_3)	Ecological environment pressure	X1	Population density	-	Persons/km^2
		X2	Industrial SO$_2$ emissions	-	ton/year
		X3	Industrial effluent per unit of output	-	ton/10^4
		X4	Industrial solid waste per unit of output	-	ton/10^4
		X5	Pesticide Usage	-	ton/year
		X6	Fertilizer Usage	-	ton/year
	Ecological environment state	X7	Per capita water resources	+	m^3/person
		X8	Number of days with good air quality	+	Days/year
		X9	Vegetation coverage rate	+	%
		X10	Per capita green space (parks)	+	m^2/person
		X11	Land desertification area	-	km^2
		X12	Disaster-affected area	-	km^2
	Ecological environment response	X13	Industrial wastewater discharge adherence rate	+	%
		X14	Industrial solid waste recycling rate	+	%
		X15	Domestic waste harmless disposal rate	+	%
		X16	Area of soil and water conservation	+	km^2
		X17	Environmental investment share of GDP	+	%
		X18	Ratio of non-fossil energy to energy consumption	+	%

Table 6. *Evaluation indicators of ecological environment quality in 30 provinces of China from 2013 to 2022*

Variables	Mean	Standard deviation	Min	Max
X1	139.4083	1.1728	136.2839	141.6672
X2	207.7415	99.7531	111.3165	431.0685
X3	0.0002	0.0000	0.0001	0.0003
X4	1.5612	0.2228	1.1728	1.8167
X5	157.5533	22.2839	117.2839	188.3228
X6	5054.4130	236.9135	4613.5701	5399.1357
X7	1659.8913	236.7078	1246.9126	1931.4691
X8	255.0339	22.2839	222.8394	276.6728
X9	0.5803	0.0223	0.5395	0.6250
X10	16.5988	2.3691	12.4691	19.3146
X11	157.5533	22.2839	117.2839	188.3228
X12	1675.0413	236.9135	1246.9135	2002.1691
X13	0.7986	0.0228	0.7571	0.8324
X14	0.5091	0.0248	0.5668	0.6453
X15	0.7259	0.0216	0.7112	0.7829
X16	167.5041	23.5020	124.6913	200.2168
X17	0.0164	0.0023	0.0123	0.0191
X18	0.1661	0.0301	0.1080	0.2425

Research methods

Lyapunov exponent

This paper utilizes the Lyapunov exponent method (Sahoo and Roy, 2022) to calculate the indices for the three systems (U_1, U_2, *and* U_3). This method can handle multidimensional data and comprehensively consider multiple evaluation indicators. Additionally, it captures the dynamic behavior of each system and analyzes the long-term evolutionary characteristics. Given that real economic data often contain noise and uncertainty, this method demonstrates strong robustness in handling noisy and uncertain data. The process for calculating the indices is as follows:

(1) Data standardization:

$$\text{Positive indicators: } Z_{ij} = \frac{x_{ij} - min_j x_{ij}}{max_j x_{ij} - min_j x_{ij}} \qquad \text{(Eq.1)}$$

$$\text{Negative indicators: } Z_{ij} = \frac{max_j x_{ij} - x_{ij}}{max_j x_{ij} - min_j x_{ij}} \qquad \text{(Eq.2)}$$

(2) Construct the state vector:

$$X_t = [Z_{t,1}, Z_{t,2}, Z_{t,3}, \ldots] \qquad \text{(Eq.3)}$$

where $Z_{t,k}$ is the standardized value of the *k-th* indicator in year *t*.

(3) Select initial conditions:

Choose an initial state X_0 and a slightly perturbed initial state X'_0 such that $\| X_0 - X'_0 \|$ is very small.

(4) Evolution trajectories

Compute the evolution trajectories of X_t and X'_t:

$$X_{t+1} = AX_t \qquad \text{(Eq.4)}$$

where *A* is a transition matrix.

(5) Calculate distance:

At each time step *t*, calculate the distance between the two trajectories:

$$d(t) = \| X_t - X_t^{'} \| \qquad \text{(Eq.5)}$$

(6) Lyapunov exponent calculation:

Calculate the logarithmic mean of the trajectory separation rate. The Lyapunov exponent λ is defined as:

$$\lambda = \lim_{t \to \infty} \frac{1}{t} \sum_{i=0}^{t-1} \ln \frac{d(i+1)}{d(i)} \tag{Eq.6}$$

Optimized coupling coordination degree (OCCD) model

Building on Wang's research (Wang et al., 2021), this paper further optimizes the CCD model. The optimized CCD model (OCCD) is presented as follows:

$$C_{\text{optimized}} = \sqrt{\left[1 - \frac{\sum_{i>j,j=1}^{n} |U_i - U_j|}{n(n-1)/2}\right] \times \frac{1}{1 + \exp\left(\sum_{i=1}^{n} \frac{\ln(U_i / \max_{k=1}^{n} U_k)}{n}\right)}} \tag{Eq.7}$$

$$T = \sum_{i=1}^{n} \alpha_i \times U_i, \sum_{i=1}^{n} \alpha_i = 1 \tag{Eq.8}$$

$$D_{optimized} = \sqrt{C_{optimized} \times T} \tag{Eq.9}$$

In this model, *U* represents the development index of low-carbon economy, green finance or environmental quality for the *i-th* year. while *C* denotes the coupling degree, *D* signifies the coordination degree, and *T* is the composite evaluation index. Both U_i and *C* range from 0 to 1. The coupling degree, *C,* decreases as discrepancies between subsystems increase and rises with greater system consistency. *n* is set to 3, and α is set at 1/3 to reflect their equal significance in the overall assessment.

From a theoretical perspective, the revised model proposed in this study is more robust and accurate than Wang et al.'s model (hereafter referred to as the "original model") in both measuring the degree of coupling and integrating indicators. This superiority is manifested in the following three aspects. Firstly, the measure of dissimilarity is more direct and robust. The original model uses $(U_i - U_j)^2$ to gauge the difference between indicators, which is numerically equivalent to $|U_i - U_j|$ but more cumbersome in notation, especially since its denominator $\sum_{m=1}^{n-1} m$ can be confusing. In contrast, the revised model uniformly rewrites the metric as $\frac{\sum_{i>j} |U_i - U_j|}{\frac{n(n-1)}{2}}$, offering a more concise form that is easier to interpret and avoids overly complicated symbols that could otherwise hinder subsequent analyses. Secondly, the introduction of the logistic function for handling the product of multiple indicators smooths out the impact of extreme values on the coupling degree. The original model captures the overall system level using $\left(\Pi\left(U_i / maxU_i\right)\right)^{\frac{1}{n-1}}$, but if any U_i is very small or close to zero, the geometric mean would be sharply pulled down, potentially distorting the coupling results. In the revised model, one instead takes the average of $\ln\left(U_i / max(U_k)\right)$ and then applies $\text{Sigmoid} = \left[1 + \exp(...)\right]^{-1}$, which theoretically compresses all indicator values smoothly into the (0,1) interval. When some indicators are too small or too large, the asymptotic property of the sigmoid function can effectively suppress the nonlinear shock of extreme values on the coupling degree, thereby enhancing tolerance for outliers. Thirdly, with respect to deriving the final coordination degree D from the coupling degree C and the comprehensive utility function T, the revised model retains the same multiplicative structure $D = C \times T$ as the original one. However, because C is now optimized using a more robust distance measure and logistic mapping, the model as a whole can portray the interactions among multiple indicators more accurately and reliably.

Dagum Gini coefficien

Given the varied economic development landscapes across China's regions, the levels of coupled and coordinated development between the low-carbon economy, green finance and environmental quality exhibit significant differences. This study employs the Dagum Gini coefficient (Zhang et al., 2022) and its decomposition method to examine regional disparities and their temporal evolution in the coupled and coordinated development of these sectors. The specific formula utilized for this analysis is detailed as follows:

$$G = G_w + G_b + G_t \tag{Eq.10}$$

$$G_w = \sum_{k=1}^{m} p_k G_k \tag{Eq.11}$$

$$G_b = \frac{1}{2\mu} \sum_{k=1}^{m}\sum_{j=1}^{m} p_k p_j \mid \mu_k - \mu_j \mid \tag{Eq.12}$$

$$G_t = \frac{1}{\mu} \sum_{k=1}^{m}\sum_{j=1}^{m} p_k p_j \int_0^{\infty} F_k(x)[1 - F_j(x)]dx \tag{Eq.13}$$

G_w measures the variability in the levels of coupled and coordinated development within a designated area. G_{nb} quantifies the disparities in these development levels between regions j and h. G_t captures the residual factor, reflecting the cross-effects between regions on their development levels.

Moran's I index

This research uses Moran's I index (Liu and Yang, 2021) to investigate the spatial correlation and dynamics of spatial agglomeration in the coupled development of the low-carbon economy, green finance and environmental quality in China. Moran's I index evaluates spatial correlation and its trends, assessing the degree of autocorrelation in geographic data. This index identifies patterns of spatial clustering or dispersion, providing insights into the spatial dynamics of these sectors.

$$I = \frac{n}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}} \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{Eq.14}$$

Kernel density estimation (KDE)

Kernel Density Estimation (KDE) (Wahbah et al., 2022) is a non-parametric method for estimating probability density functions, providing a smoother and more continuous representation without the constraints of bin widths. By summing these kernel functions, KDE generates a smooth estimate of the underlying probability density function f, offering an effective solution for statistical density estimation.

$$\hat{f}_h(x) = \frac{1}{n}\sum_{i=1}^{n} K_h\left(x - x_i\right) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{x - x_i}{h}\right) \qquad \text{(Eq.15)}$$

Spatial Markov chain analysis

This study uses spatial Markov chain analysis (Huo et al., 2022) to investigate the dynamics and evolution of high-quality, coupled, and coordinated development. This method combines traditional Markov chain analysis with spatial correlation to examine the impact of spatial effects on state transitions. Spatial effects are represented by a conditional transition probability matrix, which reveals how spatial relationships influence state transition probabilities.

$$P(X_{t+1} = j \mid X_t = i, N_t = k) = p_{ij|k} \qquad \text{(Eq.16)}$$

Research results

Model test

As shown in the *Figure 1,* in the absence of extreme values (see *Fig. 1a, b*), there is little difference between the coupling degrees measured by Wang’s model (the old model) and the new model. In *Figure 1a*, the Bland–Altman plot indicates that most differences (Old – New) cluster around the zero axis, with a mean difference (Mean diff) close to zero, and most points lie within the ± 1.96 SD range. Meanwhile, in *Figure 1b*, the violin plots for the two methods almost overlap, suggesting that under normal data conditions, the revised model and Wang’s model behave similarly overall. However, when extreme values are present (*Fig. 1c, d*), the old model becomes more sensitive to outliers. The Bland–Altman plot exhibits a higher number of scattered points, causing both the mean difference (Old – New) and its range of fluctuation to increase markedly. By contrast, under the same conditions, the new model’s distribution remains relatively stable, showing no significant stretching or collapse, which demonstrates stronger robustness and better suppression of extreme values. Therefore, when no extreme values are present, the revised model does not differ substantially from Wang’s. Yet in the presence of outliers, it more effectively withstands abnormal shocks—an empirical advantage stemming from its enhanced distance measure and the handling of product terms among indicators.

Coupling coordination degree (CCD) analysis

Based on the calculation results from *Equations 1–9*, this study derives the CCD of three major systems—low-carbon economy, green finance, and ecological environment quality. The specific classification criteria are presented in *Table 4*. As shown in *Figure 2*, between 2013 and 2022, the average CCD across 30 provinces in China

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exhibits a steady upward trend, reaching the “primary coordination” level. This outcome signifies that, under the impetus of the 13th and 14th Five-Year Plans, significant progress has been made in fostering regional synergy, reflecting the effectiveness of national green development policies. Notably, while the standard deviation of CCD expanded from 2013 to 2019, it began to narrow in 2020, suggesting that inter-provincial disparities are gradually decreasing. However, this turning point coincides with the outbreak of the COVID-19 pandemic, which has exerted both restraining and stimulating effects on green development. On the one hand, pandemic-induced lockdowns and a temporary halt in industrial production have reduced carbon emissions in certain regions, potentially narrowing provincial gaps. On the other hand, the economic uncertainties and financial liquidity pressures brought about by the pandemic have slowed green finance and low-carbon investments in some provinces, posing challenges to ecological protection efforts. As a result, although inter-provincial CCD differences have indeed narrowed to some extent, several regions experienced a transient decline or stagnation in both growth and overall coordination levels under the pandemic’s impact. Despite these hurdles, the overall development trend from 2013 to 2022 remains promising. In many provinces, the minimum CCD values continued to rise, while the maximum values also increased in parallel, indicating improvements among leading provinces as well as upward potential for others. Furthermore, the 25th, 50th, and 75th percentiles of CCD all present a generally upward trajectory, underscoring the collective impact of policy incentives, technological advancements, industrial upgrading, and environmental governance on enhancing coordination levels across most provinces. Nonetheless, it is important to recognize that the pandemic has not only introduced temporary disruptions but has also led to structural shifts in green development pathways.

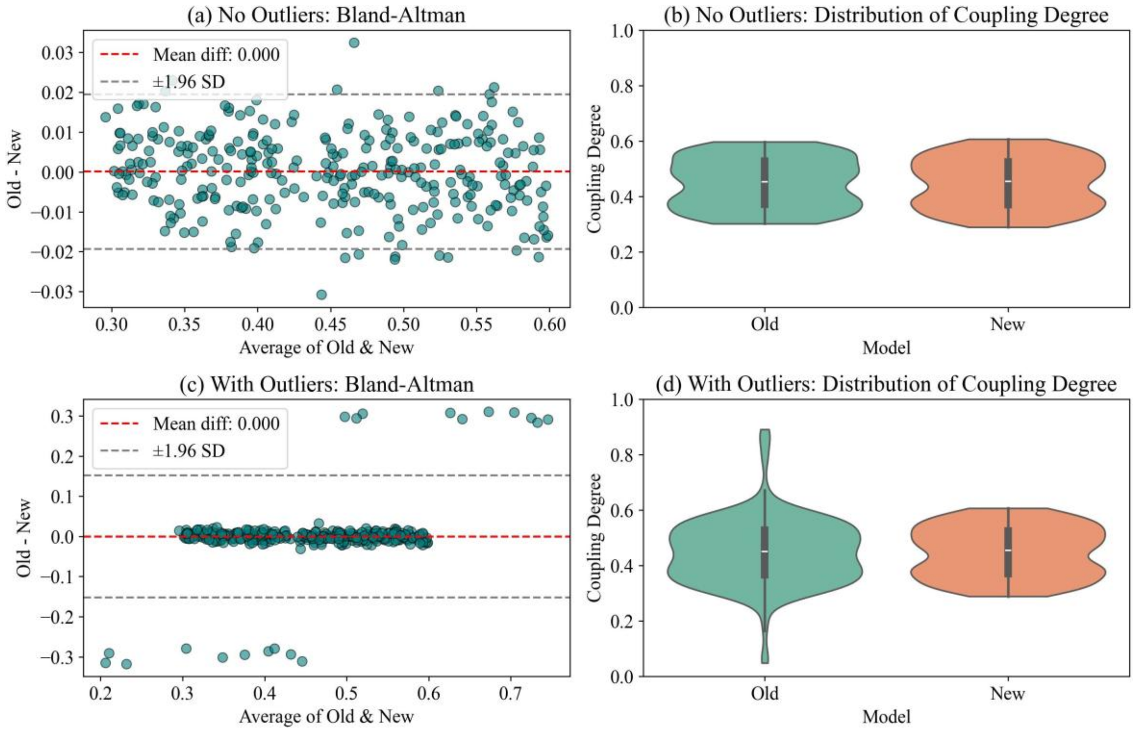
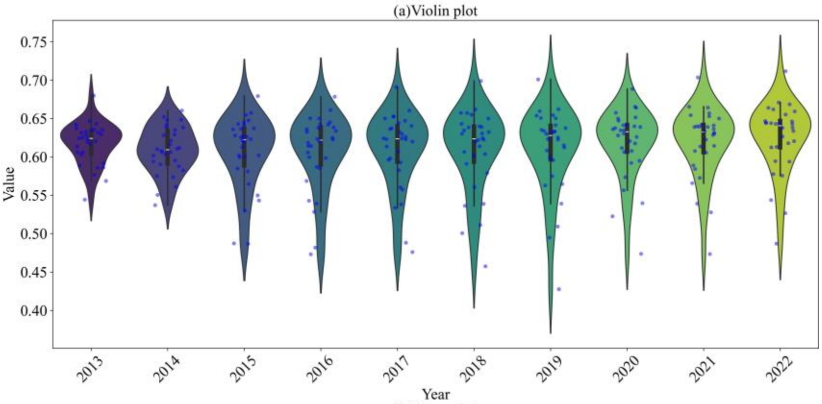


Figure 1. *Comparison of the robustness of coupling coordination degree between the optimized model and the original model under extreme-value interference*

Tabe 4. *State level of CCD*

CCD value	State level	CCD value	State level
(0.0, 0.2]	Serious disorders (State 1)	(0.4, 0.6]	Primary coordination (State 4)
(0.2, 0.3]	Slight disorders (State 2)	(0.6, 0.8]	Intermediate coordination (State 5)
(0.3, 0.4]	Barely coordination (State 3)	(0.8, 0.10]	Senior coordination (State 6)



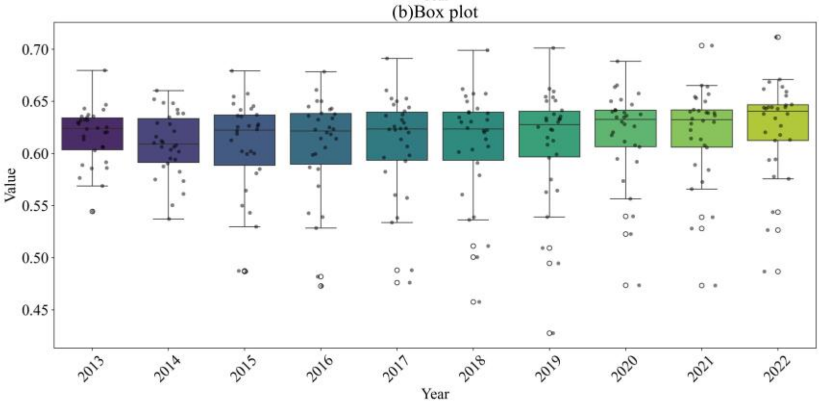


Figure 2. *Descriptive statistical analysis of CCD of 30 provinces in China (2013-2022)*

Figure 3 shows higher coupled and coordinated development (CCD) in the eastern regions and lower levels in the central and western regions. Economically developed provinces like Beijing, Shanghai, and Guangdong have consistently high and stable CCD growth. In contrast, less developed provinces like Shanxi and Inner Mongolia show lower and more fluctuating CCD. The steady growth in developed regions indicates a solid foundation for green development. Although the central and western regions started later, their CCD has significantly improved with national policy support. These resource-based economies face challenges in transition but also have significant potential.

Clustering analysis

This study performed a cluster analysis (Jaeger and Banks, 2023) on 30 Chinese provinces based on CCD results. Silhouette analysis (Hoeppner, 2022) was used to ensure accuracy, evaluating the similarity within clusters and comparing it to other clusters. A higher silhouette coefficient indicates better clustering. *Figure 4a* shows that dividing the 30 provinces into three categories yields the optimal classification.

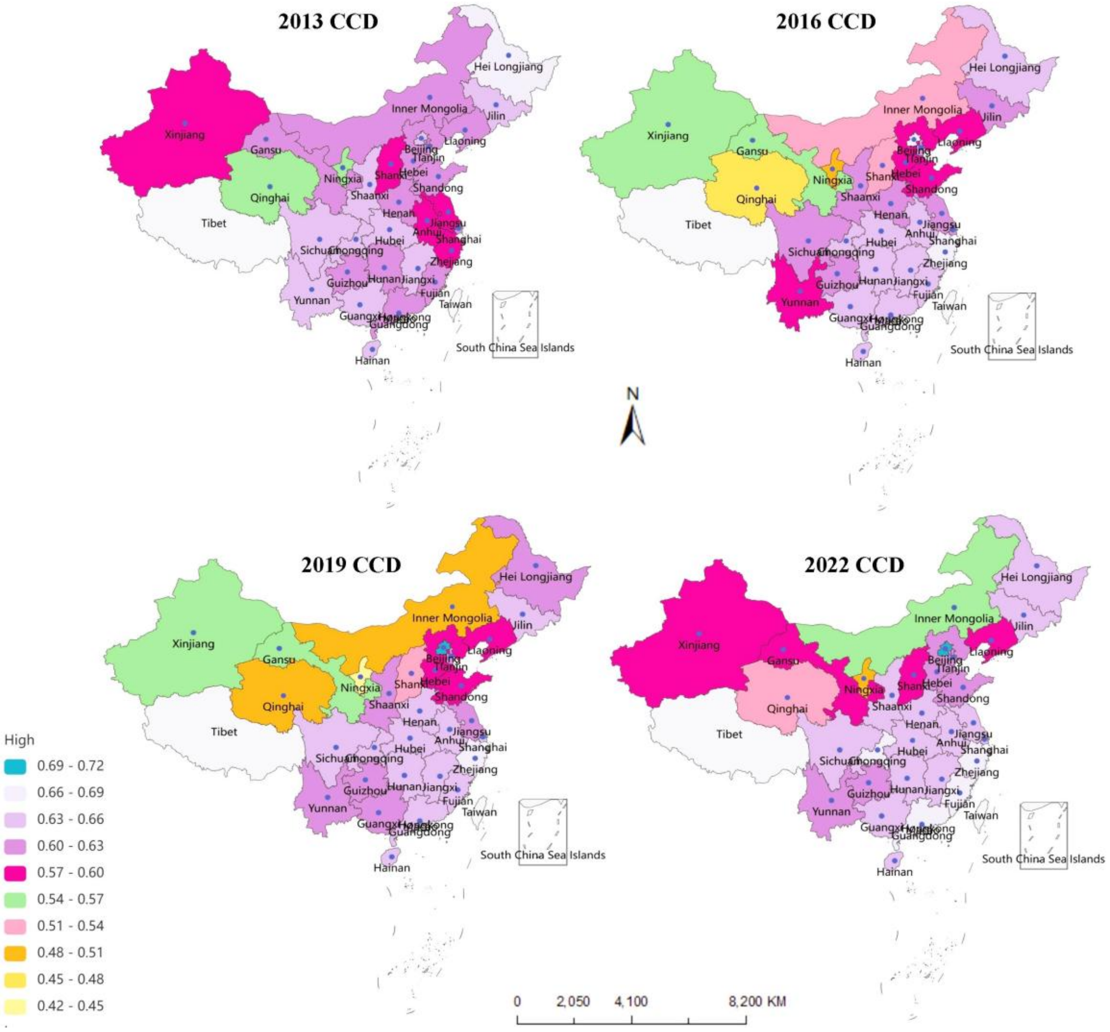


***Figure 3.** Geospatial visualization of CCD for the Years 2013, 2016, 2019, and 2022*

Figure 4b presents the specific classification results. The first category includes 18 economically developed provinces such as Beijing, Shanghai, Zhejiang, and Jiangsu, with high CCD. These provinces have diversified industrial structures, increasing emerging industries, and significant government investment in environmental protection. The second category includes seven provinces such as Tianjin and Hebei, with medium levels of coupled coordination development. These provinces have strong industrial bases and, with policy support, have improved their low-carbon economy and green finance despite internal differences. The third category includes five provinces such as Shanxi and Inner Mongolia, with relatively low levels of coupled coordination development. These provinces rely on traditional energy sources, with economies dependent on resource extraction and heavy industries.

Analysis of regional differences

Equations 10–13 is used to calculate the Gini coefficients. From *Figure 5a*, it can be observed that from 2013 to 2022, the coupled coordination development among China’s low-carbon economy, green finance, and ecological environment quality has shown increasing regional disparities. The overall Gini coefficient rose from 0.024 to 0.045,

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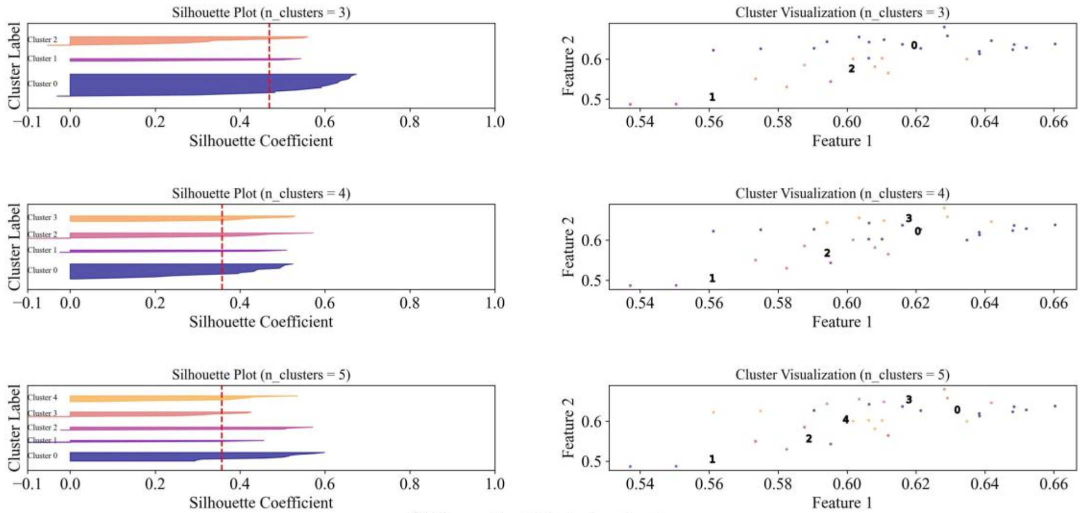
indicating growing imbalance. The intra-group Gini coefficient (*Gw*) remained relatively stable with a slight increase, indicating balanced development within regions. However, the inter-group Gini coefficient (G_b) rose significantly from 2013 to 2016, peaked in 2020, and then fluctuated, reflecting intensifying regional disparities and unbalanced development. The super density Gini coefficient (*Gt*) remained stable with slight fluctuations, indicating stable regional disparities when considering super density. *Figure 5b* shows that the inter-group Gini coefficient's contribution rate is the highest, suggesting that inter-regional differences significantly impact overall inequality.

(a) Silhouette analysis



(b)Hierarchical Clustering Dendrogram

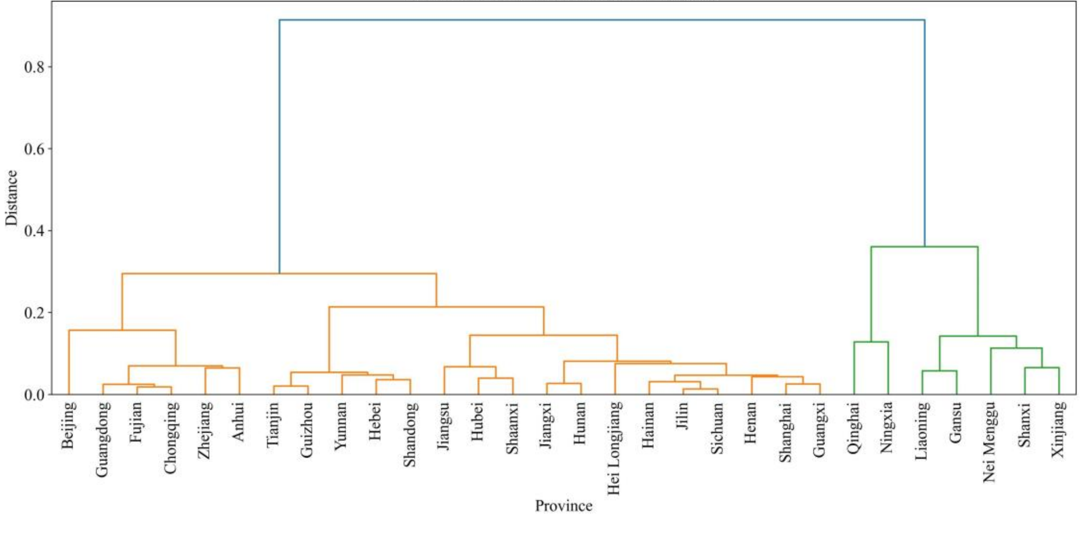


Figure 4. *Results of clustering analysiso of CCD for 30 provinces in China from 2013 to 2022*

Based on the standard geographic division adopted in this study, the eastern region comprises Beijing, Tianjin, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Hainan, Heilongjiang, Jilin, and Liaoning; the central region includes Shanxi, Anhui, Jiangxi, Henan, Hubei, and Hunan; and the western region consists of Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang. From *Figure 6a*, it can be seen that from 2013 to 2022, the intra-group Gini coefficient in the eastern region remained relatively stable, indicating a high and stable level of coupled coordination development. In the central region, the intra-group Gini coefficient increased annually from 2013 to 2015, then gradually declined from 2016 and stabilized, suggesting that low-carbon economy and green finance policies are beginning to take effect. However, the central region still needs to enhance its overall coordination development and deepen reforms and innovation. The western region showed significant fluctuations in internal coordination, particularly reaching high inequality in 2018. *Figure 6b* shows that the inter-group Gini coefficients between the central and eastern regions, central and western regions, and eastern and western regions peaked in 2015 and 2018, then improved. Disparities in the coupled coordination development level between the western region and other regions are most prominent, indicating that policymakers need to address the unique needs of the western region when promoting regional coordinated development.

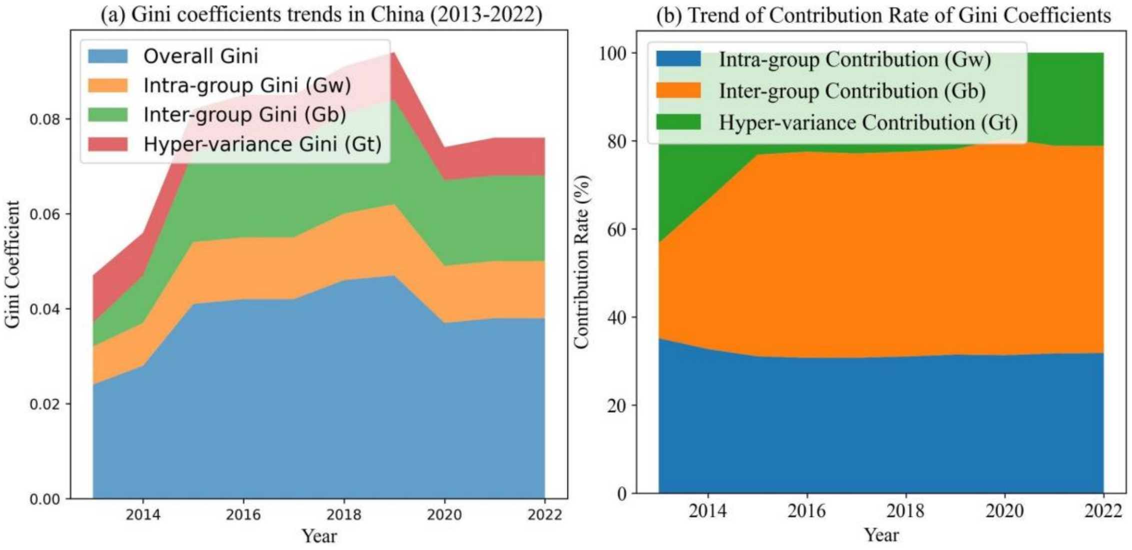


Figure 5. *Trend analysis of Dagum Gini coefficient and contribution rate results (2013-2022)*

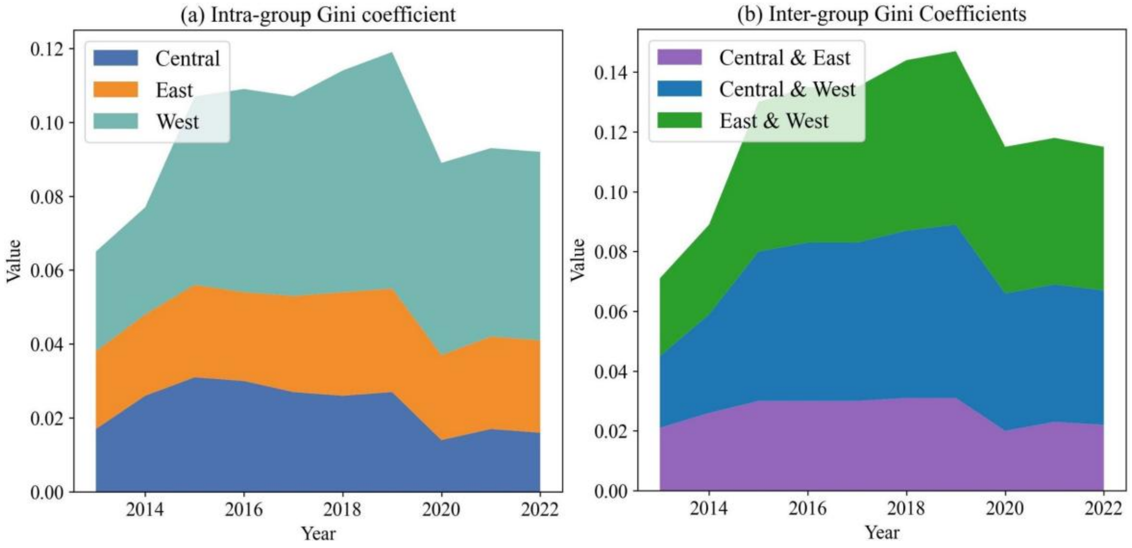


Figure 6. *Trend analysis of the decomposition results of Dagum Gini coefficient differences (2013-2022)*

Temporal and spatial evolution analysis

Equation 15 is used to calculate the KDE. *Figure 7* illustrates significant regional disparities and temporal variations in CCD values across China's eastern, central, and western regions over the past decade. The CCD values in the eastern region are relatively concentrated and stable, with the main density ranging between 0.6 and 0.7. Over time, the peak values converge to 0.65, indicating significant success in coordinated development of the low-carbon economy, green finance, and ecological environment quality, maintaining sustained stability and optimization. In contrast, the central region's CCD values display more complexity and variability, with multiple density peaks primarily between 0.6 and 0.65 and notable annual fluctuations, peaking in 2015 and 2019. This reflects greater instability and variability. The western region shows a more dispersed and volatile distribution of CCD values, with the main density ranging from 0.4 to 0.65 and peak values between 0.55 and 0.6. The time axis exhibits noticeable irregular fluctuations, with significant density peaks in 2013 and 2018.

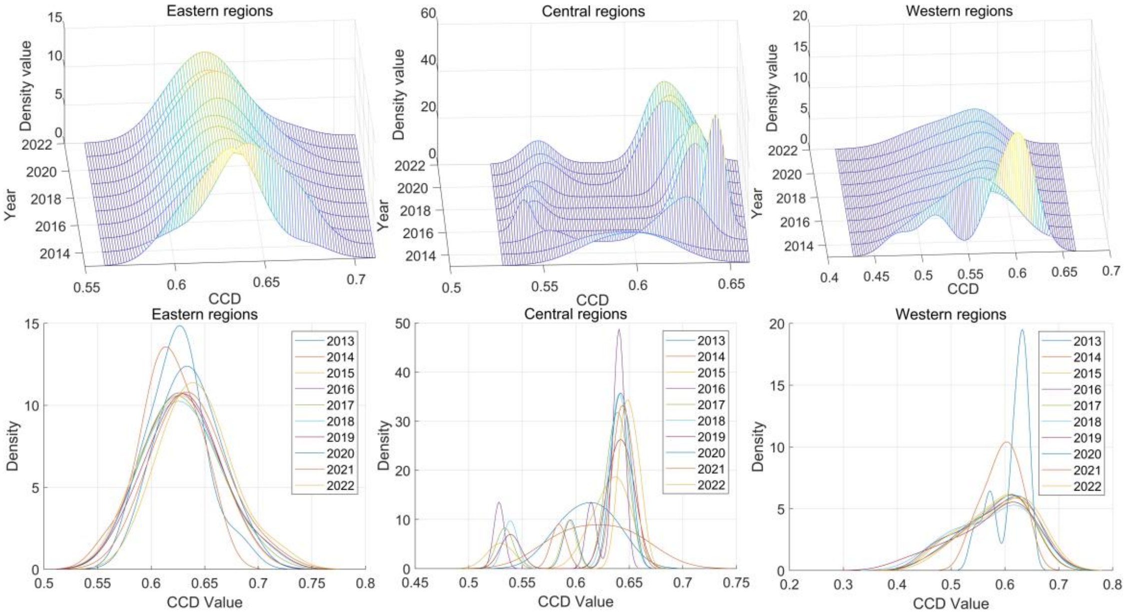


Figure 7. *KDE of CCD for eastern, central and western regions of China (2013-2022)*

Spatial correlation analysis

According to the calculations based on *Equation 14*, the Moran's I index results are detailed in *Figure 8*. As shown in *Figure 8* the coupled and coordinated development level of three systems exhibits significant spatial correlation, with this correlation showing a significant positive trend in most years. This indicates that, driven by policy and practical exploration, China has achieved a certain degree of spatial agglomeration effect in the coupled and coordinated development of the low-carbon economy and green finance across regions.

Figure 9 demonstrates significant spatial autocorrelation in the coupled and coordinated development levels of three systems. Specifically, the eastern coastal regions exhibit high-high clusters, while the western and some central regions display low-low clusters. In the Moran scatter plot, eastern regions such as Shanghai, Jiangsu, and Zhejiang consistently fall within the high-high cluster quadrant, indicating high levels of coupled coordination development and a notable spatial agglomeration effect. In contrast, western and some central regions, such as Gansu, Qinghai, and Ningxia, primarily fall within the low-low cluster quadrant, indicating lower development levels and a spatial clustering effect of these low levels.

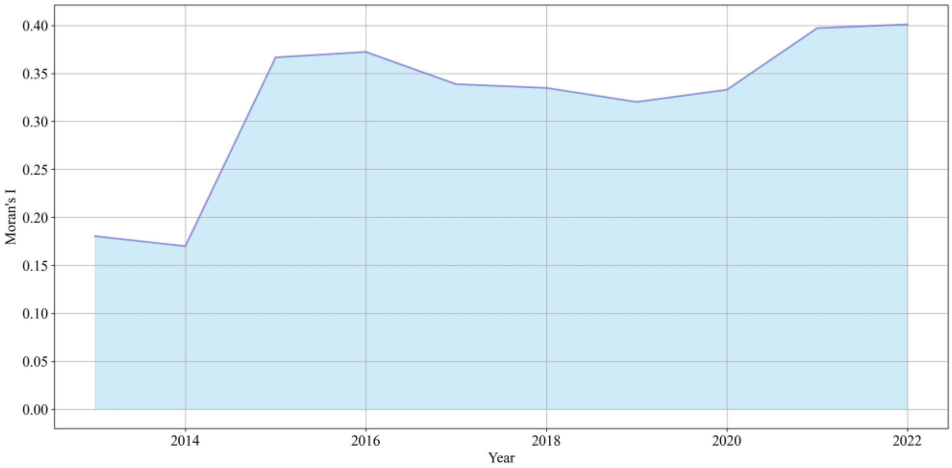


Figure 8. *Moran's I index of 30 provinces in China from 2013 to 2022*

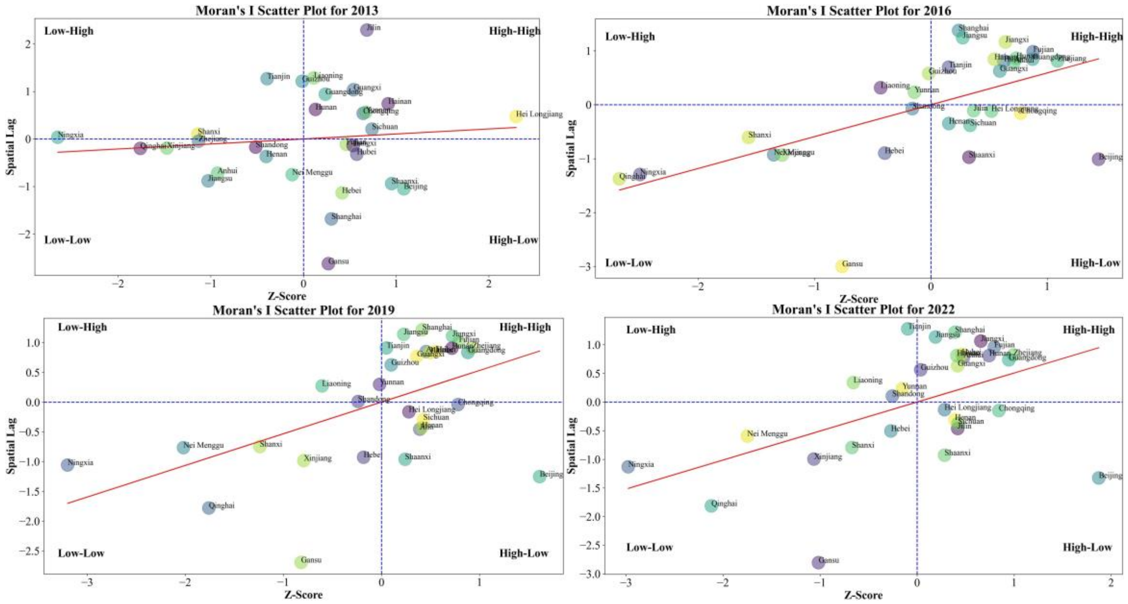


Figure 9. *Moran's scatter plots for the years 2013, 2016, 2019, and 2022*

Analysis of trends in spatial displacement

Figure 10 shows the spatial Markov transition matrix results. Initially, state transitions are minimal, indicating stability. As the lag period increases, transition probabilities grow. Notably, transitions from low-level to lower-middle and from lower-middle to upper-middle levels increase. The high-level state remains 100% stable from lag II onwards. There is significant fluidity between low and lower-middle states, suggesting potential for development. The upper-middle and high-level states are highly stable, indicating robust and steady progress in regions with high coupling and coordination.

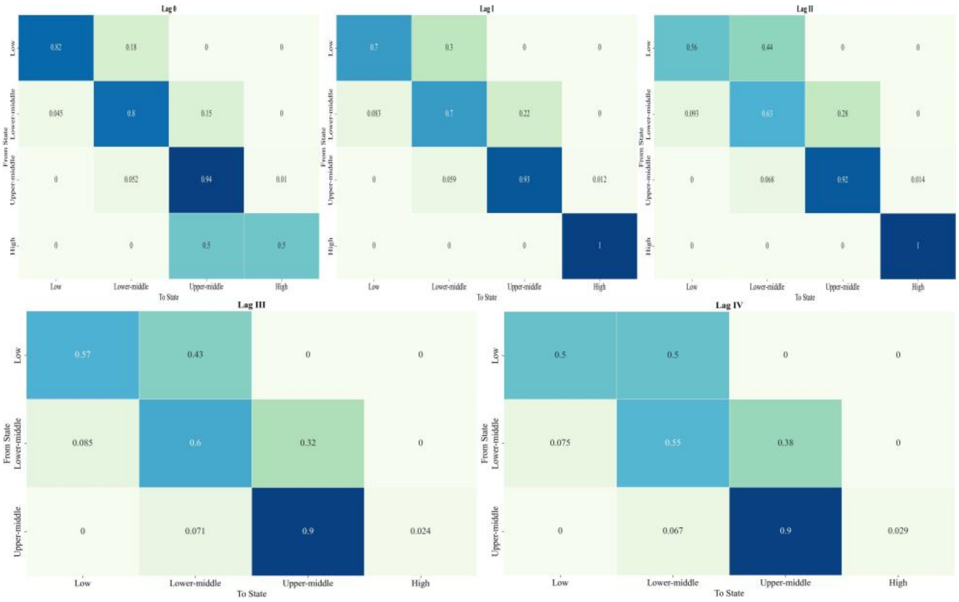


Figure 10. *Spatial Markov transition probability matrix for lag 0 to lag IV*

Discussions

The findings of this study provide critical insights into the spatiotemporal dynamics and regional disparities in the coupled and coordinated development (CCD) of China’s low-carbon economy, green finance, and ecological environmental quality. The empirical results reveal that China has achieved notable progress in advancing the coordination of these three systems, with the national average CCD reaching a “primary coordination” level by 2022. This aligns with previous studies emphasizing the role of green finance in driving low-carbon transitions (Zheng et al., 2021; Shi and Yang, 2025) and corroborates the effectiveness of China’s policy frameworks, such as the 13th and 14th Five-Year Plans, in fostering integrated sustainable development. This study’s analysis of green finance, the low-carbon economy, and ecological environment quality likewise illustrates a progression from initial imbalance to coordinated development. Whether green finance is jointly evolving with the digital economy or the low-carbon economy, the various regions of China display a similar stepwise coordination pattern in advancing financial greening and improving environmental indicators, accompanied by a marked spatial clustering effect. This finding aligns with the “significant global and local spatial autocorrelation” phenomenon reported by Zhang and Zhao (2023).

Meanwhile, our study also diverges from existing literature in several ways, underscoring its unique contribution. One prominent discrepancy lies in regional disparity trends. We find that from 2013 to 2022, imbalances between eastern and western China in terms of coupled development have intensified, as indicated by a rising Dagum Gini coefficient. This contrasts with research focusing on a single environmental quality system; for example, Lv and Zhou (2023) reported a mild narrowing of regional differences in China’s ecological environment quality in recent years. However, by adopting a comprehensive multi-system perspective (integrating economy, finance, and environment), our results suggest that when economic and

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financial factors are taken into account, regional disparities are in fact growing. In other words, provinces with stronger momentum in low-carbon economic growth and more robust green finance systems have gained an increasingly pronounced lead in environmental coordination. This finding is consistent with the east–west gradient noted by Peng et al. (2023), who observed that the coupling between green finance and environmental governance in eastern China significantly surpasses that in central, northeastern, and western regions. From a methodological standpoint, this study also differs from prior work, which predominantly focuses on pairwise relationships—such as coupling between green finance and environmental indicators, or between green finance and economic growth indicators—often relying on traditional coupling coordination models or basic correlation analyses (Zhou et al., 2022a; Liu et al., 2024b). By contrast, our study simultaneously examines three interrelated systems, thereby capturing more intricate interaction effects.

Although this study offers a relatively systematic analysis of the coupling and evolution of three major systems at the provincial level in China by employing multidimensional indicators and an optimized model, it still has certain limitations. The comprehensiveness of the indicators and the availability of data are constrained. While the indicators selected here endeavor to cover key dimensions of the low-carbon economy, green finance, and the ecological environment, it remains difficult to capture all relevant factors—such as environmental risk management, more granular carbon-trading measures, and green consumer finance. Future research could draw on longer time series or more detailed regional panel data to enrich the indicator system and enhance analytical accuracy.

Research conclusions and suggestions

Conclusions

This study optimizes the traditional CCD model to calculate the CCD of China’s low-carbon economy, green finance, and ecological environment quality using data from 2013 to 2022. Key findings include:

(1) From 2013 to 2022, the average CCD across 30 provinces showed an upward trend, reaching a primary coordination level, with significant regional differences.

(2) The regional imbalance in the coupled and coordinated development of the three systems has intensified, with the eastern region showing high stability, the central region displaying variability, and the western region experiencing significant fluctuations.

(3) The three systems exhibit significant spatial correlation, forming a high-high cluster in the eastern coastal region and a low-low cluster in the western and some central regions.

(4) The transition between different CCD levels is dynamic, with low and lower-middle levels showing potential for improvement, while upper-middle and high levels remain stable.

Suggestions

To address the issues identified in this study, the following suggestions are proposed:

(1) Optimization of Regional Development Policies: To address the issue of unbalanced regional coupled and coordinated development, the government should

increase financial support to the central and western regions for infrastructure, innovation, and industrial transformation. Financial institutions should be encouraged to develop diverse green financial products, like green bonds and green insurance, to support local low-carbon projects. Cooperation between the eastern and other regions should be fostered to share resources and technologies, and regional cooperation mechanisms should be improved to reduce development gaps.

(2) Adjustment of Industrial Structure and Development Models: To address the significant disparities in coupled and coordinated development across regions, it is essential to promote the green transformation of traditional industries in central and western regions. Strict environmental policies should be implemented to upgrade high-energy and high-pollution industries. The development of clean energy, energy-saving technologies, and emerging industries should be prioritized. Financial institutions should be encouraged to support low-carbon projects and establish a comprehensive green financial system.

(3) Enhancement of Technological Innovation and Public Participation: To address the dynamic characteristics of the coordinated development of low-carbon economy, green finance, and ecological environmental quality across regions, investment in green technology R&D should be increased, and collaboration between enterprises, universities, and research institutions should be encouraged. Talent cultivation in green development fields should be enhanced, and public participation mechanisms should be improved. Public awareness and involvement in green finance and low-carbon initiatives should be raised through education and outreach.

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