THE SPATIO-TEMPORAL COUPLING AND COORDINATION CHARACTERISTICS AND SPATIO EFFECTS OF CARBON EMISSION INTENSITY AND HIGH-QUALITY ECONOMIC DEVELOPMENT IN CHINA

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Abstract. From a strategic perspective, exploring the development relationship between carbon emission intensity and high-quality economic development is crucial for China to promote green, open, coordinated, innovative, and shared regional development, and to address climate change. The analysis encompasses 30 provincial-level administrative regions in China, utilizing provincial panel data spanning from 2008 to 2021, and employing methodologies such as coupling coordination degree model, and the spatial Durbin model, the research investigates the coupling coordination characteristics and spatial effects between carbon emission intensity and high-quality economic development within China. Key findings show a declining trend in carbon emission intensity and an increasing trend in high-quality economic development throughout the study period. A coupling relationship exists between the two variables, transitioning from mild imbalance to intermediate coordination over the period from 2008 to 2021. Additionally, a significant spatial effect influences the coupling coordination degree of carbon emission intensity and high-quality economic development. Influential factors such as innovation, environmental regulation, industrial structure, economic foundation, and urbanization significantly drive the coupling coordination degree within the province and its neighboring provinces.
Keywords: *carbon peaking, carbon neutrality goals, economic high-quality development index, coupling coordination logic relationship, spatial dubin model, driving mechanisms*

Introduction

Extreme weather events, forest fires, and species extinction induced by global climate change pose significant challenges to humanity (Li et al., 2022). The Paris Agreement underscores the critical role of low-carbon transition in addressing climate change. Carbon emission intensity, defined as the quantity of CO_2 emissions per unit of GDP, serves as a vital indicator of energy utilization and carbon emissions' efficiency within the economic developments of a country or region; high values denote low efficiency in energy utilization (Jotzo et al., 2007; Zhang et al., 2010). The Chinese government wrote the carbon emission reduction task as a binding target in the medium- and long-term plan for national economic and social development in 2009, i.e., it promised to reduce China's carbon emission intensity by 40-45% by 2020 compared to 2005. The report of the 19th National Congress of the Communist Party of China (CPC) in October 2017 clearly pointed out that China's economy needs to take a high-speed and high-quality development path, marking China's transition into an accelerated phase of economic development model adjustment. In 2020, China officially proposed to realize the "dual carbon" goals of carbon peaking and carbon neutrality, of which the carbon peaking goal emphasizes that CO_2 should peak by 2030 and the carbon neutrality goal emphasizes that before 2060, China should strive

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to realize net zero CO_2 emissions, which implies that China's economy must pay attention to the coupling and coordination relationship with carbon emission intensity in its future transformation and upgrading, so as to ensure that the "dual carbon" goal can be realized in the optimal growth path of the economy. In July 2024, the Central Committee of the Communist Party of China and the State Council issued the "Opinions on Accelerating the Comprehensive Green Transformation of Economic and Social Development", which systematically deployed the promotion of green transformation in all aspects, fields, and regions, in order to promote China's acceleration of achieving the dual carbon goals while further forming a coordinated development trend with high-quality economy.

Hryniewicz and Fujita argue that carbon emission intensity encapsulates both carbon emissions and economic growth, aiming to ensure economic expansion while minimizing carbon footprints, thereby achieving both emission reduction and economic advancement (Fujita, 2007; Hryniewicz et al., 2014). Wang Shaojian contends that quantifying emission reduction targets based on carbon emission intensity offers a more meaningful approach than using CO_2 consumption or per capita carbon emissions (Dissanayake et al., 2023). There is a substantial body of research on carbon emission intensity, encompassing various geographical scopes including countries, city clusters, demonstration zones, provinces, and counties (Fan et al., 2007; Raupach et al., 2010; Ghosh et al., 2010; Wang et al., 2024). Topics of interest include the measurement methodologies of carbon emission intensity (Sun et al., 2023, 2022; Raupach et al., 2010), regional disparities (Zhao et al., 2011; Chen et al., 2022; Yu et al., 2024), and the spatial clustering characteristics and drivers influencing carbon emission intensity (Davidsdottir et al., 2011; Hu et al., 2023; Deng et al., 2024; Li et al., 2024). These studies reveal that using carbon emission intensity as an indicator promotes the advancement of clean energy and low-carbon industries, effectively reflecting the environmental quality, green economic efficiency, technological progress, and energy utilization efficiency of a country or region. A high carbon emission intensity not only suggests low energy efficiency but also implies economic inefficiency, as more energy is required to generate equivalent economic value. As socio-economic development imposes irreversible impacts on the environment, research exploring the interplay between these factors has intensified, tracing back to British economist Boulding (Boulding, 1966). Building on Boulding's work, Pearce and Norgaad emphasized the complex process of coordinating economic growth with environmental protection, proposing the creation of feedback loops between socio-economic development and ecosystems to facilitate this coordination (Norgaard, 1990). With continuing research, carbon emissions have been incorporated as a variable in growth models to examine the dynamic relationship between the ecological environment and economic development (Stokey, 1998; Vujovic et al., 2018). Since the outbreak of COVID-19, China, one of the world's leading emitters of greenhouse gases and one of the first countries to take control measures against the outbreak, has been the first country to take control measures against the new crown. The outbreak had a significant impact on China's greenhouse gas emissions and reduction of air pollutants from January to April 2020 (He et al., 2020; Zhang et al., 2020). Liu Zhu contends that the global carbon emissions have been significantly impacted by the novel coronavirus pneumonia outbreak (COVID-19). Evaluating China's role in global change requires a precise assessment of the effect of COVID-19 on China's carbon dioxide emissions and emission patterns. According to research,

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the epidemic had varying degrees of impact on China's provinces' carbon emissions. The outbreak had the greatest impact on carbon emissions in the provinces of Jiangsu, Hubei, and Zhejiang, while it had the least impact in Qinghai and the Tibet Autonomous Region (Liu et al., 2021b).

Under new environmental and economic challenges, achieving an organic integration of ecological protection and economic development has emerged as a consensus in the academic community. Guided by novel development paradigms, exploring pathways for the green transformation of the national economy and moving beyond the traditional model of trading resource and environmental consumption for economic growth has become critically urgent. In this context, as China's economic development transitions to a new normal, investigating routes to achieve the green transformation of the national economy and to lessen socio-economic reliance on resource and environmental factors is of significant theoretical and practical value. This study focuses on provincial administrative regions in China. It estimates carbon emission intensity and assesses measures of high-quality economic development, examining the temporal and spatial characteristics and the coupling coordination evolution between these factors from 2008 to 2021. Moreover, it analyzes the driving factors and spatial spillover effects of this coupling coordination relationship, providing decision-making support to expedite the implementation of China's "dual COVID-19 carbon" goals and promoting the decoupling of socio-economic development from resource and environmental constraints.

Materials and methods

Study area

There are 34 provincial-level administrative divisions in China, but due to the lack of data in Xizang, Hong Kong, Macao and Taiwan, the remaining 30 provincial-level administrative divisions are taken as the research object in this paper. At the same time, based on the basic characteristics of adjacent locations and referring to the division of the Development Center of the State Council, China is divided into eight comprehensive economic zones. Some of the analysis methods in the results analysis will be summarized based on the eight economic zones. The specific scope of provincial and eight major economic zones for research is shown in *Figure 1*.

Theoretical framework

Coupling mechanism between carbon emission intensity and high-quality development of the economy

Carbon emission intensity promotes high-quality development of the economy through ecological functions, and the specific action path of the ecological environment in high-quality development of the economy is manifested in three aspects: (1) Giving play to the resource endowment function of the ecological environment to provide the material basis and production factors for high-quality development of the economy. (2) Giving play to the social effect of the ecological environment is the kinetic energy of high-quality development of the economy. The quality of the ecological environment plays a direct role in attracting high-quality human capital, which in turn drives the quality of economic development by promoting total factor productivity. (3) Giving the economic function of ecology is the "transmission" of high-quality development of the

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economy. Convert ecological resources into ecological products through marketization and valuation, convert ecological resources into ecological assets in the form of ecological compensation, and then realize the conversion of ecological assets into ecological capital through ecological operation, and finally realize ecological economy and help high-quality development of the economy.

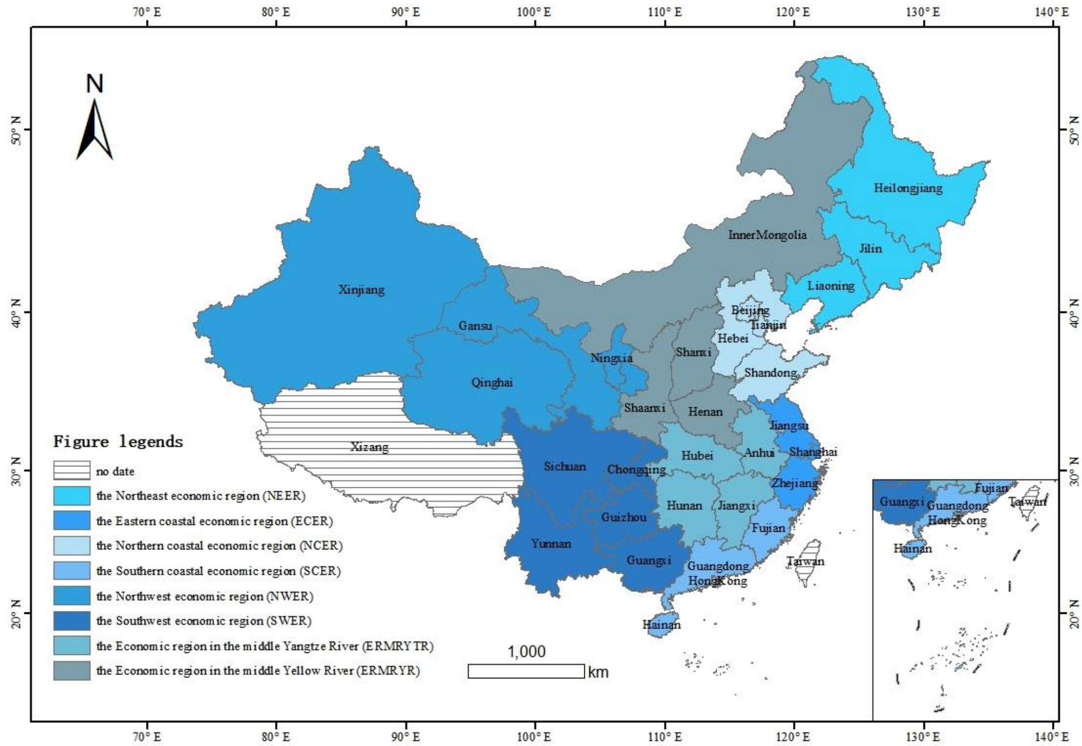

***Figure 1.** Provinces included in the eight comprehensive economic zones*

The feedback effect of high-quality development of the economy on carbon emission intensity is manifested in the scale effect, innovation effect, environmental constraint effect and structural effect on the ecological environment. Specifically: (1) Scale effect. As the quality of economic growth improves, the magnitude of inputs and outputs in social production increases, and large-scale factories and industrial clusters with highly concentrated production factors appear, which reduces energy consumption per unit of output to a certain extent. (2) Innovation effect. Based on endogenous growth theory, technological innovation improves the utilization rate of production factor resources, reduces resource loss, improves the quality of the ecological environment, and reduces carbon emissions from the production side. (3) Environmental constraint effect. As the level of economic development increases, after the material needs are fully satisfied, the public puts forward higher requirements for a good ecological environment, which promotes the improvement of environmental regulations from enterprises, factories, governments, individuals and other aspects. (4) Structural effect. Economic structural adjustment forces the green and low-carbon transformation of social production, and the rapid development of information, new energy, creativity and other new industries with high returns, low pollution and sustainability is conducive to reducing the carbon emission intensity level of the production sector.

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From a comprehensive point of view, carbon emission intensity drives high-quality development of the economy through the ecological environment to generate resource endowment capacity, social effect and economic effect; high-quality development of the economy constrains carbon emission intensity through scale effect, innovation effect, environmental constraint effect and structural effect. Thus, there exists a coupling relationship between the two systems with mutual influence and mutual constraints (*Fig. 2*).

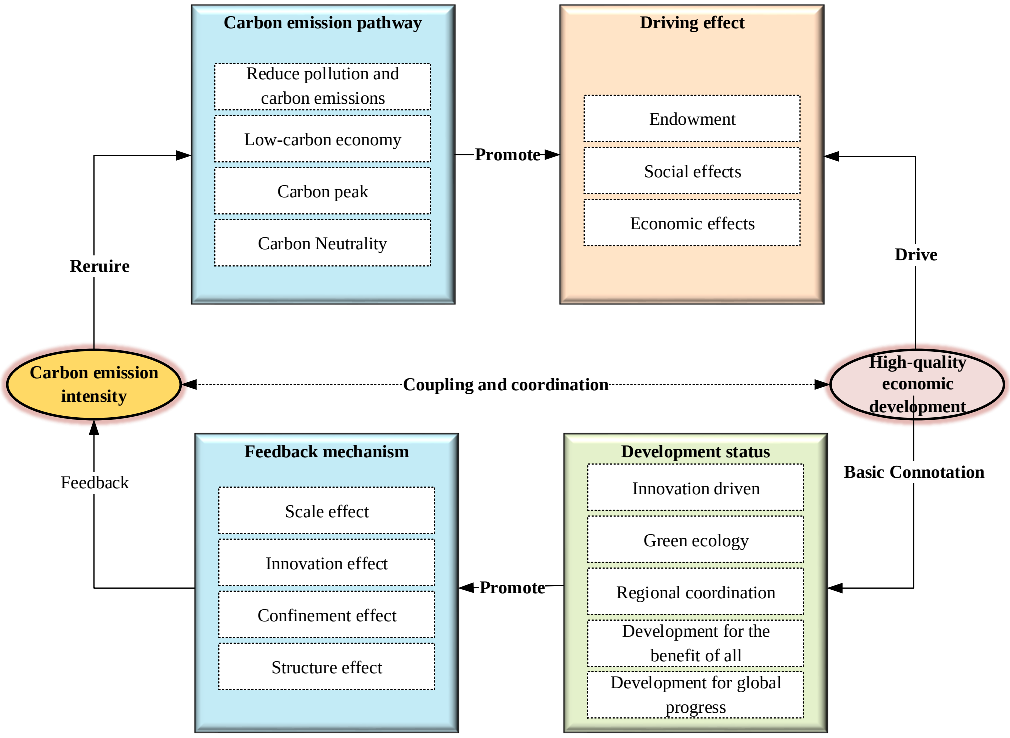

Figure 2. *Coupling mechanism framework of carbon emission intensity and high-quality economic development*

Selection of indicators for high-quality economic development

To explore the spatio-temporal dynamics of high-quality economic development across 30 provinces, this study refines an evaluation index system that reflects the nuances of economic development, the principles of high-quality growth, environmental quality, and the level of low-carbon living and production. The system is designed following the principles of scientific rigor, relevance, representativeness, and accessibility. It includes five dimensions: innovation drive, green ecology, regional coordination, open development, and shared development. Each dimension focuses on specific aspects. Innovation drive concentrates on inputs, outputs, and the environment related to innovation, selecting 10 indicators. Green ecology emphasizes resource endowment and ecological improvement, choosing 5 indicators. Regional coordination addresses urban-rural and industrial coordination, selecting 4 indicators. Shared development focuses on medical security and public services, choosing 3 indicators. Open development involves external economic interactions, selecting 3 indicators. A total of 25 indicators are chosen to measure the facets of high-quality economic development (*Table 1*).

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Table 1. *Evaluation index system of high-quality economic development*

Subsystem	Indicator & indicator type	w_1	w_2	Unit
Innovation-driven (Ren et al., 2018; Li et al., 2019; Liu et al., 2021a)	Internal expenditure of R&D funds (+)	0.048	0.025	10 thousand yuan
	R&D personnel fte (+)	0.049	0.015	Person
	Total expenditure on educations (+)	0.027	0.031	10 thousand yuan
	The number of R&D projects (+)	0.055	0.045	Pieces
	Effective number of invention patents (+)	0.060	0.039	Pieces
	Turnovers of the green technology market (+)	0.070	0.042	10 thousand yuan
	Number of ordinary institutions of higher learnings (+)	0.016	0.052	Institute
	Mobile Internet Access Ports (+)	0.033	0.050	10000
	Green coverage rate of built districts (+)	0.007	0.048	%
	Disposable incomes (+)	0.019	0.058	Yuan
Green and ecologic (Zhang et al., 2017; Fan et al., 2019)	Per capita green areas (+)	0.014	0.091	m^2
	Nature Reserves (+)	0.031	0.020	Pieces
	Harmless treatment ratio for house refuses (+)	0.008	0.105	%
	Natural gas penetration rates (+)	0.026	0.057	%
	Park greenbelts (+)	0.030	0.060	hm^2
Regional coordination (Zhang et al., 2021; Xiang et al., 2022; Ren et al., 2022; Han et al., 2022)	Per capita income ratio of urban and rural residents (-)	0.010	0.054	%
	Output value of the first industry (+)	0.024	0.011	10 thousand yuan
	Output value of secondary industry (+)	0.030	0.018	10 thousand yuan
	Output value of the third industry (+)	0.033	0.008	10 thousand yuan
Shared development (Li et al., 2019)	Number of insured persons in medical insurance (+)	0.032	0.013	Person
	Public book ownership (+)	0.049	0.024	Pieces
	Number of beds in medical institutions (+)	0.023	0.044	Pieces
Open development (Wei et al., 2018)	Foreign-invested enterprises registered Enterprises (+)	0.145	0.013	Institute
	Imports of goods (+)	0.055	0.039	One hundred million dollar
	Exports of goods (+)	0.104	0.039	One hundred million dollar

Research methods

Calculation of carbon emission intensity

This study employs the carbon emission coefficient method, which is widely utilized by researchers to calculate carbon emissions and carbon emission intensity. Drawing on the IPCC's carbon emission estimation guidelines and incorporating methods proposed by Su Yongxian and others (Su et al., 2013), this research selects nine types of energy consumption to estimate carbon emissions (*CE*) from the production side. Carbon emission intensity (*CEI*) is then calculated as the ratio of carbon emissions to GDP for each province. The calculation formulas are as follows:

$$CE = \frac{44}{12} \times \sum_{i=1}^{9} K_j \times E_{ijk} \qquad \text{(Eq.1)}$$

$$CEI = CE_{ik} / GDP_{ik} \qquad \text{(Eq.2)}$$

where *i* denotes the province, *k* the year, and *j* the type of energy. *CE* represents carbon emissions, with 44 being the molecular weight of CO_2 and 12 the molecular weight of carbon. *CEI* denotes carbon emission intensity. K_j indicates the carbon emission coefficient for energy type *j*; E_{ijk} represents the consumption of energy type *j* in province *i* in year *k*; CE_{ik} denotes the carbon emissions in province *i* in year *k*; GDP_{ik}

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represents the gross domestic product in province *i* in year *k*. *Table 2* shows the energy carbon emission coefficient and standard coal conversion Factors used in this article. Referencing the IPCC carbon emission estimation methods, this approach clearly differentiates and defines the total carbon emissions from various energy sources, thereby avoiding the problem of double-counting in the estimation of energy consumption volumes.

Table 2. *Energy carbon emission coefficient and standard coal conversion factors*

Type	Raw coal	Coke	Crude oil	Gasoline	Kerosene	Diesel	Fuel oil	Natural gas	Electricity
Carbon emission coefficient (tC/tce)	0.756	0.855	0.586	0.554	0.571	0.592	0.619	0.448	0.272
Standard coal conversion factor (kgce/kg)	0.714	0.971	1.429	1.471	1.471	1.457	1.429	1.330	0.113

Data sourced from the IPCC and China Energy Statistical Yearbook. The carbon emission coefficients are expressed in 104 tC per 104 tce, while the conversion factors for natural gas are measured in kgce/m³ and electricity in kgce/kW.h; other energy units are in kgce/kg

High-quality assessment based on combination of coefficient of variation method and analytic hierarchy process

(1) Coefficient of variation method

In the process of processing economic data, panel data (based on *m* years, *k* districts and counties, *j* indicators) is used for comprehensive evaluation. The specific process is as follows (Xi et al., 2023):

Firstly, indicators are normalized to remove dimensional disparities. The normalization formulae are:

$$r_{ij} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)} (i = 1, 2, ..., m; j = 1, 2, ..., n) \quad \text{(Eq.3)}$$

$$r_{ij} = \frac{\max(x_j) - x_{ij}}{\max(x_j) - \min(x_j)} (i = 1, 2, ..., m; j = 1, 2, ..., n) \quad \text{(Eq.4)}$$

Equations 3 and *4* represent the normalization of positive and negative indicators, respectively. In these formulas, r_{ij} and x_{ij} denote the normalized and original values of the *j*th indicator in province *i*, respectively; *m* is the number of provinces; *n* is the number of indicators.

Secondly, the information entropy and weight of the indicators are calculated using the following formulas:

$$\bar{x} = \frac{1}{n} \sum_{i=1}^{n} xij \quad \text{(Eq.5)}$$

$$s_j = \sqrt{\frac{\sum_{i=1}^{n} \left(x_{ij} - \overline{x_j}\right)^2}{n-1}} \quad \text{(Eq.6)}$$

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$$v_j = \frac{s_j}{\overline{x}_j} \tag{Eq.7}$$

$$w_1 = \frac{v_j}{\sum_{j=1}^{n} v_j} \tag{Eq.8}$$

In these formulas, $\bar{x}$ is the mean, s_j is the standard deviation, v_j is the coefficient of variation, w_1 is the weight.

(2) Analytic hierarchy process

$$w_2 = \frac{\left(\prod_{j=1}^{n} a_{ij}\right)^{\frac{1}{n}}}{\sum_{i=1}^{n}\left(\prod_{j=1}^{n} a_{ij}\right)^{\frac{1}{n}}} \tag{Eq.9}$$

a_{ij} is the score, and i is the i th evaluation index in the ordinate of the judgment matrix. Let j be the jth evaluation index in the abscissa of the judgment matrix. n is the number of evaluation indexes, that is, the order of judgment matrix.

$$CR = \frac{CI}{RI} \tag{Eq.10}$$

$$CI = \frac{\lambda \max - n}{n-1} \tag{Eq.11}$$

In the formula, *CR* is the consistency ratio, when CR is less than 0.1, the consistency test is passed, and *RI* is the random consistency index.

(3) Comprehensive evaluation index

$$w_j = 0.5 \times w_1 + 0.5 \times w_2 \tag{Eq.12}$$

$$H = \sum_{j=1}^{n} w_j x_{ij} \tag{Eq.13}$$

w_1 is the weight of the variation coefficient method, and w_2 is the weight of the AHP. The linear weighting method is used to calculate the comprehensive score H of high-quality economic development.

Coupling coordination degree model

The coupling degree represents the close cooperation and mutual influence between two or more systems. Employing the coupling degree function uncovers the inherent synergistic mechanism of the interaction between carbon emission intensity and high-quality development across various provinces in China. The coupling degree is calculated as follows (Dong et al., 2021; Luo et al., 2021; Yuan et al., 2023):

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$$C = \left[(U_1 \times U_2) / \left(\frac{U_1+U_2}{2}\right)\right]^2 \quad \text{(Eq.14)}$$

It is important to note that since carbon emission intensity is a negative indicator, its reciprocal is taken to convert it into a positive indicator for effective coupling and coordination with the high-quality economic development index. Here, U_1 and U_2 respectively represent the reciprocal of carbon emission intensity and the high-quality economic development index. The value of C, ranging from 0 to 1, indicates the degree of coupling; higher values suggest better coordination and a closer relationship between the systems.

However, the coupling degree function's limitation is its inability to determine whether the systems enhance each other at a higher level or are merely connected at a basic level. To address this, the study introduces a coupling coordination degree function, which not only reflects the coordination degree but also the stage of coordinated development. The model is expressed as:

$$D = \sqrt{C \times T},\ T = \alpha U_1 + \beta U_2 \quad \text{(Eq.15)}$$

Here, α and β are constants with a value of 0.5, signifying equal importance for carbon emission intensity and high-quality economic development. This approach builds on prior methodologies (Wang et al., 2019; Yang et al., 2020; Dou et al., 2024), systematically categorizing both the degree of coupling and coordination into distinct levels and types, as shown in *Table 3*.

Table 3. *Coupling coordination level and type division standard of carbon emission intensity and high-quality economic development*

Coupling coordination degree	Level	Coupling coordination degree type
$0.8 < C \leq 1$	I	Great coordination
$0.7 < C \leq 0.8$	II	Good coordination
$0.6 < C \leq 0.7$	III	Intermediate coordination
$0.5 < C \leq 0.6$	IV	Primary coordination
$0.4 < C \leq 0.5$	V	Mild disorders
$0.3 < C \leq 0.4$	VI	Moderate imbalance
$0 < C \leq 0.3$	VII	Extreme disorder

Spatial Durbin model

Among the commonly used spatial econometric models are the spatial lag model, spatial error model, and spatial Durbin model. The spatial Durbin model, employed for model testing and analysis, is formulated as follows (Sun et al., 2024):

$$Y(t) = \alpha IN + \rho WY(t) + \gamma X(t) + \theta WX(t) + \varepsilon \quad \text{(Eq.16)}$$

where $Y(t)$ represents the dependent variable; $x(t)$ is the independent variable; α is a constant; IN is the identity matrix; ρ, γ, θ are the parameters to be estimated; w is the spatial weight matrix; $\rho WX(t)$ and $\theta WX(t)$ represent the spatial spillover effects of the dependent and independent variables of adjacent regions, respectively; $\mathcal{E}$ is the error term.

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Research data

The study employs production-end energy consumption data to estimate carbon emissions, referencing the IPCC's carbon emission estimation method. Nine types of energy consumption—raw coal, coke, crude oil, gasoline, kerosene, diesel, fuel oil, natural gas, and electricity—are used to calculate CO_2 emissions from production activities. The ratio of carbon emissions to GDP is subsequently used to calculate the carbon emission intensity for each province. Energy consumption data are sourced from the "Energy Consumption" section of the "2009-2022 China Energy Statistical Yearbook," with GDP data obtained from the "National Economic Accounting" section of the same yearbook. The data for the evaluation indicators of high-quality economic development mainly comes from statistical yearbooks on China's energy, urban construction, environment, industry, society, health and other related areas from 2009 to 2022. China's administrative division vector data is sourced from the 1:1,000,000 National Basic Geographic Information Data. The detailed sources of indicators are shown in *Table 4*.

Table 4. *Source of raw data acquisition*

Indicators	Data sources
Internal expenditure of R&D funds, R&D personnel fte, total expenditure on educations, The number of R&D projects, effective number of invention patents, technology market turnovers, number of ordinary institutions of higher learnings, per capita income ratio of urban and rural residents, output value of the first industry, output value of secondary industry, output value of the third industry	https://data.cnki.net/yearBook/single?id =N2023110024&pinyinCode=YINFN
Mobile internet access ports, number of insured persons in medical insurance, public book ownership, number of beds in medical institutions, foreign-invested enterprises registered enterprises, imports of goods, exports of goods	https://data.cnki.net/yearBook/single?id =N2024050590&pinyinCode=YZGCA
Green coverage rate of built districts, per capita green areas, nature reserves, harmless treatment ratio for house refuses, park greenbelts	https://data.cnki.net/yearBook/single?id =N2024050561&pinyinCode=YHJSD
Natural gas penetration rates	https://data.cnki.net/yearBook/single?id =N2023110029&pinyinCode=YCJTJ
raw coal, coke, crude oil, gasoline, kerosene, diesel, fuel oil, natural gas, electricity	https://data.cnki.net/yearBook/single?id =N2024050932&pinyinCode=YCXME
China's administrative division vector	http://www.ngcc.cn/?eqid=be1d02ee001 1c7cb00000003647897c1

Results

Temporal and spatial evolution characteristics of carbon emission intensity

Temporal evolution characteristics of carbon emission intensity

Based on the production-side energy consumption data and GDP data from 2008 to 2021, the carbon emission intensity of the research area is measured by using *Equations 1–2*, and the descriptive statistical results of carbon emission intensity are summarized (*Table 5*). The results show that from 2008 to 2021, the maximum, minimum, and average values of China's carbon emission intensity all show a downward trend, indicating that the carbon emission intensity has decreased and the green efficiency of economic development has increased during the research period. Judging from the change trend of carbon emission intensity, it can be divided into three stages as a whole: First, the rapid decline period from 2008 to 2012, the average carbon emission intensity is between 0.647 and 0.993, the decline from the beginning to the end of this period is the largest, with a decline rate of 35.80%. During this period, the high-

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carbon emission and high-pollution traditional industrial industry types in the Northeast Economic Zone, the northern coastal economic zone, and the middle reaches of the Yellow River economic zone began to be greatly rectified, shut down and relocated, and the carbon emission intensity level dropped rapidly; second, the fluctuating decline period from 2012 to 2016, the average carbon emission intensity is between 0.518 and 0.599, with a decline rate of 13.52%. During this period, the average carbon emission intensity is stable between 0.5 and 0.6. The main reason is that this period was in a critical period of industrial upgrading and transformation, high-energy-consuming industries were transforming into low-energy-consuming and high-return information technology industries, and the service industry had become a new pillar industry; third, the low-level stable period from 2016 to 2021, the average carbon emission intensity is between 0.462 and 0.505, the decline from the beginning to the end of this period is 8.51%. During this period, the development of low-carbon economy and green economy has achieved remarkable results, the development and application of technological innovation and new materials have made the carbon emission intensity steadily decline. In addition, the coefficient of variation shows a downward trend during the research period, indicating that the degree of dispersion of carbon emission intensity is gradually decreasing.

Table 5. *Descriptive statistical results of China's carbon emission intensity*

Year	Maximum score	Minimum score	Average score	Coefficient of variation
2008	3.630	0.246	0.933	0.249
2009	2.381	0.244	0.810	0.215
2010	2.118	0.234	0.730	0.192
2011	2.350	0.240	0.692	0.182
2012	2.150	0.214	0.647	0.169
2013	2.073	0.193	0.599	0.156
2014	1.996	0.173	0.565	0.146
2015	2.067	0.160	0.544	0.140
2016	2.001	0.141	0.518	0.133
2017	1.988	0.130	0.505	0.130
2018	2.112	0.122	0.494	0.127
2019	2.253	0.103	0.503	0.129
2020	2.310	0.100	0.506	0.130
2021	2.124	0.099	0.462	0.118

Spatial evolution characteristics of carbon emission intensity

Using *Equations 1–2*, this study calculated the carbon emission intensity for 30 provinces in China over the period from 2008 to 2021. By analyzing data from four time points (2008, 2012, 2016, and 2021), this study classifies the 30 provinces into three categories based on their carbon emission intensity levels and coefficients of variation: high-intensity carbon emission (0.7-2.5), medium-intensity carbon emission (0.3-0.7), and low-intensity carbon emission (0.01-0.3). Using ArcGIS, maps illustrating the distribution of carbon emission intensity types across Chinese provinces for the years 2008, 2012, 2016, and 2021 were created. These maps demonstrate the spatio-temporal evolution of carbon emission intensity in Chinese provinces (*Fig. 3*).

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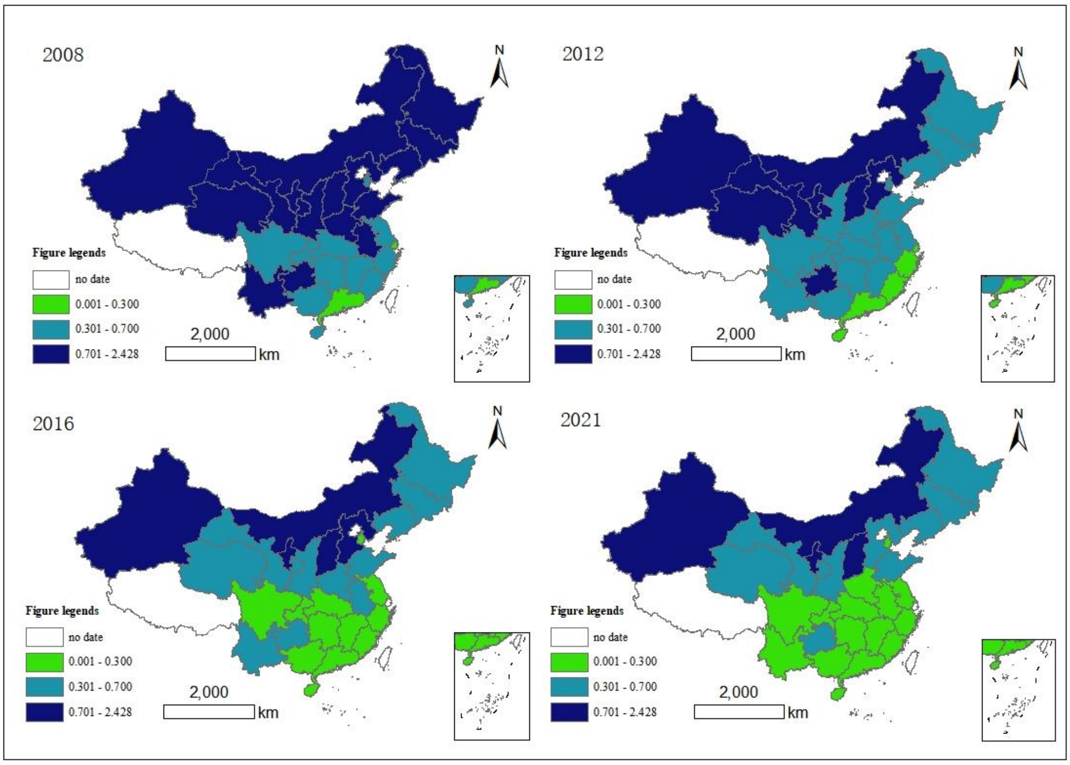

Figure 3. *Spatio-temporal distribution of carbon emission intensity types in China*

From the onset of the study period in 2008 to its conclusion in 2021, the carbon emission intensity across the provinces has evolved into three distinct types:

(1) Low Carbon Steady Type: This category predominantly includes Beijing, Guangdong, and Shanghai. Situated in the northern coastal, eastern coastal, and southern coastal regions respectively, these areas benefit from substantial advantages in capital, technology, and talent. They have progressively transitioned high-energy-consuming industries to regions with lower costs, optimized their industrial structures, and fostered a new wave of industrial upgrading and transformation. As a result, these regions maintain high resource utilization efficiencies, possess advanced technological capabilities in industrial enterprises, and exhibit low energy consumption per unit of product, consistently upholding a low-carbon stance.

(2) High Carbon Steady Type: Comprising Ningxia, Xinjiang, Inner Mongolia, and Shanxi, these provinces exhibit significantly higher natural resource consumption per unit of economic output compared to provinces with lower carbon emission intensities. Located in the northwest and along the midstream of the Yellow River basin, these areas are heavily reliant on mining, electricity, and coal industries. Characterized by low environmental thresholds and high energy consumption per unit of product, these provinces are dominated by traditional industries that have been slow to adopt structural adjustments and technological innovations.

(3) Types of change: This category includes Anhui, Shandong, Henan, Yunnan, Jilin, Jiangsu, Zhejiang and Fujian. It is worth noting that the carbon emission intensity of Anhui, Shandong, Henan, Yunnan and Jilin declines relatively slowly, which is because these five provinces are all resource-rich regions in China. Resource-based industries occupy the leading industries in the regions, and the cost and

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transformation time of energy conservation and carbon reduction are relatively long; the carbon emission intensity of provinces such as Sichuan, Zhejiang, Jiangsu and Hunan declines faster, the most typical ones are Zhejiang and Jiangsu provinces. Since they belong to the eastern coastal economic zone together with Shanghai, the three places have basically formed an integrated pattern with clear industrial division, developed transportation systems and complementary resource advantages. Therefore, the carbon emission intensity of Zhejiang and Jiangsu provinces has declined significantly.

Temporal and spatial characteristics of the high-quality economic development

Temporal evolution characteristics of high-quality economic development level

Based on *Equations 3–13*, it can be calculated that the high-quality economic development index of 30 provinces and regions showed an upward trend from 2008 to 2021. Due to space limitations, this article only presents descriptive statistical results of China's overall high-quality economic development growth index, as shown in *Table 6*. The results show that from 2008 to 2021, China's high-quality economic development level continued to improve, and the annual growth rate of the average value was 6.41%. It can be divided into three stages as a whole: The first stage is the rapid growth period from 2008 to 2012. During this period, the average annual growth rate of the high-quality economic development level is 8.751%. In 2008, the State Environmental Protection Administration was upgraded to the Ministry of Environmental Protection of the People's Republic of China, provinces actively promoted ecological protection work, various measures strengthened the protection and economical use of the ecological environment by social and economic activities, thereby directly improving the quality of economic development. The second stage is the slow growth period from 2012 to 2016. During this period, the average score of high-quality economic development in various provinces is 0.228, the average annual growth rate of high-quality economic development level is 5.128%. Economic structural adjustment has become an inevitable trend of economic development, technological innovations represented by information technology, biotechnology and new material technology continue to emerge, significantly improving the situation of high-quality national economic development. The third stage is the stable growth period from 2016 to 2021. During this period, the average score of high-quality economic development in various provinces is 0.303. However, the index growth rate slows down, and the average annual growth rate is 5.053%. During this period, the Chinese government gradually established an economic system of low-carbon circular development through supply-side reforms and formed an intensive economic development mode. The high-quality economic development level rapidly improved and the results of economic development were remarkable.

Spatial evolution characteristics of high-quality economic development level

In *Table 6*, it can be seen that the characteristics of the temporal evolution of the high-quality economic development level have a high degree of similarity with the temporal evolution of carbon emission intensity, which is divided into three stages of 2008-2012, 2012-2016, and 2016-2021 with the time nodes of 2012 and 2016, and draws the distribution of high-quality economic development index of national provinces and regions in 2008, 2012, 2016, 2021 (*Fig. 4)*.

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***Table 6.** Descriptive statistics of the overall characteristics of China's high-quality economic development index*

Year	Total score	Maximum score	Minimum score	Average score	Standard deviation
2008	4.327	0.291	0.053	0.144	0.063
2009	4.757	0.314	0.058	0.159	0.067
2010	5.375	0.417	0.068	0.179	0.075
2011	5.597	0.372	0.071	0.187	0.083
2012	6.042	0.420	0.082	0.201	0.084
2013	6.332	0.445	0.091	0.211	0.091
2014	6.746	0.467	0.105	0.225	0.097
2015	7.019	0.491	0.105	0.234	0.103
2016	7.379	0.526	0.115	0.246	0.110
2017	7.848	0.563	0.119	0.262	0.123
2018	8.272	0.620	0.125	0.276	0.142
2019	8.663	0.725	0.130	0.289	0.142
2020	9.037	0.702	0.137	0.301	0.139
2021	9.590	0.764	0.140	0.320	0.154

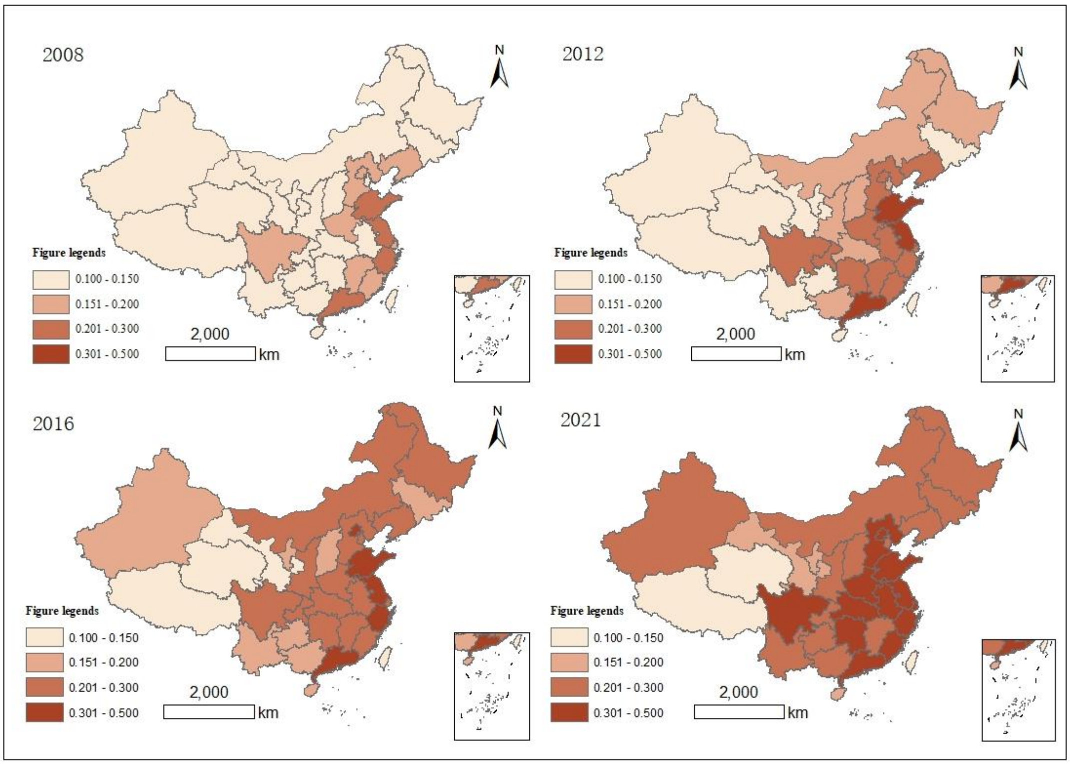

***Figure 4.** The distribution of high-quality economic development index of national provinces and regions*

From *Figure 4*, it can be seen that the high-quality economic development index shows significant differences of high in the east and low in the west, and high in the south and low in the north during the research period, there are four gradient levels from

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high to low, respectively. The first gradient is Guangdong, Jiangsu, Zhejiang, and Shandong in the southeast coast. The high-quality economic development of these four provinces is also the highest level in the country, which is attributed to the strong economic strength, stable industries, superior natural conditions and good industrial foundations, as well as the significant agglomeration effect of urban agglomerations of such kind of provinces and regions; the second gradient is mostly located in the northern coastal economic zone and the middle reaches of the Yangtze River economic zone, specifically including Beijing, Hebei, Shanghai, Anhui, Fujian, Jiangxi, Henan, Hunan, Hubei, and Sichuan. These regions have good natural conditions and their geographical locations are distributed around the provinces at the first gradient level, attaching importance to high-quality development; the third gradient is central and western provinces and regions and other provinces and regions, including Tianjin, Shanxi, Liaoning, Inner Mongolia, Jilin, Heilongjiang, Chongqing, Guizhou, Guangxi, Yunnan and Shaanxi, with an overall upward trend of high-quality economic development level during the research period, which is mainly radiated by the spatial proximity effect, as well as its own natural conditions and resource advantages to promote the high-quality economic development. In addition, the leading industries in these provinces are relatively more dependent on resources, and it is more difficult to achieve high-quality transformation; the fourth gradient includes Xinjiang, Gansu, Qinghai, Ningxia and Hainan, most of them are concentrated in the northwest economic zone. Unreasonable industrial development and non-intensive economic growth methods significantly limit high-quality economic development. Moreover, due to inconvenient locations, these provinces are difficult to be affected by the trickle-down effect of developed economic zones.

Spatio-temporal evolution characteristics of coupling coordination degree between carbon emission intensity and economic high-quality development

The classification of levels and types is essential for understanding the dynamics of coupling coordination between carbon emission intensity and high-quality economic development. Using *Equations 14–15*, the coupling and coordination relationship between carbon emission intensity and high-quality economic development was calculated for each province. Based on the average coupling coordination degree of each province and the evolution of coordination states over the study period (*Fig. 5*), categorizes the coupling coordination into five distinct levels:

Level I: Exclusively Guangdong, with an average coupling coordination degree of 0.805, indicative of high-quality coordination.

Level II: Includes Jiangsu and Shandong, with average coupling coordination degrees within the range of (0.7-0.8], signifying good coordination.

Level III: Encompasses 11 provinces including Zhejiang, Beijing, Sichuan, Henan, and Shanghai, with degrees between (0.6-0.7], representing moderate coordination.

Level IV: Comprises 11 provinces such as Jiangxi, Chongqing, and Shaanxi, with degrees between (0.5-0.6], indicative of primary coordination.

Level V: Consists of Xinjiang, Hainan, Ningxia, Gansu, and Qinghai, with degrees between (0.4-0.5], representing a mild imbalance.

In summary, there are pronounced disparities in coupling coordination levels across China’s provinces, with southeastern coastal regions generally showing better coupling conditions compared to the economically less developed northwestern provinces. These variances are likely attributable to differences in economic development levels,

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ecological foundations, industrial structures, public awareness, and policy orientations between these regions.

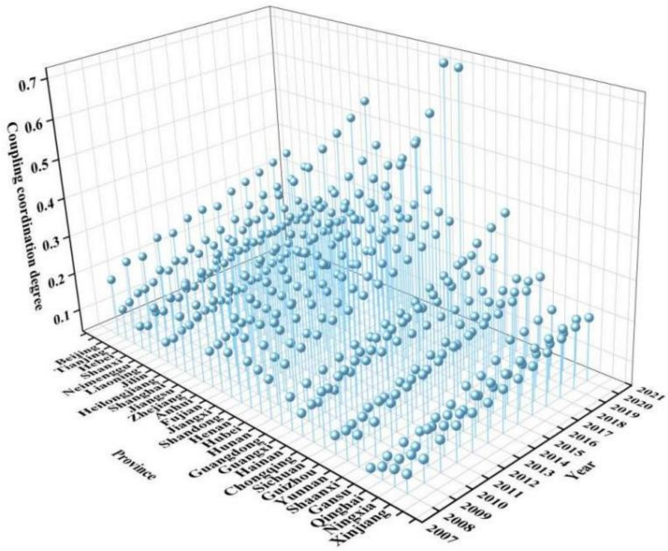

Figure 5. *Coupling coordination degree of provinces (autonomous regions) in China from 2008 to 2021*

Spatial effects of carbon emission intensity and economic high-quality development coupling coordination

The degree of coupling coordination between carbon emission intensity and high-quality economic development in China exhibits potential for enhancement. Despite a gradual narrowing of regional disparities, significant differences persist, influenced by regional industrial structures, economic foundations, and policy orientations. Given that provinces act as geographical units which inherently experience spatial effects through the interchange of resources, information, and technology, it is imperative to examine the determinants of coupling coordination from a spatial perspective.

Refer to the research findings of other scholars, this study identifies five key drivers: innovation input (Ln*Rdgdp*) (Yang et al., 2023), environmental regulation (Ln*Eigdp*) (Cui et al., 2023), industrial structure (Ln*Tidi*) (Pan et al., 2022), economic foundation (Ln*Idst*) (Chen et al., 2024), and urbanization (Ln*Urban*) (Hua 2021), and employs spatial econometric analysis to investigate their impact on the coupling coordination between carbon emission intensity and high-quality economic development. Utilizing LM, Wald, and LR Hausman tests, the Spatial Durbin Model (SDM) is determined to be the most suitable for analyzing these drivers and estimating the spatial spillover effects of the coupling coordination degree. *Table 7* presents the total, direct, and indirect effects, alongside the significance levels of each driver on the coupling coordination level, revealing notable variances in the impacts of these variables.

(1) Direct Effects: The coefficient for innovation input, represented as Ln*Rdgdp*, is positive and statistically significant at the 5% level. This indicates that an increase in innovation input positively influences the provincial coupling coordination level. Specifically, a 1% rise in innovation input directly enhances the coupling coordination

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degree between carbon emission intensity and high-quality economic development by 0.041%. This result underscores the role of innovation input in fostering low-carbon economic development through improved resource utilization, the development of new technologies, and a reduction in carbon emissions at the production stage. Moreover, it supports the synergy of industrialization and informatization, as posited by endogenous growth theory, facilitating comprehensive societal progress. For environmental regulation, represented as Ln*Eigdp*, the coefficient is negative and statistically significant, suggesting a direct adverse effect on the coupling coordination degree. Specifically, a 1% increase in environmental regulation correlates with a 0.036% decrease in the provincial coupling coordination degree, a consequence likely due to the lagging impact of environmental regulations. The coefficient for industrial structure, denoted by Ln*Tidi*, is negative and significant at the 1% level, indicating that a 1% enhancement in industrial structure directly reduces the provincial coupling coordination degree by 0.033%. The economic foundation, denoted by Ln*Idst*, also shows a negative coefficient, although it is not statistically significant. This implies that higher economic levels may be associated with increased energy consumption, leading to a reduced coupling coordination degree between carbon emission intensity and high-quality economic development. The coefficient for urbanization, represented as Ln*Urban*, is negative and significant at the 1% level. A 1% increment in urbanization level decreases the provincial coupling coordination degree by 2.930%. This finding reflects that urbanization in China remains entrenched in the mid-to-late stages of industrialization, with the traditional industrial-driven development path showing little sign of transformation.

Table 7. *Spatial effect decomposition of driving factors of coupling coordination degree*

Variable	Direct effect	Indirect effect	Gross effect
Ln*Rdgdp*	0.041**(2.27)	0.077(1.34)	0.118*(1.76)
Ln*Eigdp*	-0.036***(-3.00)	-0.172***(-5.99)	-0.208***(-6.36)
Ln*Tidi*	-0.329***(-8.28)	0.265**(2.30)	0.064(-0.54)
Ln*Idst*	-0.029(1.37)	-0.213***(-3.65)	-0.243***(-3.61)
Ln*Unban*	-2.930***(-6.83)_	-3.355**(-4.53)	-6.285***(-6.35)

*, * *, and * * * represent significant levels at 10%, 5%, and 1%, respectively

(2) Indirect Effects: Innovation input (Ln*Rdgdp*) exhibits a positive but statistically non-significant spillover effect on the coupling coordination degree between carbon emission intensity and high-quality economic development, with a 1% increase in innovation input boosting the coordination degree in neighboring provinces by 0.077%. This suggests that the benefits of technological innovation may create a “siphon effect,” drawing young talent and resources from neighboring areas, potentially exacerbating existing regional disparities. Environmental regulation (Ln*Eigdp*) shows a negative spillover effect, with a 1% increase in environmental regulation indirectly reducing the coupling coordination degree in neighboring provinces by 0.172%. This is attributed to the relocation of polluting industries and the resultant impact on shared responsibilities among neighboring provinces. Industrial structure (Ln*Tidi*) displays a significant positive spillover effect. A 1% increase in industrial structure indirectly raises the coupling coordination degree in neighboring provinces by 0.265%, indicative of a

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substantial positive spatial spillover effect. This is primarily due to the upgrading of industrial structures, especially the maturation of modern service industries, which facilitates the formation of well-defined industrial clusters with surrounding provinces and realizes scale benefits. The economic foundation (Ln*Idst*) presents a negative indirect effect. A 1% increase in the economic foundation level results in a 0.213% decline in the coupling coordination degree in neighboring provinces, indicating a considerable negative spillover effect. This suggests that improvements in local economic foundations may negatively affect neighboring regions by depleting resources and creating barriers to regional economic development, thereby fostering polarization. Urbanization (LnUrban) also demonstrates a negative impact, with a 1% rise in urbanization level decreasing the coupling coordination degree in neighboring provinces by 3.355%, showing a significant negative spillover effect. Although urbanization might be expected to have a demonstration effect on neighboring provinces, this impact appears delayed and not immediate.

Conclusions

Global climatic extremes and natural disasters necessitate a unified global response. Within this context, the harmonious integration of ecological environmental protection and economic development has emerged as a central theme in contemporary academic discourse. This study, anchored by the overarching objective of realizing the “dual carbon” targets and guided by theoretical frameworks such as new development concepts, spatial spillover theory, and coupling coordination theory, investigates pathways towards the high-quality transformation of China’s national economy. Following a structured analytical framework that encompasses “analyzing coupling coordination mechanisms, comprehensive evaluation, measuring coupling coordination levels, analyzing spatiotemporal evolution characteristics, revealing spatial effects, and proposing recommendations,” this study refines the research framework for analyzing the interplay between carbon emission intensity and high-quality economic development. Employing methodologies including the IPCC production-side energy consumption estimation method, multi-indicator comprehensive evaluation models, coupling coordination degree models, kernel density estimation, and spatial econometric models, the study delineates the spatiotemporal evolution and driving forces of coupling coordination between carbon emission intensity and high-quality economic development across China. The principal conclusions of this research are as follows:

(1) Trends in Carbon Emission Intensity:

Throughout the designated study period, carbon emission intensity consistently demonstrated a downward trajectory. This trend can be segmented into three distinct phases based on national carbon emission intensity changes: a rapid decline, a period of fluctuation, and a stable low-level phase, with pivotal transitions occurring in 2012 and 2016. Provincially, carbon emission intensity can be classified into three categories:

Low Carbon Stable Type: Provinces like Beijing, Guangdong, and Shanghai, where carbon emission intensity remains below 0.3.

High Carbon Stable Type: Regions including Ningxia, Xinjiang, Inner Mongolia, and Shanxi, where carbon emission intensity consistently exceeds 0.7.

Changing Type: Comprising the remaining 23 provinces that displayed varying intensity types throughout the study period.

(2) Economic High-Quality Development Trends:

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The trajectory of economic high-quality development has been ascending throughout the study period, with spatial analyses revealing more pronounced development in the eastern and southern regions compared to the west and north. The regions are differentiated into four tiers:

Highest Level: Including provinces such as Guangdong and Jiangsu.

Second Highest Level: Featuring areas like Beijing and Hebei.

Lower Level: Comprising regions such as Tianjin and Shanxi.

Lowest Level: Including less developed areas like Gansu and Qinghai.

(3) Coupling Coordination Characteristics:

The coupling coordination between carbon emission intensity and economic high-quality development manifests within the same spatiotemporal coordinates, characterized by mutual influence and constraints. Overall, the study period witnessed a shift in coupling from mild misalignment to intermediate coordination, reflecting an overall enhancement in coordination and a decrease in disparities between 2008 and 2021.

(4) Spatial Effects and Driving Factors:

Significant spatial effects are evident in the coupling coordination between carbon emission intensity and economic high-quality development. Increasing innovation input can promote the improvement of coupling coordination level in the province, while strengthening environmental regulations, transforming industrial structure, improving economic foundation, and enhancing urbanization will inhibit the improvement of coupling coordination level in the province. In addition, the increase in innovation input and industrial structure transformation have a positive spatial spillover effect on the coupling coordination between carbon emission intensity and high-quality economic development in neighboring provinces, while the strengthening of environmental regulations, improvement of economic foundation, and enhancement of urbanization level have a negative spatial spillover effect on the coupling coordination between carbon emission intensity and high-quality economic development in neighboring provinces.

Discussion

The interplay between carbon emission intensity and high-quality economic development in China is characterized by low levels, high coupling, and low coordination. Within the dual context of achieving the “dual carbon” goals and fostering high-quality economic transformation, the relationship between these two facets is progressively evolving towards a more optimized and coordinated state. Nevertheless, in certain provincial areas, the integration and alignment between these systems are still in nascent stages. In light of these observations, the results of the discussion are as follows:

(1) Reduce Carbon Emission Intensity and Enhance Comprehensive High-Quality Economic Development:

Reduction of Carbon Emission Intensity: For provinces such as Ningxia, Xinjiang, Inner Mongolia, and Shanxi, which exhibit relatively high carbon emissions, it is crucial to persistently advocate for the modernization and phasing out of industries characterized by high energy consumption and pollution. Measures should also include ecological restoration in areas of urban subsidence that are dependent on resources, the repurposing of abandoned mines, and a transition from traditional to renewable energy sources.

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Enhancement of Economic High-Quality Development: In regions like Gansu, Qinghai, and Ningxia, where high-quality economic development is less advanced, it is advisable to adopt the principle of “coordinated sharing.” This involves deepening East-West cooperation, implementing ecological compensation, and reinforcing targeted assistance policies.

(2) Improve Coupling and Coordination Levels Between the Two Systems:

Development of Differentiated Paths: Provinces should develop tailored development strategies based on their existing levels of coupling and coordination. Coastal areas in the East, North, and South, generally exhibiting intermediate to advanced coordination levels, should capitalize on their developmental strengths, attract resources, and align with supportive policies to augment the influence of major hubs like Shanghai, Beijing, and Guangdong.

Primary Coordination Regions: Areas such as the Middle Reaches of the Yangtze River, Southwest, Middle Reaches of the Yellow River, and the Northeast, characterized by elemental coordination levels, should prioritize the strategic distribution of high-quality resources, extend their influence to adjacent areas, and cultivate multiple regional sub-centers to enhance regional integration and coordination.

Western Regions: The Northwest, marked by lagging coordination levels, should enhance regional connectivity with adjacent areas, dismantle regional barriers, and leverage local resource endowments and fiscal support to rectify imbalances and elevate coordination levels.

(3) Attach importance to the spatial effect of the coupling coordination degree between carbon emission intensity and high-quality economic development among provinces and regions, and strengthen the positive spatial spillover effect between regions.

Referring to the results of the spatial effect model, the coupling coordination level of carbon emission intensity and high-quality economic development will be jointly affected by various driving factors such as innovation, economy, environment, and industry. Among them, innovation input has a significant direct positive effect and a positive spatial spillover effect. Therefore, each province needs to continuously strengthen the scientific and technological input in industrial transformation and upgrading, ecological environment restoration, and urbanization construction, so as to promote the coupling coordination of carbon emission intensity and high-quality economic development in its own province, and at the same time create positive incentives for the coordination of the two in the neighboring provinces. In addition, the transformation and upgrading of industrial structure also has a significant positive spatial spillover effect on the coupling coordination degree of neighboring provinces, indicating that the spatial club phenomenon of industries is obvious and can form a relatively complete gradient effect, so as to achieve orderly division of labor and complementary resource advantages. While promoting coordinated development within the eight major economic zones, each province in China should further promote the construction of urban agglomerations and metropolitan areas to provide more favorable development space for the transformation, upgrading and orderly transfer of industries. Although the influence factor of environmental regulations, economic foundations and urbanization is negative drive, it also shows that China’s economic development and carbon emission intensity still have a strong dependence. To this end, while increasing innovation input and industrial transformation and upgrading, we should learn from the integrated models of urban agglomerations such as the Yangtze River Delta and the

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Pearl River Delta in industrial layout, rail transit construction, and sharing of education and medical care, so as to form a joint development force and reduce resource waste and redundant construction.

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