Journal of Environmental Management 392 (2025) 126696

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Coupling coordination and future pathways forecasting of circular economy, green financial strategies and carbon emissions: A provincial level assessment

Yanzhi Jiang *

Nanjing University of Finance and Economics Hongshan College, Nanjing, China, No.66 Luming Avenue, Gubai Street, Gaochun District, Nanjing, Jiangsu Province, 211300, China

A R T I C L E I N F O

Handling editor: Jason Michael Evans

Keywords:
Circular economy
Green finance
Carbon emissions
Coupling coordination

A B S T R A C T

A circular economy is a basic path for strengthening ecological civilization construction. This study takes the regional circular economy, green finance, and carbon emissions as object, the coupled coordination model is used to verify the relationship between the three, and the GM (1, 1) model is used to make predictions, and finally recommendations are made to promote the development of the three coupled coordination. Findings as follows: (1) The three-system coupling degree rose from 2011 to 2023, but the overall rise was small. The three-system coupling degree of the eastern region was the highest, with Guangdong the highest and Inner Mongolia the lowest. For the type of coupling degree, there were seventeen cases in which there was a leap from the medium to the high coupling stage, five cases in which there was a leap from the antagonistic to the medium and then to the high coupling stage, and six provinces remained in the high coupling stage after 2014. (2) The coordination degree of the three systems showed an upward trend from 2011 to 2023, with a larger overall increase. Most of the regions in the coordinated development range were concentrated in the eastern coastal region. The degree can be divided into four phases: on the verge of dysfunction (2011–2013), little coordination (2014–2017), primary coordination (2018–2020), and intermediate coordination (2021–2023). (3) From the prediction results, in the period from 2024 to 2028, national coupling coordination will continue to steadily increase, and the intermediate coupling coordination stage will be entered in 2028, reaching 0.921 in the eastern, 0.689 in the central, and in 0.505 the western regions. The research in this paper is of great relevance to sustainable economic and social development.

1. Introduction

The Chinese economy has moved beyond the phase of rapid expansion and is now in a pivotal period characterized by a shift towards high-quality development. In industrialization process, the demand pressure for energy and minerals is gradually increasing, and the emission of various wastes in industrial production is gradually increasing. It not only causes serious environmental pollution, but also brings great waste of natural resources (Rees, 2003; Ferraro and Brans, 2012). How to realize sustainable development is important in China. Circular economy means that people consciously abide by the law of ecological development in the process of production and life, efficiently utilize production resources, reduce pollution emissions and harm to the surrounding environment. Circular economy and the establishment of a resource-saving society have become important measures to solve the current development problems in China, and are highly valued by our government. This concept has gradually been emphasized by governments and economists, and has become a hot spot of academic research (Sgroi, 2022). Circular economy is different from a traditional economic production method, which has an open-loop development of "resource–product–waste". A circular economy contains a closed-loop economic development of "resource–product–waste recycling–product" with the purpose of the reuse and recycling of resources and minimization of waste products. It is of great significance in solving the current energy and ecological dilemma of developing countries (Pereira and Montao, 2024; Agarwal et al., 2022).

Circular economic development cannot be separated from green financial support. Distinct from conventional finance, green finance

* Coresponding author
E-mail address: jyz201904@163.com.

https://doi.org/10.1016/j.jenvman.2025.126696
Received 12 January 2025; Received in revised form 19 July 2025; Accepted 19 July 2025
Available online 28 July 2025

prioritizes the wellbeing of humans and the ecological environment, as noted by Lee and Du (2024). It involves financial entities integrating environmental considerations into their investment and lending choices, treating environmental conservation and resource efficiency as critical factors. The goal is to foster environmental enhancement, combat climate change, and optimize resource utilization, all while ensuring the financial sector's sustainability (Anwar et al., 2024). Through green finance to encourage enterprises' green development, green finance facilitates the consolidation of diverse resources for environmental conservation and the advancement of green industries. It enhances market operational efficiency, effectively channels resource flows, and expedites the growth of the green sector in order to transform the mode of economic growth, eliminate backward production capacity (Jamali et al., 2023). Green finance is becoming an essential requirement for developing green industry, encouraging green investment.

It is the basic path to strengthen the fundamental solution to solve the problem of resources and ecology; it has the ability to effectively promote "double carbon" goal (Moustakas and Loizidou, 2023). As a key tool for "double carbon" management, a circular economy mainly reduces carbon emissions in the whole industrial chain through the recycling of resources and carbon emissions (Abbasi and Choukolaei, 2023; Abbasi et al., 2024, 2025), represented by the "3Rs" of reduce, reuse, and recycle (Moustakas and Loizidou, 2023). The "3R principle" has become an important standard to guide global enterprises to optimize production (Baidas, 2024). For example, "remanufacturing", part of a circular economy, has a circular manufacturing mode that reduces energy consumption by 85 % and carbon emissions by 60 % compared with the ordinary linear manufacturing mode. From the international community's point of view, there is general consensus that a circular economy has a wide range of synergistic effects on improving carbon emissions.

From the viewpoint of existing research, there are still several aspects in the research on circular economy: firstly, most of the research on circular economy focuses on a specific industry, but lacks the overall research on the region, especially the research on circular economy at the provincial level is relatively small. Secondly, most of the previous studies are on circular economy and influencing factors, and lack of coupling and coordination studies. The contributions of work as follows: (1) dividing China into three regions by the degree of economic development, comparing their difference, due to the formulation of regional differentiation policies; (2) existing studies rarely incorporate the circular economy, green finance and carbon emissions into a framework to study the coordinated development of their problems; and (3) putting forward proposals to promote the coupled and coordinated development of the three.

The structure as follows: the introduction part explains the background and environment, research gap and significance, objectives and scope of the paper's research; the literature review analyzes the current major research and the possible innovations of this paper; the method part includes the coupled coordination method and the GM(1, 1) prediction method, and lays the foundation for the following; the empirical analysis section demonstrates the findings and process of this paper; the fifth part is the conclusion part of the paper, which explains the main findings derived, the shortcomings, and the future outlook. The research framework of the thesis is as follows Fig. 1.

2. Literature review

2.1. Circular economy and green finance

Globally, researchers have dedicated significant efforts to individually examining their relationships, yielding substantial findings. However, investigations into how these two domains can complement each other's development are comparatively scarce. The initial forays into green finance were predominantly theoretical, aiming to understand financial institutions in safeguarding the environment and fostering sustainable economic growth. Green financial institutions have a positive impact on environmental protection by implementing differentiated credit policies that combine resource allocation with the fulfillment of social responsibility and also reduce the financial institutions' own risk level (Godfrey, 2005). Building upon the theories of green finance and circular economy, Zhu et al. (2019) dissected the interplay and synergy between the two domains, they found that an advanced and market-driven green financial framework is instrumental in circular

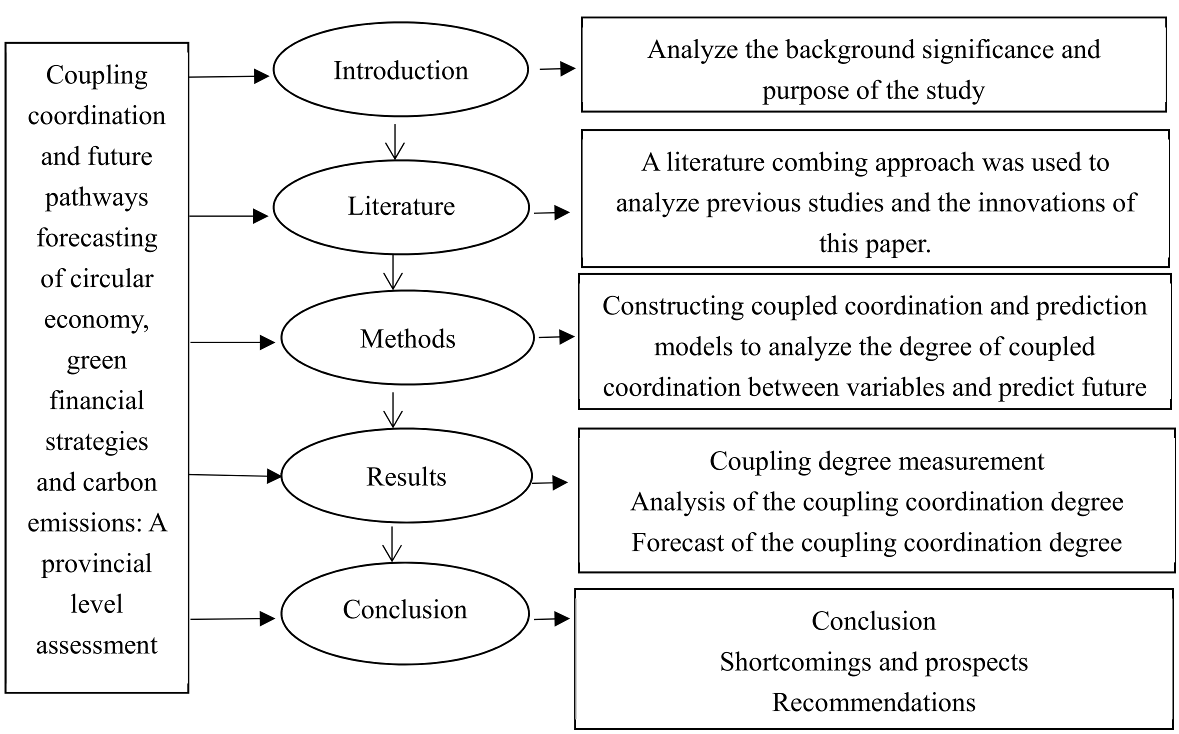

Fig. 1. Research framework of the thesis.

economy development. Zhang et al. (2020) and Yan (2022) argued that there is mutual support between them. Several researchers, including Li and Wang (2022) identified that the integration of circular economy with green finance is beneficial for the sustainability of economic and societal progress. These scholars employed the synergy between them to foster advancements in the economic and social realms. Moreover, they utilize green financial systems to enhance economy growth. Kang et al. (2022) took green finance subsystem as a starting point, selected green investment as a representative, and analyzed its coupled and coordinated development with the circular economy, which has an invaluable role to play in a green economy, which is beneficial to accelerating the construction of ecological civilization (Wei et al., 2021).

2.2. Circular economy and carbon emissions

Xu and Liu (2024) believe that a circular economy is important in achieving green development, implement "double carbon" governance, and solve the resource and environmental constraints of the basic policy. Fu and Su (2022) took the National Circular Economy Demonstration Zone in Gansu Province as example and found that the national recycling economy demonstration zone policy reduced carbon emissions; this effect gradually increased. Liu et al. (2023) concluded that there was positive spatial autocorrelation, and basically opposite spatial agglomeration areas formed between them. Mathews and Tan (2016) argued that extending the reuse of products and parts through circular remanufacturing and then improving the efficiency of product use reduced energy resource consumption and enterprises' carbon emission intensity, as well as in industries and society as a whole. Li and Wang (2017) showed that the low carbon value of the coal circular economy accounted for 7.81 % of the overall carbon emission coefficient, and the circular economy had a certain carbon reduction effect. Meanwhile, the study pointed out that the CO2 emission coefficient of coal utilization was high, and improving the utilization efficiency of coal should be the aim for emissions reduction in the whole coal circular economy industrial park.

2.3. Green finance and carbon emissions

Jalil and Feridun (2011) used the ARDL model to reach a similar conclusion. Shahbaz et al. (2016) showed that financial development increased carbon emissions. Scholars Fan (2022) indicated green finance promotes carbon emission reduction initiatives, thereby aiding in carbon emission reduction for enterprises with high emission levels through substantial financial backing. Su and Lian (2018) examined the carbon emission efficiency of major polluters pre- and post-green credit policy implementation, revealing that it inhibits the carbon emissions of these polluters via financial disincentives and curbed investment. Jiang et al. (2020) demonstrated that green credit exert a substantial impact in lowering carbon emissions.

This section systematically organizes the existing literature along the three main lines. The existing research on the connotation, measurement methods, and mutual influence provides a theoretical framework and many research perspectives for this paper's subsequent research; however, in general, there is room for optimization. (1) Literature combing reveals that the current research is mostly focused on the circular economy or green finance as a single subject, and the research on the synergistic relationship between the two is mostly confined to the existing problems of green finance, with relatively few studies on the measurement of the coupling coordination degree of regional circular economy and green finance. (2) A single research perspective, the research on circular economy efficiency is mostly concentrated on the time dimension, and lacks the multi-perspective research of both time and space two-dimensional comprehensive measurement, as well as analyzing its influencing factors. (3) Studying the relationship between the three has theoretical, practical and policy implications. Therefore, this work uses measurement results to test the coupling and coordination relationship, explores coupling coordination relationships, and finally predicts the coupling coordination through the grey prediction model, with a view to enriching the relevant research.

3. Methods

3.1. Constructing a coupled coordination model

Coupling is often subdivided into benign and undesirable coupling. Benign coupling describes synergistic and positive interactions between two systems; conversely, poor coupling describes uncoordinated or negative interactions between systems. Coupling is a state of interaction between systems, and carbon emissions, green finance and circular economy are two by two. Firstly, reducing carbon emissions can promote circular economy development; circular economy development in turn provides a basis for reducing carbon emissions. Secondly, reducing carbon emissions can obtain more green credits for enterprises that meet the green financial allocation standards; green finance provides capital for pollutant-emitting enterprises. Finally, the circular economy can get money through green finance. The three-dimensional systems of carbon emission, green finance and circular economy complement each other. Therefore, this paper firstly analyzes the evaluation of each subsystem; secondly, studies the degree of three-dimensional system coupling coordination; then, analyzes three-dimensional system coupling coordination and further predict and put forward suggestions. It is mainly divided into three parts: the coupling degree (C), the coordination degree (T), and the coupling coordination degree (D).

3.1.1. Calculation of the coupling degree C

This section uses the coupling degree model to analyze the coupling between circular economy, green finance and carbon emissions. The formulas for the coupling degree model of the three systems are as follows:

$$C = \sqrt[3]{\left(\frac{X \times Y \times Z}{3}\right)^3} = \frac{3\sqrt{X \times Y \times Z}}{X + Y + Z} \tag{1}$$

In equation (1), C is the coupling degree,X, Y, and Z are three systems in a certain aspect, and the larger value means closer interaction (Li and Wang, 2022). The classification as Table 1.

The coupling degree cannot reflect whether the influence between the three systems is positive or not, especially when three systems is very low, and the coupling degree may also be at a high level. In order to avoid such false judgments and accurately reflect the relationships, the coupling coordination degree is introduced in the work.

3.1.2. Calculation of coordination degree T

The degree of coupling is solely indicative of the extent to which subsystems influence each other and do not provide insight into their coordination level. Consequently, this model is employed to assess the coordination and interconnectivity among the subsystems. This degree not only considers the coupling relationship, but also the level and quality of development within each system (Wang and Zhao, 2025). The formula is shown in equation (2):

$$T = \alpha X + \beta Y + \Upsilon Z, \tag{2}$$

Table 1
Classification.

Coupling level	Coupling degree
[0.99,1]	very high
[0.8,0.99)	high
[0.5,0.8)	medium
[0.3,0.5)	antagonistic
[0,0.3)	low

Where α, β, and ϒ are coefficients for three subsystems. Generally, since the three systems have the same importance for the problem under study, α = β = ϒ = 1/3. X, Y, and Z represent the indexes of three subsystems. The T-values are calculated according to the format (2) and are given in Table 2 below.

3.1.3. Degree of coupling and coordination of the three systems D

This degree integrates both the coupling and coordination degrees, serving as a metric to assess the integrated of multiple systems (Dang, 2025). The formula for its computation is presented in Equation (3):

$$D=\sqrt{C\times T} \tag{3}$$

First, we need to summarize the scores of the first-level indicators in the multi-indicator comprehensive evaluation system. Then, the calculation is carried out according to formula (3); the aim is to calculate degree values for the trio of systems. To set the criteria for identifying the coupling patterns among these systems, the criteria for discriminating the type of three-system coupling were established, as shown in Table 3. This step aims to clarify the coupling types corresponding to different coupling degree values through interval division, providing a basis for further analysis (Jia and Jian, 2025).

3.2. Forecasting model

Owing to the limited data available for each province in this study, to offer tailored recommendations for provincial development, the grey prediction model was selected to forecast. The GM (1,1) model is capable of processing randomly collected original discrete non-negative data series. By accumulating these data once, it generates new discrete data series, establishes a corresponding differential equation model, and employs the solution of first-order linear differential equations to approximate the pattern exhibited by the new time series post-accumulation. This method allows for the calculation through a sequence, effectively constituting a first-order linear dynamic model (Sun et al., 2025). Referring to the scholar Zhang (2025) the modeling steps are as follows:

Table 3
Classification of coupling coordination degree.

Level of coordination	Coupling coordination degree	Level of coordination	Coupling coordination degree
[0.9,1]	Quality coordination	[0.4,0.5]	On the verge of disorder
[0.8,0.9]	Good coordination	[0.3,0.4]	Mildly dysfunctional
[0.7,0.8]	Intermediate coordination	[0.2,0.3]	Moderate disorder
[0.6,0.7]	Elementary coordination	[0.1,0.2]	Severe disorder
[0.5,0.6]	Barely coordinated	[0,0.1]	Extreme disorder

(1) Establish the time series with known data variables. Let the original sequence be equation (4):

$$x^{(0)}=\left(x^{(0)}(1),x^{(0)}(2),\dots,x^{(0)}(n)\right), \tag{4}$$

where n indicates that there are n sample observations; to ensure the feasibility of method, we need to carry out the level ratio calculation and judgment, and the level ratio of the series is shown in equation (5):

$$\lambda(\mathrm{k})=\frac{x^{(0)}(k-1)}{x^{(0)}(k)},k=2,3,\dots,n. \tag{5}$$

If all the level ratios fall within $X=\left(e^{\frac{-2}{n+1}},e^{\frac{2}{n+1}}\right)$, the prediction model can be built for grey prediction; otherwise, a further transformation process is required.

(2) The accumulative generation overcomes the randomness and volatility of the original series, which is important in grey system theory.

$$x^{(1)}=\left(x^{(1)}(1),x^{(1)}(2),\dots,x^{(1)}(n)\right) \tag{6}$$

Table 2
T-values.

	Region	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Eastern	Beijing	0.686	0.680	0.721	0.704	0.721	0.830	0.808	0.813	0.875	0.857	0.891	0.961	0.978
	Tianjin	0.584	0.597	0.592	0.599	0.620	0.682	0.724	0.805	0.799	0.803	0.846	0.903	0.932
	Hebei	0.444	0.495	0.499	0.568	0.611	0.562	0.591	0.715	0.720	0.692	0.689	0.798	0.828
	Liaoning	0.452	0.470	0.484	0.543	0.585	0.565	0.615	0.687	0.696	0.725	0.723	0.737	0.744
	Shanghai	0.657	0.691	0.666	0.719	0.814	0.810	0.835	0.865	0.893	0.882	0.906	0.943	0.949
	Jiangsu	0.675	0.686	0.722	0.696	0.710	0.822	0.810	0.833	0.858	0.902	0.879	0.882	0.960
	Zhejiang	0.681	0.700	0.721	0.674	0.685	0.833	0.831	0.825	0.859	0.888	0.887	0.939	0.975
	Fujian	0.603	0.614	0.644	0.673	0.661	0.684	0.709	0.717	0.722	0.715	0.784	0.809	0.824
	Shandong	0.682	0.736	0.592	0.718	0.718	0.785	0.820	0.846	0.872	0.852	0.852	0.902	0.928
	Guangdong	0.761	0.780	0.812	0.852	0.821	0.842	0.910	0.926	0.961	0.987	0.981	0.988	0.999
	Hainan	0.573	0.551	0.587	0.619	0.642	0.637	0.637	0.698	0.719	0.695	0.715	0.776	0.827
Central	Shanxi	0.173	0.187	0.331	0.344	0.301	0.301	0.351	0.309	0.376	0.567	0.702	0.759	0.738
	Jilin	0.172	0.194	0.319	0.292	0.346	0.421	0.344	0.392	0.492	0.516	0.735	0.729	0.747
	Heilongjiang	0.209	0.219	0.313	0.293	0.320	0.392	0.426	0.424	0.419	0.443	0.471	0.506	0.519
	Anhui	0.435	0.435	0.506	0.461	0.458	0.596	0.563	0.551	0.727	0.793	0.794	0.799	0.816
	Jiangxi	0.211	0.233	0.415	0.379	0.379	0.491	0.503	0.515	0.536	0.537	0.548	0.632	0.683
	Henan	0.295	0.345	0.460	0.473	0.429	0.358	0.375	0.564	0.563	0.499	0.449	0.613	0.738
	Hubei	0.361	0.387	0.417	0.411	0.447	0.484	0.529	0.585	0.623	0.657	0.605	0.636	0.828
	Hunan	0.373	0.389	0.411	0.394	0.429	0.519	0.554	0.613	0.723	0.736	0.737	0.758	0.777
Western	Neimenggu	0.204	0.209	0.214	0.225	0.170	0.346	0.395	0.323	0.327	0.507	0.526	0.535	0.554
	Guangxi	0.241	0.343	0.326	0.336	0.397	0.409	0.396	0.404	0.505	0.517	0.526	0.535	0.548
	Chongqing	0.295	0.333	0.345	0.405	0.375	0.497	0.567	0.544	0.609	0.640	0.664	0.673	0.690
	Sichuan	0.243	0.276	0.371	0.377	0.402	0.419	0.418	0.391	0.457	0.535	0.546	0.553	0.566
	Guizhou	0.204	0.170	0.316	0.345	0.322	0.400	0.422	0.442	0.389	0.469	0.532	0.570	0.602
	Yunnan	0.197	0.322	0.313	0.301	0.410	0.415	0.432	0.439	0.456	0.463	0.472	0.476	0.512
	Shanxi	0.231	0.323	0.336	0.339	0.312	0.420	0.431	0.436	0.391	0.464	0.537	0.563	0.611
	Gansu	0.232	0.312	0.333	0.333	0.309	0.385	0.411	0.393	0.467	0.454	0.501	0.520	0.529
	Qinghai	0.244	0.316	0.327	0.338	0.303	0.403	0.418	0.400	0.441	0.487	0.513	0.511	0.535
	Ningxia	0.243	0.310	0.318	0.271	0.409	0.409	0.430	0.443	0.398	0.409	0.497	0.512	0.531
	Xinjiang	0.294	0.332	0.309	0.400	0.415	0.423	0.432	0.448	0.436	0.440	0.512	0.509	0.531

(3) Perform neighbor-mean generation on the sequence after cumulative generation. Neighborhood mean represents the new data generated by constructing the average of neighboring data.

$$z^{(1)}(k) = 0.5x^{(1)}(k) + 0.5x^{(1)}(k-1), k = 2, 3, ..., n \quad (7)$$

(4) Construct data matrix B and data vector Y.

$$B = \begin{bmatrix} \left(-\frac{1}{2}\left(z^{(1)}(1) + z^{(1)}(2)\right) & 1 \\ \left(-\frac{1}{2}\left(z^{(1)}(2) + z^{(1)}(3)\right) & 1 \\ \left(-\frac{1}{2}\left(z^{(1)}(n-1) + z^{(1)}(n)\right) & 1 \end{bmatrix} \quad (8)$$

$$Y = \begin{bmatrix} x^{(0)}(2) \\ x^{(0)}(3) \\ x^{(0)}(n) \end{bmatrix} \quad (9)$$

(5) Calculate coefficient a and grey action u in equation (10):

$$\begin{bmatrix} a \\ u \end{bmatrix} = \left(B^T * B\right)^{-1} B^T Y \quad (10)$$

(6) Model to solve the time–response function and make predictions. The coefficients a and u are first solved, and then the coefficients a and u are introduced into Eq. (11) to solve this differential equation to obtain whitened form prediction model. The model is shown in equation (12):

$$\frac{dx^{(1)}}{dt} + ax^{(1)} = u \quad (11)$$

$$\hat{\mathscr{X}}^{(1)}(k+1) = \left(x^{(1)}(1) - \frac{u}{a}\right)e^{(-ak)} + \frac{u}{a}, k = 1, 2, ..., n \quad (12)$$

The model accuracy was determined according to accuracy scale (Wang et al., 2025), which is shown in Table 4.

3.3. Construction of a variable evaluation system

Carbon emission. Carbon emission data were estimated according to the method recommended by the IPCC (2006), including eight major fossil energy sources. The calculation method as equation (13).

$$CO_2 = \sum_{i=1}^{8} C_i = \sum_{i=1}^{8} E_i \times \mathrm{SCC}_i \times \mathrm{CEF}_i \quad (13)$$

Where CO_2 denotes carbon emissions; i denotes the various energy sources; E_i represents the energy consumption sources, which are derived from the energy end-consumption data; SCC_i represents the energy sources discounting the coal coefficient; CEF_i is the carbon emission factor as Table 5.

Based on the above methodology, the carbon emission subsystem data are derived as follows in Table 6.

Table 4
GM (1,1) accuracy scale.

Model Accuracy Grade	P	C
Grade 1 (Excellent)	$0.95 \leq P$	$C \leq 0.35$
Grade 2 (Good)	$0.80 \leq P < 0.95$	$0.35 < C \leq 0.5$
Grade 3 (Pass)	$0.70 \leq P < 0.80$	$0.5 < C \leq 0.65$
Grade 4 (Unqualified)	$P < 0.70$	$0.65 < C$

Note: In the table, P is the probability. C is the ratio of the variance of the model's prediction error to the variance of the residuals.

Green finance. Given the nascent stage of green finance's evolution, a standardized approach for gauging the advancement of green finance in urban areas is yet to be universally adopted. The prevailing consensus leans towards the evaluation index system , which encompasses five distinct financial product categories as Table 7. This framework serves to assess green finance initiatives maturity. Concurrently, the present study employed the entropy weight method across the period from 2011 to 2023, aiming to provide a more impartial and precise reflection of the indicators' weights; the results as Table 7.

Circular economy: In most of the existing research, the selection of evaluation indexes includes a single index, composite index, and other methods. Generally speaking, it is difficult to accurately portray the content of the study using a single index system, which will lead to bias in the research results. Therefore, most scholars use the composite index method. For example, Huang et al. (2015) constructed a measurement system for circular economic development from resource reduction and utilization, and waste reduction and resource recycling. Yang and Zhang (2005) constructed index system containing the three levels of an economic system, ecological environment system, and social system, totaling 40 specific indicators. Lv and Gao (2014) measured circular economic development from economic, green, and humanistic development. This research synthesized the work of many scholars, selected three subsystems, namely, economy, ecology and environment, and society, and selected 15 indicators of the three subsystems (Table 8).

3.4. Data sources

The data come from the statistical yearbooks, insurance yearbooks, statistical bulletins, financial accounts published by the Finance Bureau, and other relevant data sources for each region for the period 2011–2023.

4. Results

4.1. Coupling degree measurement

The coupling degree of them is shown in Table 9 and Fig. 2, and it is categorized, as shown in Fig. 3.

First, in Table 9, the coupling degree go upward from 0.482 (2011) to 0.620 (2023), with an increase of 0.286 %. From the specific value of each year, the degree of change was small, around 0.6 with a lower value. The coupling degrees of the eastern, central, and western regions increased from 0.700, 0.425, and 0.321 in 2011 to 0.819, 0.581, and 0.465, with increases of 17 %, 36.71 %, and 44.86 % respectively. In the eastern region, the value was higher than 0.6 in all years except 2011, but the growth rate of 17 % was relatively slow. Although the value in the western region was the lowest, the growth rate was faster, at 44.86 %, indicating that the western region grew rapidly. However, overall, the coupling degree was still low, and there was no great leap and breakthrough. This is mainly because of the large difference in regional development, which results in improvements on the front end in the developed regions for the economy, green finance, and ecological environment, while the less developed regions lack green financial products, industries, and other aspects. The developed regions gradually widen the gap, limiting the coupling of the system's development.

Secondly, at a provincial level, from integrated level value and ranking, the average value of 14 provinces, including Beijing, Fujian, and Guangdong (highest with 0.945), was higher than the national average value. As Guangdong is a representative typical coastal province, the latest policies and systems are always tried first there. East Guangdong has taken the lead in green development by eliminating outdated production capacity, implementing industrial transformation, and focusing regional development on tertiary industries and light industries with low pollution and high capacity and efficiency, promoting overall high-quality development, and continuously providing funding

Table 5
Indicators and coefficients.

Fuel type	coals	coke	crude oil	fuel oil	diesel	gasoline	diesel fuel	petroleum
Discount factor(SCC)	0.7143	0.9714	1.4286	1.4286	1.4714	1.4714	1.4571	1.33
Carbon emission factor(CEF)	0.7559	0.855	0.5538	0.5857	0.5921	0.5714	0.6185	0.4483

Table 6
Carbon emission subsystem data.

	Region	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Eastern	Beijing	0.096	0.091	0.085	0.076	0.080	0.074	0.072	0.071	0.068	0.066	0.065	0.064	0.064
	Tianjin	0.153	0.156	0.158	0.163	0.168	0.172	0.65	0.163	0.160	0.164	0.158	0.156	0.161
	Hebei	0.512	0.536	0.558	0.591	0.613	0.651	0.678	0.701	0.722	0.735	0.758	0.783	0.822
	Shanghai	0.182	0.185	0.187	0.182	0.176	0.179	0.175	0.174	0.172	0.168	0.165	0.169	0.178
	Liaoning	0.502	0.505	0.512	0.514	0.522	0.535	0.542	0.540	0.539	0.545	0.556	0.572	0.589
	Hainan	0.023	0.025	0.023	0.024	0.026	0.028	0.028	0.029	0.031	0.033	0.032	0.034	0.037
	Shandong	0.559	0.573	0.589	0.654	0.688	0.701	0.725	0.744	0.786	0.802	0.842	0.876	0.915
	Jiangsu	0.433	0.438	0.449	0.463	0.477	0.489	0.493	0.512	0.523	0.536	0.544	0.568	0.602
	Zhejiang	0.215	0.223	0.235	0.246	0.253	0.254	0.258	0.263	0.266	0.273	0.271	0.274	0.283
	Fujian	0.113	0.126	0.135	0.144	0.153	0.165	0.173	0.186	0.196	0.201	0.202	0.205	0.209
	Guangdong	0.312	0.321	0.325	0.335	0.345	0.359	0.372	0.389	0.404	0.411	0.425	0.436	0.456
Central	Shanxi	0.553	0.572	0.583	0.612	0.638	0.663	0.685	0.696	0.711	0.723	0.744	0.766	0.796
	Anhui	0.223	0.224	0.226	0.235	0.238	0.241	0.245	0.251	0.256	0.259	0.266	0.275	0.288
	Jiangxi	0.115	0.125	0.126	0.134	0.142	0.144	0.146	0.152	0.159	0.163	0.165	0.167	0.175
	Jilin	0.132	0.135	0.139	0.148	0.145	0.144	0.146	0.143	0.142	0.144	0.140	0.136	0.145
	Henan	0.412	0.418	0.423	0.435	0.454	0.477	0.489	0.496	0.490	0.488	0.486	0.483	0.462
	Hubei	0.211	0.213	0.214	0.216	0.220	0.223	0.218	0.219	0.221	0.223	0.227	0.230	0.231
	Heilongjiang	0.189	0.196	0.201	0.211	0.213	0.215	0.217	0.223	0.221	0.225	0.227	0.224	0.233
	Hunan	0.215	0.218	0.220	0.223	0.219	0.218	0.215	0.217	0.221	0.215	0.214	0.223	0.226
Western	Neimenggu	0.385	0.396	0.412	0.425	0.446	0.475	0.496	0.516	0.538	0.568	0.596	0.624	0.658
	Gansu	0.111	0.113	0.115	0.117	0.119	0.121	0.115	0.118	0.123	0.125	0.128	0.131	0.135
	Guangxi	0.128	0.129	0.135	0.144	0.148	0.153	0.166	0.175	0.179	0.188	0.196	0.203	0.215
	Chongqing	0.100	0.102	0.109	0.113	0.119	0.125	0.119	0.118	0.119	0.115	0.114	0.115	0.117
	Ningxia	0.096	0.112	0.116	0.126	0.135	0.138	0.142	0.155	0.158	0.162	0.169	0.173	0.189
	Sichuan	0.210	0.212	0.215	0.217	0.221	0.223	0.221	0.225	0.223	0.221	0.220	0.216	0.223
	Guizhou	0.158	0.163	0.162	0.162	0.164	0.167	0.169	0.172	0.179	0.173	0.174	0.173	0.177
	Yunnan	0.125	0.129	0.133	0.135	0.141	0.142	0.141	0.149	0.155	0.142	0.139	0.132	0.121
	Shanxi	0.211	0.213	0.221	0.223	0.225	0.236	0.238	0.239	0.245	0.247	0.253	0.255	0.267
	Qinghai	0.053	0.054	0.055	0.056	0.052	0.051	0.053	0.054	0.055	0.059	0.064	0.053	0.046
	Xinjiang	0.142	0.153	0.176	0.193	0.214	0.228	0.239	0.256	0.288	0.310	0.322	0.352	0.376

Table 7
Index system.

Level 1 indicators	Secondary indicators
Green credit	Total green credit/Total loans
	Total bank loans to environmental protection enterprises/Total loans to monetary institutions
Green securities	Total market capitalization of environmental protection companies/Total A-share market capitalization
	Total market capitalization of energy-consuming industries/Total A-share market capitalization
Green insurance	Agricultural insurance expenditure/Total insurance expenditure
	Agricultural insurance income/Gross agricultural output
Green investment	Total investment in environmental pollution control/GDP
	Financial environmental protection expenditures/Financial general budget expenditures
Carbon finance	Number of CDM projects

Table 8
Circular economy evaluation system.

Composite index	Primary indicator	Secondary indicator
Circular economy evaluation system	economic system	GDP per capita
		Tertiary sector as a percentage of GDP
		Industrial wastewater emissions
		Industrial waste gas emissions
		Energy output rate
	ecosystem	Centralized urban sewage treatment rate
		Greening coverage rate of built-up areas
		Harmless treatment rate of domestic garbage
		Green space per capita in urban parks
	social system	Share of employees in tertiary industry
		Urban registered unemployment rate
		Participation rate of residents' basic pension insurance
		Urban disposable income per capita
		Expenditure on social security and employment
		Science and technology investment as a share of GDP

sources for ecological and environmental construction. From the development of Guangdong Province, we can see that under rapid economic development, the use of advanced technology development and scientific management to achieve a mature economy of scale and thus reduce emissions, as well as moving the balance of funds from recycling to environmental governance helps to realize the three systems in an effective way. The degree in Inner Mongolia is the worst, and it is the only city in all of China with an average value lower than 0.4, maybe because of its economic development.

Third, from the type of coupling, during the period of 2011–2023, there was a "leaping" behavior in the type of coupling in some provinces, of which there were seventeen provinces with a leap from the medium to the high coupling stage, five provinces with a leap from the antagonistic to the medium and then to the high coupling stage, and six provinces remained in the high coupling stage after 2014. Combined with the

Table 9
Results of the coupling measurements.

	Region	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	Mean
Eastern	Beijing	0.764	0.777	0.789	0.849	0.855	0.864	0.903	0.916	0.936	0.977	0.981	0.985	0.992	0.883
	Tianjin	0.662	0.675	0.696	0.758	0.781	0.838	0.845	0.864	0.896	0.934	0.951	0.968	0.976	0.822
	Hebei	0.593	0.609	0.635	0.649	0.664	0.738	0.748	0.756	0.769	0.828	0.845	0.857	0.864	0.699
	Shanghai	0.772	0.788	0.849	0.857	0.879	0.898	0.915	0.922	0.931	0.968	0.971	0.985	0.998	0.895
	Liaoning	0.578	0.584	0.621	0.637	0.664	0.712	0.723	0.746	0.751	0.772	0.793	0.821	0.847	0.679
	Hainan	0.593	0.649	0.661	0.678	0.687	0.722	0.743	0.751	0.772	0.816	0.846	0.858	0.865	0.731
	Shandong	0.692	0.775	0.786	0.832	0.854	0.867	0.887	0.889	0.892	0.926	0.942	0.951	0.966	0.858
	Jiangsu	0.753	0.764	0.775	0.848	0.852	0.873	0.898	0.917	0.929	0.934	0.975	0.987	0.994	0.875
	Zhejiang	0.753	0.759	0.766	0.852	0.863	0.878	0.894	0.922	0.935	0.966	0.981	0.986	0.995	0.880
	Fujian	0.681	0.692	0.699	0.716	0.731	0.745	0.764	0.776	0.815	0.838	0.843	0.858	0.873	0.746
	Guangdong	0.858	0.877	0.886	0.894	0.947	0.958	0.975	0.987	0.983	0.991	0.993	0.994	0.997	0.945
Eastern mean		0.700	0.694	0.717	0.737	0.772	0.792	0.823	0.839	0.853	0.867	0.897	0.914	0.926	0.819
Central	Shanxi	0.344	0.351	0.353	0.366	0.421	0.447	0.522	0.652	0.731	0.752	0.768	0.751	0.789	0.519
	Anhui	0.521	0.534	0.543	0.621	0.653	0.662	0.771	0.812	0.824	0.838	0.851	0.875	0.894	0.694
	Jiangxi	0.437	0.442	0.456	0.522	0.544	0.561	0.595	0.624	0.658	0.725	0.776	0.827	0.859	0.576
	Jilin	0.358	0.362	0.391	0.456	0.453	0.496	0.613	0.636	0.762	0.777	0.798	0.826	0.844	0.555
	Henan	0.459	0.461	0.448	0.457	0.462	0.573	0.581	0.592	0.606	0.719	0.824	0.841	0.918	0.562
	Hubei	0.468	0.473	0.514	0.551	0.598	0.632	0.667	0.694	0.712	0.735	0.845	0.857	0.869	0.626
	Heilongjiang	0.341	0.353	0.376	0.427	0.444	0.457	0.465	0.482	0.518	0.535	0.559	0.568	0.589	0.451
	Hunan	0.469	0.486	0.524	0.597	0.647	0.687	0.744	0.763	0.776	0.797	0.813	0.832	0.851	0.664
Central mean		0.425	0.425	0.433	0.451	0.500	0.528	0.564	0.620	0.657	0.698	0.735	0.779	0.797	0.581
Western	Neimenggu	0.218	0.223	0.234	0.248	0.359	0.362	0.330	0.413	0.522	0.537	0.542	0.557	0.562	0.393
	Gansu	0.323	0.336	0.343	0.355	0.408	0.424	0.437	0.477	0.485	0.518	0.527	0.538	0.543	0.439
	Guangxi	0.347	0.345	0.367	0.403	0.411	0.421	0.456	0.513	0.521	0.535	0.548	0.553	0.566	0.460
	Chongqing	0.356	0.383	0.423	0.448	0.533	0.578	0.585	0.631	0.658	0.677	0.682	0.697	0.702	0.566
	Ningxia	0.311	0.324	0.332	0.411	0.425	0.437	0.442	0.451	0.515	0.529	0.521	0.534	0.541	0.444
	Sichuan	0.327	0.385	0.397	0.412	0.428	0.433	0.451	0.523	0.532	0.541	0.552	0.561	0.572	0.470
	Guizhou	0.235	0.333	0.355	0.367	0.412	0.426	0.432	0.424	0.511	0.565	0.594	0.615	0.624	0.453
	Yunnan	0.327	0.336	0.363	0.435	0.447	0.458	0.467	0.469	0.474	0.487	0.494	0.517	0.524	0.446
	Shanxi	0.332	0.343	0.352	0.368	0.423	0.434	0.441	0.448	0.532	0.565	0.594	0.625	0.633	0.468
	Qinghai	0.328	0.338	0.347	0.354	0.416	0.427	0.432	0.471	0.505	0.519	0.523	0.539	0.543	0.442
	Xinjiang	0.346	0.358	0.413	0.426	0.437	0.443	0.452	0.456	0.479	0.521	0.530	0.541	0.555	0.458
Western mean		0.321	0.347	0.364	0.395	0.434	0.449	0.460	0.490	0.526	0.548	0.559	0.575	0.583	0.465
National mean		0.482	0.488	0.505	0.528	0.568	0.590	0.616	0.649	0.679	0.705	0.730	0.756	0.769	0.620

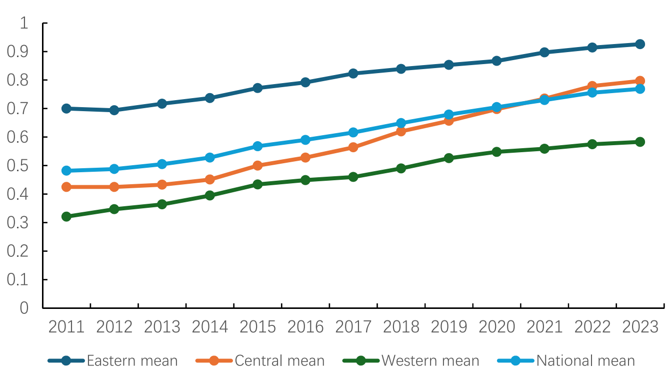

Fig. 2. Average coupling of the three major regions and the nation from 2011 to 2023.

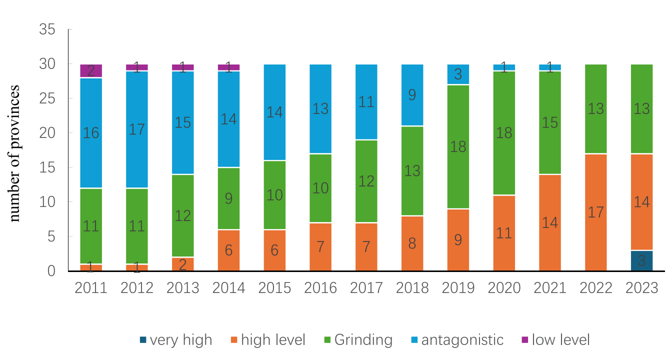

Fig. 3. Time evolution trend of the coupling type from 2011 to 2023.

regional trend shown in Fig. 3, the coupling degree into the high coupling stage shows an upward trend, which shows that the strong and weak promoting roles of the three subsystems are relatively high, and there is a high correlation between the three systems with good integrity, which means that there are mutual constraints and promotion between the three systems.

4.1.1. *Analysis of the coupling coordination degree*

This paper studies the future direction of the development of three systems and to fully reflect the strength of the mutual constraints and interactions among them. The development index, as well as the coupling degree were measured; the results and trend of the degree as Table 10, Figs. 4 and Fig. 5a.

Coupling coordination degree in 2011–2023 rising from 0.424 (2011) to 0.571 (2023), with a change of 0.347 %. The growth rate increased year by year and was consistent with the coupling degree, but based on the provinces, cities, and regions with large differences and strong characteristics, the degree showed significant regional differences. By drawing the corresponding subregional maps according to the coupling coordination degree intervals, we can see that ten regions had a value between 0.3 and 0.4, three regions were in the range of 0.4–0.5 on the verge of dysfunctional decline, four regions were in the range of 0.5–0.6 with barely coordinated development, four regions in the range of 0.6–0.7 with primary coordinated development, three regions were in the intermediate harmonized development interval of 0.7–0.8, five regions were in the 0.8–0.9 good harmonized interval, and one region was in the high quality harmonized interval of more than 0.9. Most of the regions in the coordinated development range were concentrated in the eastern. The degree shows the characteristics of subregional changes. Therefore, this paper analyzed and evaluated the degree by taking the average value of the eastern, central, and western regions based on the national geographic regions and the division of local provinces and

Table 10
Coupling coordination measurement results.

	Region	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	Mean
Eastern	Beijing	0.724	0.727	0.754	0.773	0.785	0.847	0.854	0.863	0.905	0.915	0.935	0.973	0.985	0.849
	Liaoning	0.511	0.524	0.548	0.588	0.623	0.634	0.667	0.716	0.723	0.748	0.757	0.778	0.794	0.662
	Tianjin	0.622	0.635	0.642	0.674	0.696	0.756	0.782	0.834	0.846	0.866	0.897	0.935	0.954	0.780
	Hebei	0.513	0.549	0.563	0.607	0.637	0.644	0.665	0.735	0.744	0.757	0.763	0.827	0.846	0.681
	Fujian	0.641	0.652	0.671	0.694	0.695	0.714	0.736	0.746	0.767	0.774	0.813	0.833	0.848	0.737
	Shanghai	0.712	0.738	0.752	0.785	0.846	0.853	0.874	0.893	0.912	0.924	0.938	0.964	0.973	0.859
	Zhejiang	0.716	0.729	0.743	0.758	0.769	0.855	0.862	0.872	0.896	0.926	0.933	0.962	0.985	0.847
	Jiangsu	0.713	0.724	0.748	0.768	0.778	0.847	0.853	0.874	0.893	0.918	0.926	0.933	0.977	0.842
	Shandong	0.687	0.755	0.682	0.773	0.783	0.825	0.853	0.867	0.882	0.888	0.896	0.926	0.947	0.828
	Guangdong	0.808	0.827	0.848	0.873	0.882	0.898	0.942	0.956	0.972	0.989	0.987	0.991	0.998	0.921
	Hainan	0.583	0.598	0.623	0.648	0.664	0.678	0.688	0.724	0.745	0.753	0.778	0.816	0.846	0.703
Eastern mean		0.657	0.678	0.689	0.722	0.742	0.777	0.798	0.825	0.844	0.860	0.875	0.903	0.923	0.792
Central	Shanxi	0.244	0.256	0.342	0.355	0.356	0.367	0.428	0.449	0.524	0.653	0.734	0.755	0.763	0.479
	Jiangxi	0.304	0.321	0.435	0.445	0.454	0.525	0.547	0.567	0.594	0.624	0.652	0.723	0.766	0.535
	Jilin	0.248	0.265	0.353	0.365	0.396	0.457	0.459	0.499	0.612	0.633	0.766	0.776	0.794	0.510
	Heilongjiang	0.267	0.278	0.343	0.354	0.377	0.423	0.445	0.452	0.466	0.487	0.513	0.536	0.553	0.423
	Anhui	0.476	0.482	0.524	0.535	0.547	0.628	0.659	0.669	0.774	0.815	0.822	0.836	0.854	0.663
	Henan	0.368	0.399	0.454	0.465	0.445	0.453	0.467	0.578	0.584	0.599	0.608	0.718	0.823	0.535
	Hubei	0.411	0.428	0.463	0.476	0.517	0.553	0.594	0.637	0.666	0.695	0.715	0.738	0.848	0.595
	Hunan	0.418	0.435	0.464	0.485	0.527	0.597	0.642	0.684	0.749	0.766	0.774	0.794	0.813	0.627
Central mean		0.342	0.358	0.422	0.435	0.452	0.500	0.530	0.567	0.621	0.659	0.698	0.735	0.777	0.546
Western	Neimenggu	0.211	0.216	0.224	0.236	0.247	0.354	0.361	0.365	0.413	0.522	0.534	0.546	0.558	0.289
	Gansu	0.274	0.324	0.338	0.344	0.355	0.404	0.424	0.433	0.476	0.485	0.514	0.529	0.536	0.364
	Guangxi	0.289	0.344	0.346	0.368	0.404	0.415	0.425	0.455	0.513	0.526	0.537	0.544	0.557	0.386
	Qinghai	0.283	0.327	0.337	0.346	0.355	0.415	0.425	0.434	0.472	0.503	0.518	0.525	0.539	0.370
	Chongqing	0.324	0.357	0.382	0.426	0.447	0.536	0.576	0.586	0.633	0.658	0.673	0.685	0.696	0.457
	Sichuan	0.282	0.326	0.384	0.394	0.415	0.426	0.434	0.452	0.493	0.538	0.549	0.557	0.569	0.395
	Ningxia	0.275	0.317	0.325	0.334	0.417	0.423	0.436	0.447	0.453	0.465	0.509	0.523	0.536	0.368
	Guizhou	0.219	0.238	0.335	0.356	0.364	0.413	0.427	0.433	0.446	0.515	0.562	0.592	0.613	0.349
	Yunnan	0.254	0.329	0.337	0.362	0.428	0.436	0.449	0.454	0.465	0.475	0.483	0.496	0.518	0.371
	Shanxi	0.277	0.333	0.344	0.353	0.363	0.427	0.436	0.442	0.456	0.512	0.565	0.593	0.622	0.373
	Xinjiang	0.319	0.345	0.357	0.413	0.426	0.433	0.442	0.452	0.457	0.479	0.521	0.525	0.543	0.393
Western mean		0.273	0.314	0.337	0.357	0.384	0.426	0.440	0.450	0.480	0.516	0.542	0.556	0.572	0.374
National mean		0.424	0.450	0.483	0.505	0.526	0.568	0.589	0.614	0.648	0.678	0.705	0.731	0.757	0.571

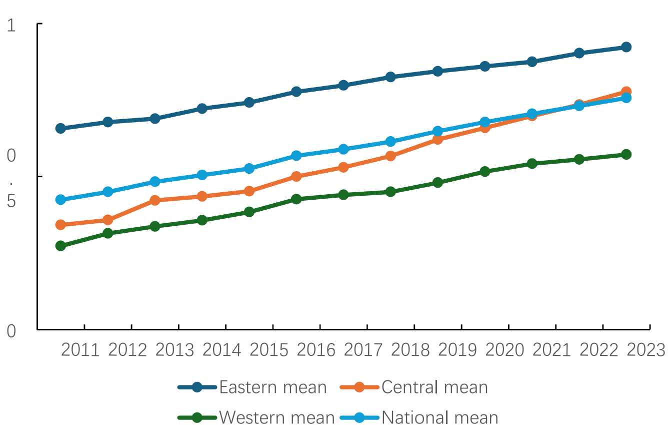

Fig. 4. Average coupling harmonization for the three regions and the nation, 2011–2023.

cities. By plotting the line graphs of the degree, there are indeed differences. The degree is ranked in the order of the eastern, central, and western regions. The eastern part of the country is mostly a coastal area with superior natural conditions and is often a pilot area for financial development and national reform policies, with stronger financial strength, more advanced technology, more advanced governance and protection of the environment, and an industrial structure that is mainly based on primary processing or hi-tech industries, with stricter management and control of carbon emissions. With relatively low carbon emissions and high efficiency, ecological construction has improved. The central and western regions are mostly inland with relatively remote locations, complex geographical conditions, relatively poor transportation and other infrastructure and public facilities, less green space and vegetation, high frequency of severe weather and geological disasters, and weaker natural ecological systems, and they lag behind in financial development compared to the eastern coastal cities. Due to the special geographical location, the central and western regions are rich in minerals and fossil energy, which naturally leads to the development of local mining and processing of ores and energy, and the economic and industrial structure is more inclined to heavy industry, which results in the indiscriminate exploitation of natural resources without restraint, irreparably harming the environment. The rapid economic growth inevitably causes the rapid depletion of energy, massive generation of waste, serious pollution of the atmosphere, land, and water, and so on. Heavy industry, which seems to develop faster, tends to have higher carbon emissions but lower carbon productivity. The overall carbon emission efficiency is low, which leads to a serious imbalance in the ecological environment. Differences between innate endowments and acquired development conditions have led to obvious regional differences.

Thirdly, the value in 2011–2013 was located in the interval [0.4,0.5); in 2014–2017, [0.5,0.6); in 2018–2020, [0.6,0.7); and in 2021–2023, [0.7,0.8). The degree can be divided into four stages: near-disorder (2011–2013), barely coordinated (2014–2017), primary coordination (2018–2020), and intermediate coordination (2021–2023). The degree from near-disorder to the very low coordination stage had a long-time span of 7 years, mainly due to the damage to the ecological environment; hence, the environmental restoration capacity was weak, with slow and poor restoration, so the three systems remained in the dysfunctional stage for a long time. With the improvement in China's environment, financial development, legal, socio-economic, and political ecosystems, the systems began to move from dysfunction to coordination. After only three years, the barely coordinated stage was transformed into an intermediate coordinated stage, and the degree of coupling coordination growth was not small in relative terms, mainly because of green bond market, which pushed forward green financial market development. At this stage, although the three systems were still in the barely coordinated stage, their degree of primary coordination reached 0.571, and they will soon move into the high end of primary coordination.

4.2. Forecast of the coupling coordination degree

Through the grey prediction model, the degree in each region from 2011 to 2023 was selected as the model training data, the trend from 2024 to 2028 was predicted and analyzed, and results as Table 11 and Fig. 5b.

During the period 2024–2028, the national coupling coordination level will continue its steady upward trend, with a value of 0.721 in 2028, entering the intermediate coupling coordination stage. In different regions, the basic trend in the east, center, and west is basically the same as national, with the value in the east reaching 0.921 in 2028; the central region will develop at a lower rate than the east, with 0.689 by 2025; the western region will be developing at a higher rate than the east and central regions, with 0.505 by 2025. Overall, the coupling coordination in all regions will maintain a steady upward trend, but the speed and level of increase still needs improvement; hence, it is necessary to formulate strong policy guidance to promote the regions to reach the stage of high-quality coupling and coordinated.

4.3. Discussion

Through empirical analysis we find that firstly, the coupling degree and coordination degree of the three systems show an upward trend, which is similar to the conclusions of some scholars' studies, for example, Zhang et al. (2022) concluded that the coupling degree of the circular economy and green finance shows an upward trend based on the region of Guangdong Province. Zhang et al. (2024), Zhu et al. (2019) and Jiang (2021) analyze from the coastal region, Guizhou Province, and Guangdong Province, and other regions, also found that they also show an upward trend; Wang et al. (2022) based on the Beijing-Tianjin-Hebei region, and also reached a similar conclusion. From the results of the above scholars can be seen that most scholars based on two-dimensional system to analyze, have not yet found scholars to analyze the three-dimensional system, and have not found the coupling and coordination of carbon emissions and circular economy research, and all of them are analyzed by specific regions, only a few scholars from the perspective of different regions, and to analyze the differences between different regions, for example Liu et al. (2024) and Liu and Chen (2023) explore the differences between different regions, but also based on two-dimensional system; can be seen in this paper from the three-dimensional system to start the analysis is an innovation of the existing research, can enrich the theoretical research in this field; in addition, from the practical point of view, China's regions have different advantages in resources, there are differences in the mode of development, so that the degree of coordinated development of them in each region varies greatly, there is a big difference in the degree of coordinated development, and there is a big obstacle for the government to implement policies according to the region. Therefore, the government needs to understand differences of each region and the linkage of coordinated development among regions when planning for the development of each region and implementing policies according to the local conditions. This study provides a reference for emission reduction policies, and puts forward targeted recommendations, which are important to support the implementation of differentiated emission reduction efforts in the region.

Table 11
Coupling coordination degree prediction results.

	2024	2025	2026	2027	2028
National	0.576	0.652	0.678	0.701	0.721
East	0.816	0.853	0.877	0.898	0.921
Central	0.577	0.603	0.623	0.652	0.689
West	0.401	0.423	0.442	0.478	0.505

5. Conclusions and recommendations

5.1. Conclusion

(1) The coupling degree of systems from 2011 to 2023 rose; however, the overall rise was small, and the degree in the eastern region was higher than other regions, mainly because of the large difference in regional development. For the economies of the developed regions, the green finance and ecological environment appeared at the front-end, and the less-developed regions lacked green finance, industries, and so on, which gradually widened the gap with the developed regions, limiting the coupled development of the system. The coupling degree of 14 provinces was higher than the national level, with Guangdong being the highest and Inner Mongolia the lowest. During the period of 2011–2023, there was a "leaping" behavior in the type of coupling in some provinces, among which there were seventeen provinces with a leap from the medium to the high coupling stage, five provinces with a leap from the antagonism to the medium and then to the high coupling stage, and six provinces remained in the high coupling stage after 2014.

(2) The coupling coordination degree showed an upward trend from 2011 to 2023. The degree of coupling coordination increased year by year and was more consistent with the coupling degree. Most of regions in the coordinated development range were concentrated in the eastern coastal region, and those with a lower degree were located in the central and western inland areas. From the type of coupling degree of coordination, there were four phases: on the verge of dislocation (2011–2013), barely coordinated (2014–2017), primary coordination (2018–2020), and intermediate coordination (2021–2023). In terms of phases, the development of coordination had a longer time span from the near-disorder to the very low coordination stage, at seven years, while the barely coordinated stage was transformed into the intermediate coordination stage after only three years.

(3) From the forecast results, the national coupling coordination level will continue to rise from 2024 to 2028, entering the intermediate coupling coordination stage in 2028. Distinguishing between different regions, the trend in the east, center, and west is basically the same as the national, with the value in the east reaching 0.921 in 2028; the central reaching 0.689 by 2028; and the western region reaching 0.505 in 2028.

5.2. Recommendations

From a global perspective, the role of technology in the development of the circular economy should be continuously utilized. By vigorously promoting and applying new technologies, the efficiency of regions lagging behind in circular economy due to technological backwardness should be driven up. In order to enhance the efficiency of the circular economy in a sustained and powerful manner, the circular economy should be driven by improving the corresponding circular economy system, enhancing the relevant management level and realizing scale effectiveness through the enhancement of technological efficiency.

We recommend strong support for technological innovation and energy consumption structures. For technological innovation, we should not only increase the investment in independent innovation but also actively introduce foreign advanced technology to complement our strengths. For foreign products with a higher technological level, it is necessary for our government to incentivize our enterprises to develop and learn their advanced technology by means of tax exemption and

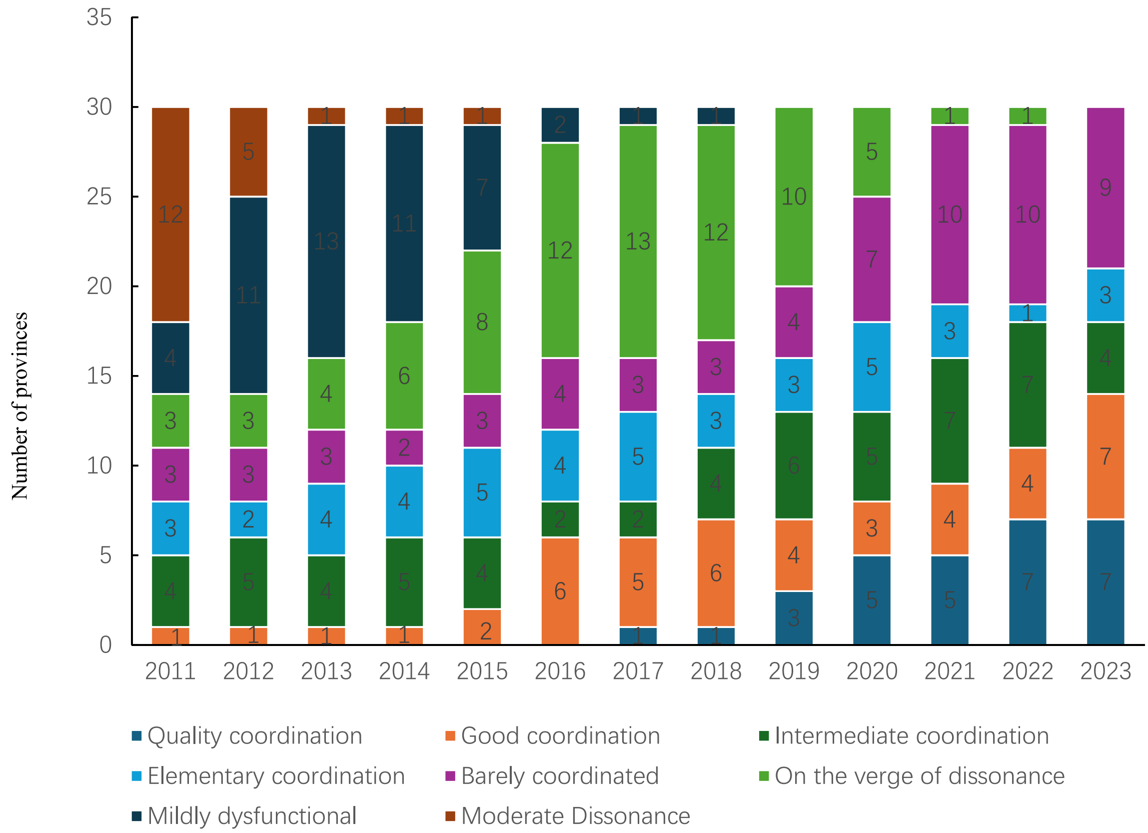

Fig. 5a. Time evolution trend.

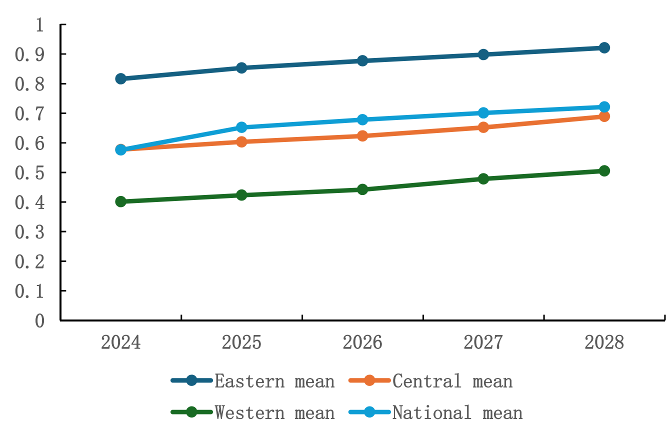

Fig. 5b. Trends in coupling harmonization by region, 2024–2028.

interest reduction, in addition to developing an advanced technology management system. In a good technological innovation environment, there will be a steady stream of advanced technology development, in order to better implement advanced technology in the production chain. For the industrial structure, the government should optimize the industrial structure, so that there is support for green finance for green development. For the energy consumption structure, China should strongly support photovoltaic, hydrogen energy, wind energy development, reduce the dependence on coal and oil resources, and optimize the energy structure. For carbon emissions, China can promote carbon curing, carbon recycling and other high-tech areas, to achieve carbon neutrality goal.

China should foster the convergence of green finance and the circular economy. This holds immense potential for growth, benefiting economic sustainability and environmental protection and social responsibility initiatives. Currently, green finance development in many Chinese provinces has not achieved optimal levels, which signifies substantial room for enhancement. It presents a valuable chance to further propel green finance's development through strategic policy guidance, market mechanisms, innovation-driven approaches, and deeper integration efforts. This will expedite the circular economy's transformation and improvement. By reinforcing this connection, we can achieve a seamless fusion of financial capital with the environmental protection sector, catalyzing the swift growth of the circular economy.

Continuously study and improve policies on green development. Further refine and improve laws and regulations. Ensure that there is a clear legal basis for implementation of policies, improve the authority and enforcement of policies, and impose strict penalties for violations of policies. Through education and training, raise the awareness and understanding of government personnel, entrepreneurs, researchers and the public of green low-carbon and recycling development. Form a benign interactive mechanism of policy guidance, market operation and social supervision to strengthen the benign interaction of green finance and circular economy.

China should combine each region's own characteristics and formulate differentiated carbon emission reduction strategies. Taking into account the differences in the economic foundation, natural resources, geographical location, and other conditions between regions and closely combining these with the actual development situation of the region, we can implement locally adapted circular economy development programs, accurately positioning circular economy development policy implementation and maximizing the synergistic impact of regional circular economy development.

5.3. Shortcomings and prospects

(1) By measuring the efficiency of circular economy, the level of geospatial difference can be screened, which points out the

direction for circular economy. However, the efficiency will be affected by many factors, including the development foundation, development mode, technology type, economic environment, etc., and the degree of its role in this paper does not give a clear position, and in the different stages of circular economy and different spatial resource constraints, how to adjust the influencing factors to improve circular economy in cities is an important content for further discussion in the future. is an important element for further discussion in the future.

(2) Carbon emissions and circular economy may have significant spatial spillover effects, this paper analyzes only spatial differences and does not explore spatial spillovers, future research can be based on the spatial measurement model to further expand the research.

(3) This study mainly analyzes the corresponding analysis from the time dimension, and lacks the spatial dimension; at the same time, due to the unavailability of microdata, the study is only carried out at the provincial level, and there is no basic data and corresponding analysis from the municipal, county and other microlevels, which is of limited reference value to counties and cities. The next step of the study is to conduct research at the municipal and county levels, and to conduct long-term and continuous tracking between the three more comprehensively, with a view to putting forward more targeted suggestions and countermeasures for circular economy.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was funded by Jiangsu Education Department, China (Ref. No. 2022SJYB2270).

Data availability

Data will be made available on request.

References

Abbasi, S., Choukolaei, H., 2023. A systematic review of green supply chain network design literature focusing on carbon policy. Decision Analytics Journal 6, 100189.
Abbasi, S., Mazaheri, S., Talaie, H.R., Ghasemi, P., 2024. Designing green logistics networks under carbon tax policy: post-COVID condition. Results Eng. 23, 102830.
Abbasi, S., Rokhva, S., Farahmand, K., Ghasemi, P., Shahab, E., 2025. Designing sustainable closed-loop supply chain network based on a circular economy approach: under uncertainty during the Post-COVID era. Circ. Econ. Sustain. 5 (3), 2229–2271.
Agarwal, S., Tyagi, M., Garg, R.K., 2022. Framework development and evaluation of industry 4.0 technological aspects towards improving the circular economy-based supply chain. Ind. Robot 3, 555–581.
Anwar, H., Waheed, R., Aziz, G., 2024. Importance of FinTech and green finance to achieve the carbon neutrality targets: a study of Australian perspective. Environ. Res. Commun. 6 (11), 115007.
Baidas, S., 2024. Carbon capture technologies in OAPEC member countries and the circular carbon economy: a roadmap to zero emissions by 2050. Open J. Energy Effic. 13 (2), 25–37.
Dang, B., 2025. Coupling and coordinating relationship between land use carbon emission efficiency and new urbanization in Huaihe River ecological economic zone. Value Eng. 44 (7), 74–77.
Ferraro, G., Brans, M., 2012. Trade-offs between environmental protection and economic development in China's fisheries policy: a political analysis on the adoption and implementation of the Fisheries Law 2000. Nat. Resour. Forum 36 (1), 38–49.
Fu, D.P., Su, J., 2022. Impact of national circular economy demonstration zone policy on carbon emission reduction. Statistics and Decision Making. 38 (22), 180–183.
Godfrey, P.C., 2005. The relationship between corporate philanthropy and shareholder wealth: a risk management perspective. Acad. Manag. Rev. 30 (4), 777–798.
Huang, Y.B., Dong, L.C., Fang, T., 2015. Evaluation study on the development of circular economy in counties of ecologically fragile poverty-stricken areas–Taking Dingxi City as an example. Research on Agricultural Modernization 36 (6), 927–933.
Jalil, A., Feridun, M., 2011. The impact of growth, energy and financial development on the environment in China: a cointegration analysis. Energy Econ. 33 (2), 284–291.
Jamali, R., Bughio, A., Tunio, R.A., 2023. Mitigating the economic impact of COVID-19 on wind energy: assessing the role of green finance policies and the levelized cost of energy. Environ. Sci. Pollut. Res. Int. 30, 92662–92673.
Jia, X.M., Jian, Y.M., 2025. Measurement and obstacle factors of the coupling coordination of digitalization and greening in logistics industry. China Price 2, 51–57.
Jiang, H.L., Wang, W.D., Wang, L., Wu, J.H., 2020. Research on the carbon emission reduction effect of China's green financial development–Taking green credit and green venture capital as an example. Financial Forum 25 (11), 39–48.
Jiang, X.Q., 2021. Research on the coupled and coordinated development of circular economy and green finance in Guangdong Province. Financial Economy 3, 29–37.
Kang, X.H., Zhao, L.J., Hong, H., 2022. Analysis of the coupled and coordinated development of green investment and circular economy–Taking Inner Mongolia as an example. Friends of Accounting 2, 70–75.
Li, J.K., Wang, F.H., 2017. Measurement of low-carbon potential of coal circular economy based on carbon emission factor. Ecol. Econ. 3, 76–80.
Li, M., Wang, L., 2022. Research on the coupling and coordinated development of circular economy and green finance in beijing-tianjin-hebei region. Journal of Industrial Technological Economics 41 (5), 72–77.
Liu, J.Y., Wang, M.Y., Li, WeT., Gao, W.B., 2024. Research on the spatio-temporal coupling and influencing factors of green finance and carbon emission efficiency. Zhejiang Finance 10, 43–54.
Liu, L., Chen, Z., 2023. Coupling and coordination analysis of agricultural carbon emission efficiency and green finance development level. Journal of Fuyang Normal University: Natural Science Edition 40 (2), 87–98.
Liu, X., Cao, W., Lu, Y.S., 2023. Research on the impact of circular economy on carbon emission reduction under spatial perspective. Research on Coal Economy 43 (8), 66–74.
Lee, C.C., Du, L., 2024. Can green finance improve eco-efficiency? New Insights from China. Environ. Sci. Pollut. Res. 31 (28), 40976–40994.
Lv, W.H., Gao, Z.G., 2014. Evaluation of circular economy development level and efficiency analysis between Xinjiang and national provinces and regions. Arid Zone Resources and Environment 2, 37–43.
Mathews, J.A., Tan, H., 2016. Circular economy: lessons from China. Nature 531 (7595), 440–442.
Moustakas, K., Loizidou, M., 2023. Effective waste management with emphasis on circular economy. Environ. Sci. Pollut. Res. Int. 30 (4), 8540–8547.
Pereira, M.M., Montao, M., 2024. The integration of circular economy and impact assessment: a bibliometric analysis. J. Environ. Sci. Eng. 13 (4), 136–150.
Rees, W.E., 2003. Economic development and environmental protection: an ecological economics perspective. Environ. Monit. Assess. 86 (1/2), 29–45.
Sgroi, F., 2022. Circular economy and environmental protection. aims environmental science 9 (2), 106–111.
Shahbaz, M., Mahalik, M.K., Shah, S.H., 2016. Time-varying analysis of CO2 emissions, energy consumption, and economic growth nexus: statistical experience in next 11 countries. Energy Policy 98, 33–48.
Sun, C., Weng, S.W., Du, S.Z., 2025. Current situation and outlook of the development of ship digital intelligence under the background of "double carbon". Ship Materials and Markets 33 (2), 14–18.
Su, D.W., Lian, L.L., 2018. Does green credit affect the investment and financing behavior of heavily polluting enterprises? Financial Research 12, 123–137.
Wang, D., Song, C., Zhang, X.Y., 2022. Research on the coupling degree of green finance development level and agricultural carbon emission efficiency in beijing-tianjin-hebei region. Journal of Agricultural Big Data 4 (3), 116–125.
Wang, J., Zhou, W., Yang, Y.Q., 2025. Analysis of safety early warning evaluation of Erhe lock based on gray model (GM) prediction and logistic regression model. Jiangsu Water Resources 1, 14–20.
Wang, Q.Q., Zhao, S.N., 2025. Study on the spatial and temporal coupling and coordination of carbon emission-technological innovation-green development in the Yangtze River economic zone. Yangtze River Basin Resources and Environment 3, 494–506.
Wei, W.D., Chen, Z.J., Geng, Y., 2021. Paths and countermeasures suggestions for promoting carbon neutrality through circular economy. Proceedings of the Chinese Academy of Sciences 36 (9), 1030–1038.
Xu, M.C., Liu, H., 2024. Development of circular economy to help equipment manufacturing industry carbon peak carbon neutral path analysis. Finance and Economics Monthly 45 (12), 125–129.
Yan, X.F., 2022. Research on the action mechanism of circular economy development and green finance based on entropy method and big data. J. Enterprise Inf. Manag. 35 (4), 988–1010.
Yang, H.F., Zhang, H.L., 2005. On the construction of evaluation index system of circular economy. Science and Science and Technology Management 26 (9), 123–128.
Zhang, F., Lu, J.F., Wen, Y.J., 2022. Analysis of coupled and coordinated development of circular economy and green finance based on Guangdong Province. Knowledge Economy 36, 38–40.
Zhang, T., Zhang, C., Wang, Q., 2024. Research on sustainable land use in alpine Meadow Region based on coupled coordination degree model—from production–living–ecology perspective. Sustainability 216 (12), 1–12.

Zhang, X.C., 2025. Cold chain logistics demand forecast of fresh agricultural products in Guangdong Province based on gray GM(1,1) model. Modern Agricultural Science and Technolog 1, 154–157.
Zhang, Y.G., Dou, R.Y., Bai, Y.J., 2020. Measurement of the construction level of China's green, low-carbon and recycling development economic system. Research on Quantitative Economics and Technical Economics 37 (8), 83–102.
Zhu, J.H., Wang, H.J., Zheng, P., 2019. Research on the coupled and coordinated development of circular economy and green finance in Guizhou Province. Econ. Geogr. 39 (12), 119–128.