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Greening the marine map: a comprehensive study of China's marine ecological and economic synergy

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Introduction: This research examines the coupling coordinated development dynamics between marine ecological governance and marine economic development in China's coastal provinces. The marine ecological governance and economic development data of China's 11 coastal provinces were comprehensively analyzed from 2011 to 2021.

Methods: We established a multi-dimensional evaluation index system for marine ecological governance and economic development, employing the global entropy weight method for quantification. Furthermore, the research examines and analyzes the trends in coordinated development and divergence between these two systems by constructing a coupled coordination degree (CCD) model, utilizing the Theil index decomposition method, and employing the geodetector detector.

Results: The Northern marine economic circle outperforms the Eastern and Southern ones regarding marine ecological governance, while the Eastern marine economic circle is the most advanced in marine economic development. The results of the CCD model indicate that Guangdong, Shandong, Hebei, and Jiangsu have the best coupling coordinated development, while Hainan, Tianjin, and Guangxi are at the bottom. The results of the Theil index decomposition method indicate that intra-regional disparities are the primary cause of coupling coordinated regional development variations. At the same time, the results of the geographic detector further substantiate that energy structure, degree of industrial agglomeration, and foreign overseas direct investment are the principal influencing factors.

Discussion: The study presents policy recommendations derived from the findings intended to foster the integrated advancement of marine ecology and economy in coastal provinces, reduce regional development disparities, and establish a scientific foundation for achieving a sustainable marine economy.

KEYWORDS

marine ecological governance, marine economy development, China's coastal provinces, coupling coordination degree model, geographic detector

1 Introduction

In the context of economic globalization, the Chinese government has been vigorously advancing the rapid growth of the marine economy, achieving significant advances in critical sectors such as fisheries, marine energy development, and maritime transportation (Ding et al., 2021; Yang et al., 2019; Lau et al., 2024; Sirimanne et al., 2019). This strategy's execution seeks to augment the nation's marine economic might and bolster its international influence. As to the 2024 statistics, China's Gross Marine Product (GMP) has maintained a robust yearly growth rate of 5.6% (World Bank Group, 2024).

The rapid growth of the marine economy has presented significant problems to ecological governance, particularly with the environmental restoration and management of coastal regions (Liu and Ma, 2024). Consequently, the Chinese government revised the "Marine Environmental Protection Law" in 2023 to safeguard marine ecosystems and create a more robust ecological and environmental governance framework in marine regions (Gao, 2023). In 2024, The State Council's "White Paper on Marine Ecological Environmental Protection in China" further underscores China's commitment as a staunch advocate and proactive participant in marine ecological preservation, accentuating the strategic significance of sustaining a robust marine ecological environment in achieving the vision of a "Beautiful China" and establishing a formidable maritime nation (SCIO, 2024).

Consequently, as domestic maritime economic activities expand, ecological governance and economic development interplay has become more intricate (Khan and Chang, 2020). In this context, it is essential to thoroughly examine the existing situation and the coordination framework between marine ecological governance and economic development in China's coastal provinces. This is crucial for the scientific development of marine management policies, the enhancement of marine environmental protection measures, and the successful advancement of sustainable marine economic models (Chang and Shi, 2020).

The coastal provinces of China exhibit significant physical and economic variety, and they are organized into three major maritime economic zones from north to south. This variety offers a distinct viewpoint for examining the synergistic interaction between marine ecological governance and economic growth. These provinces not only physically include China's main maritime areas but also represent a significant share of China's marine economy, making their developmental state essential for comprehending China's marine economic trends. Furthermore, these provinces have implemented varying policies and laws on maritime ecological governance and economic growth, creating a valuable opportunity for comparative analysis.

The remainder of this research is organized as follows: The second section presents a comprehensive review of the relevant literature, highlighting the essential findings and debates in the field of marine ecological governance and economic development. The third section describes the materials and methods used in this research, including the study area, establishing a comprehensive evaluation indicator system, and the methodologies applied for data analysis. Section four details the results of our analysis, discussing the measurement results from the global entropy method, the CCD model, the Theil index decomposition method, and the geographic detector. The fifth section provides a comprehensive conclusion of the findings and policy recommendations to foster the integrated advancement of marine ecology and economy in China's coastal provinces.

2 Literature review

Previous researchers analyzed the ideas of ecosystems and economic systems from a multidimensional viewpoint, comprehensively delineating their borders and purposes (Sandhu, 2017; Cao and Shi, 2021; O'Higgins et al., 2020; Chang et al., 2014). These research enhance comprehension of the successful integration of ecosystems into economic development objectives while safeguarding ecological sustainability in the pursuit of economic goals. Moreover, additional researches have evaluated the trade-offs inherent in ecosystem governance by correlating ecological factors with economic considerations (Chenavaz et al., 2024; Wang et al., 2021; Qiu et al., 2021). This approach underscores the significance of comprehending the effects of human activities on ecosystem services and their subsequent influence on human well-being.

Academicians have implemented numerous quantitative assessment methodologies to evaluate the marine ecosystem and economic system. For example, Sun et al. employed an energy analysis method to assess the value of marine ecosystem services in the coastal regions of China (Sun et al., 2018a). Addamo et al. examined the importance of employing a standardized assessment methodology to map and evaluate marine ecosystems in European waters using spatially explicit data (Addamo et al., 2024). Ji et al. implemented the entropy-weight-TOPSIS methodology to assess and quantify the extent of marine economy development in coastal regions (Ji et al., 2024). The fuzzy set qualitative comparative analysis (fsQCA) method was employed by Liu and Huang to establish the marine economic resilience of 11 provinces in China's coastal regions. The empirical foundation for sustainable development strategies in the marine ecological and economic systems is established by applying these innovative assessment tools and methods (Liu and Huang, 2024).

Existing research underscores various countries' diverse strategies to pursue coordinated development between marine ecosystems and economic systems. China's marine management efforts date back to the enactment of the "Marine Environmental Protection Law" in 1982, which initiated the formation of China's marine policy framework. With the advancement of legislation for a "Basic Law of the Sea," China has innovated its marine policy system, aiming to foster the development of the marine economy while providing significant policy support for establishing Marine Ecological Security Shelters (MESS). This reflects China's dual objectives of pursuing economic growth and emphasizing marine ecological protection and sustainability (Fang et al., 2024). Integrated Ocean Management (IOM) has been fully implemented in Norway, with a marine spatial management strategy encompassing various local and international management practices. Norway's marine management includes local marine management, cross-regional departmental

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coordination, management at the scale of regional seas or ocean basins, and international cooperation in large marine areas beyond national jurisdiction. This integrated approach to managing different marine economic sectors and spatial scales has effectively facilitated the coordinated development of marine ecology and economy (Winther et al., 2020). Seychelles incorporates climate change adaptability at the core of its marine spatial planning to support its economic and environmental objectives. Seychelles' marine spatial planning initiative aims to address climate change, protect 30% of its waters, and support the blue economy roadmap and other national strategies. This demonstrates Seychelles' high regard for marine ecological protection and climate change adaptability while promoting marine economic development (Kılıç, 2024). The practices of these countries not only showcase their unique strategies in marine management but also collectively reflect the global emphasis on sustainable marine management. Through these diverse approaches, nations strive to achieve integrated marine resource management and collectively address global challenges such as climate change, biodiversity loss, and marine pollution.

Even though previous research has investigated the coordinated relationship between marine ecological governance and economic development from various perspectives and proposed various assessment methods and models that offer valuable insights into the intricate interactions between the economy and marine ecology, they still need to be improved in certain respects. Initially, most existing research was limited to specific regions or shorter periods, and there was a paucity of comprehensive and long-term data analysis of China's coastal provinces. More critically, While integrating marine ecological governance with economic development has been a focal point in the environmental literature, applying advanced quantitative methods like the Coupled Coordination Degree (CCD) model and Theil index within the specific context of China's coastal provinces remains relatively uncharted. Additionally, previous studies have laid the groundwork for understanding the dynamics between marine ecosystems and economic systems, primarily focusing on ecological sustainability or economic growth in isolation. However, the synergistic application of the CCD model and Theil index to assess and quantify the intricate interplay between marine ecological governance and economic development offers a novel perspective. This approach allows for a more nuanced understanding of the coupling coordination degree and the underlying disparities driving regional development variations, which has been a significant gap in the current literature. By employing these methodologies, our study comprehensively assesses the coastal provinces' performance over a decade. It identifies critical regional disparities and driving factors, thus advancing the field by offering a more holistic and nuanced framework for policy formulation and regional development strategies.

As a result, the purpose of this research is to rectify the deficiencies in existing research by conducting a thorough examination of panel data. The research will examine the current state of coordinated development, trends, regional distinctions, and interactions of critical factors between marine ecological governance and economic development in 11 coastal provinces of China. The following are the innovations of this study: (1) the establishment of a multidimensional indicator system for the marine ecological governance and economic development of China; (2) the examination of the causes of the variations in coordinated development among various provinces and the differences among them; (3) the application of geo-detection techniques to provide novel analytical concepts and methodologies for the examination of coordinated development in the region.

3 Materials and methods

3.1 Study area

The coastal provinces examined in this paper are distributed within China's three primary marine economic spheres: North, East, and South. The Northern marine economic circle primarily encompasses the water and land areas of Liaoning Province, Hebei Province, Tianjin Municipality, and Shandong Province. The Eastern marine economic circle mainly encompasses the coastal and inland regions of Jiangsu Province, Shanghai Municipality, and Zhejiang Province. The Southern marine economic circle primarily includes the sea and land areas of Fujian Province, Guangdong, Guangxi Zhuang Autonomous Region, and Hainan Province. In China's administrative system, autonomous regions, municipalities, and provinces are all classified at the same administrative level. Consequently, this research encompasses numerous autonomous regions, municipalities directly under the central government, and provinces, all of which are equivalent in their administrative structures.

In this study, the indicator data related to ecological conditions were primarily sourced from the "China Marine Statistical Yearbook," compiled by the State Oceanic Administration, which offers comprehensive and detailed data on marine environmental and resource conditions. The data for pollution management indicators were derived from "the Bulletin on the Ecological and Environmental Status of China's Marine Areas (https://www.mee.gov.cn/hjzl/sthjzk/jagb/) "issued by national and local environmental departments, providing official statistical data on pollutant discharge and management activities. Data for Ecological Correspondence indicators were sourced from the "China Marine Statistical Yearbook" and the "Regional Economic Statistical Yearbook," with the latter providing investment and expenditure data related to marine ecological protection projects. Indicators related to economic efficiency, industrial structure, and production capacity were primarily obtained from the "China Marine Economy Yearbook," "China City Statistical Yearbook," and the "Regional Economic Statistical Yearbook," published by the National Bureau of Statistics and relevant ministries, offering detailed statistical information on marine economic activities. To ensure the accuracy of the data, we procured relevant data from the CSMAR database, WIND database, and EPS data platform.

3.2 Establishment of comprehensive evaluation indicator system

In order to create a set of indicators for ecological governance and marine economic growth in China's coastal provinces, this

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study applies the concepts and methods of marine ecological governance and economic development. The marine ecological governance indicator system comprises three subsystems: ecological conditions, pollution management, and ecological correspondence (Chen et al., 2023; Addamo et al., 2024; Liu and Ma, 2024). This system emphasizes the management and protection of the ecological environment in China's coastal provinces. On the other hand, the marine economic development indicator system consists of three aspects: marine economic efficiency, industrial structure, and production capacity (Ding et al., 2021; Lau et al., 2024; Ji et al., 2024). This system highlights the level of development, efficiency, and economic activity of various industries within the marine economy of the coastal provinces. The whole structure of the indicator system is presented in Table 1.

3.3 Method

3.3.1 Global entropy method

The global entropy method is an objective multi-attribute decision analysis tool that assesses the relative significance of attributes by analyzing their correlation with the evaluation outcome or ultimate target. The method's fundamental concept is to use information entropy to quantify the extent of discrete data, hence evaluating the significance of each indication. With this methodology, the indicators first need to be standardized:

$$X'_{ij} = \frac{X_{ij} - X_{jmin}}{X_{jmax} - X_{jmin}} + 0.0001 \tag{1}$$

$$X'_{ij} = \frac{X_{jmax} - X_{ij}}{X_{jmax} - X_{jmin}} + 0.0001 \tag{2}$$

TABLE 1 Evaluation indicator system for marine ecological governance and marine economic development.

Evaluation Target	Subsystems	Evaluation Indicator	Direction	Weight
Marine Ecological Governance	Ecological Conditions	Area of marine wetlands (1000 hectares)	Positive	0.106
		Marine aquaculture area (hectares)	Positive	0.099
		Area of marine protected areas (square kilometer)	Positive	0.171
	Pollution Management	Volume of direct sewage discharged into the sea per capita (ton/person)	Negative	0.028
		Volume of direct chemical oxygen demand discharged into the sea per capita (tons/10000 people)	Negative	0.076
		Volume of direct ammonia nitrogen discharged into the sea per capita (tons/10000 people)	Negative	0.049
		Volume of direct total phosphorus discharged into the sea per capita (tons/10000 people)	Negative	0.045
	Ecological Correspondence	Share of current year's investment in pollution control projects in regional GDP (%)	Positive	0.161
		Ratio of investment expenditures on environmental protection projects (%)	Positive	0.206
		R&D expenditures of marine scientific research institutions (1000 RMB)	Positive	0.059
Marine Economic Development	Economic Efficiency	Gross marine product as a share of regional GDP (%)	Positive	0.201
		Percentage of value added of major marine industries (%)	Positive	0.064
		Percentage of value added of marine-related industries (%)	Positive	0.069
		Productivity of marine industries (100M RMB/10000 people)	Positive	0.164
	Industrial Structure	Percentage of marine secondary industry (%)	Positive	0.049
		Percentage of marine tertiary industry (%)	Positive	0.064
		Advanced index of marine industry structure	Positive	0.075
	Production Capacity	Total regional cargo throughput (10000 tons)	Positive	0.100
		Total amount of seawater products (10000 tons)	Positive	0.093
		Total marine passenger traffic (10000 people)	Positive	0.122

The weights presented in the table are computed using the global entropy method.

Where Equations 1, 2 represent the normalization of positive and negative indicators, respectively, $X_{ij}$is the original value of the ith sample on the jth indicator. $X_{j\,min}$ is the minimum value of the jth indicator. $X_{j\,max}$ is the maximum value of the jth indicator. $X_{ij}^{'}$ is the normalized value.

$$P_{ij} = \frac{X_{ij}^{'}}{\sum_{i=1}^{n} X_{ij}^{'}} \tag{3}$$

Second, calculate the percentage P_{ij} of each indicator's normalized value over all samples, n being the number of samples.

$$e_j = -\frac{1}{LNn}\sum_{i=1}^{n} P_{ij} \times Ln(P_{ij}) \tag{4}$$

$$W_j = \frac{g_j}{\sum_{k=1}^{m} g_k} \tag{5}$$

Third, the information entropy and weights are computed. The information entropy of each indicator is denoted by e_j, while the coefficient of variation, g_j ($g_j = 1 - e_j$), is a value between 0 and 1. The increase in value suggests that the indicator's data is more variable, which provides more information. Consequently, it should be given a higher weight in decision-making. m is the total number of indicators, W_j is the weight of the jth indicator, and the sum of the weights of all the indicators is 1, ensuring that the weights are normalized.

$$S_i = \sum_{j=1}^{m} w_j \times X_{ij}^{'} \tag{6}$$

Finally, the standardized value of each indicator is multiplied by its corresponding weight. Then, all the indicators are summed to get the composite score of each sample, where S_i is the composite score of the ith sample.

3.3.2 Coupled coordination degree model

The CCD refers to an evaluation indicator showing the coordination level in the coupling effect. This indicator considers the development levels of two or more systems or dynamic forms. CCD models have extensively been applied across various disciplines (She et al., 2024; An et al., 2024; Shi et al., 2020; Du et al., 2022). Therefore, this paper will use the CCD model to analyze the coupling coordinate relationship between marine ecological governance and economic development in China's coastal provinces.

The specific calculation steps for the degree of coupling coordination are as follows. Firstly, the coupling degree is calculated by

$$C = 2\left[\frac{U_i^* \times V_i^*}{(U_i^* + V_i^*)^2}\right]^{\frac{1}{2}} \tag{7}$$

C denotes the CCD between marine ecological governance and economy development; U_i^* and V_i^* are the normalized values of the comprehensive evaluation scores for the marine ecological governance and economic development in the i-th provincial-level region. When normalizing the comprehensive scores, this study follows the practice in relevant literature (Hao et al., 2022) and adopts min-max normalization. The comprehensive coordination index can be given by

$$T = \alpha U_i^* + \beta V_i^* \tag{8}$$

Where T represents the comprehensive coordination index between marine ecological governance and economic development in coastal regions; α and β are the coefficients. Given the equal significance of the marine ecology and economy in ensuring the long-term growth of coastal provinces, both α and β are assigned a value of 0.5. Building upon this, the CCD can be worked out by

$$D = \sqrt{C \times G} \tag{9}$$

Where D signifies the CCD between marine ecological governance and economic development in coastal regions, the degree can be categorized into different levels based on its value range. Following the practices in relevant studies (Yuan et al., 2024), this paper defines them as shown in Table 2.

3.3.3 Theil index decomposition method

The Theil index is a measurement that is derived from the generalized entropy index. It is used to quantify the internal variation of the sample as a whole and to analyze differences between groups and within groups by decomposing the index. It has been widely used to measure regional and industry disparities (Zhang et al., 2022; Hong and Guan, 2024; Sun et al., 2023). Therefore, by taking advantage of the Theil index decomposition method, this study aims to assess variations within the coupled and coordinated development levels between marine ecological governance and marine economy development along Chinese coast provinces. The Theil index can be calculated by

$$T = \frac{1}{k}\sum_{q=1}^{k}\left(\frac{D_q}{\overline{D}} \times \ln\frac{D_q}{\overline{D}}\right) \tag{10}$$

$$T_p = \frac{1}{k_p}\sum_{q=1}^{k_p}\left(\frac{D_{pq}}{\overline{D_p}} \times \ln\frac{D_{pq}}{\overline{D_p}}\right) \tag{11}$$

$$T = T_w + T_b = \sum_{p=1}^{3}\left(\frac{k_p}{k} \times \frac{\overline{D_p}}{\overline{D}} \times T_p\right) + \sum_{p=1}^{3}\left(\frac{k_p}{k} \times \frac{\overline{D_p}}{\overline{D}} \ln\frac{\overline{D_p}}{\overline{D}}\right) \tag{12}$$

TABLE 2 Classification of coupled and coordinated development.

Classification Criteria	Coupling Coordination Type
$D < 0.5$	Imbalance stage
$0.5 \le D < 0.6$	Barely Coordinated Development
$0.6 \le D < 0.7$	Primary Coordinated Development
$0.7 \le D < 0.8$	Intermediate Coordinated Development
$0.8 \le D < 0.9$	Good Coordinated Development
$0.9 \le D < 1$	High-Quality Coordinated Development

The variable T represents the comprehensive Theil index, which measures the overall differentiation in the coordinated development of marine ecological governance and economic development in coastal provinces of China. Its value ranges from 0 to 1. A lower index value signifies a smaller overall disparity. The variable q represents the detonation of provinces, k is the number of provinces, $D_q$represents the CCD development of province q, and $\overline{D}$ represents the average degree of coupled and coordinated development of coastal provinces. T_p denotes the overall difference Theil index of region p, k_p detonates the number of provinces in region p (p=1,2,3), D_{pq} represents the CCD of province q in region p, and $\overline{D_p}$ represents the average CCD of the provinces in region p. Furthermore, the overall difference Theil index T is broken down into the Theil index for intra-regional variance (labeled as T_w) and the Theil index representing inter-regional disparities (labeled as T_b). The contribution of intra-regional variance (W_w), inter-regional variance (W_b), and the individual contribution of regional disparities (W_d) can also be calculated by

$$\mathbf{W_w = T_w/T} \tag{13}$$

$$\mathbf{W_b = T_b/T} \tag{14}$$

$$\mathbf{W_d = (D_p/D) \times (T_p/T)} \tag{15}$$

Where D_p denotes the cumulative coupled and coordinated development degrees among provinces within region P, and D signifies the aggregate coupled and coordinated development degrees of coastal provinces.

3.3.4 Geographic detector

The geographic detector is a statistical technique used to identify and analyze regional spatial differences and the underlying causes that contribute to them. This method has found extensive application across various disciplines (Yan et al., 2023; Yuan et al., 2023; Guo et al., 2022), and geographic detectors have yet to be used much in China's marine sector. Therefore, based on the data features, this research utilizes differentiation factor detection and interaction detection to evaluate the factors driving differentiation in the coupled and coordinated development of the Chinese provinces' marine ecology and economy. The primary objective of differentiation factor detection is to evaluate the degree to which a factor contributes to explaining the spatial divergence in coordinated regional growth. The method of analysis is based on the Q-value ($Q \in [0,1]$) metric, which measures the strength of the factors' explanatory power. Higher values suggest a stronger explanatory power.

$$\mathbf{Q = 1 - \frac{\sum_{h=1}^{L} N_h \delta_h^2}{N\delta^2} = 1 - \frac{SSW}{SST}} \tag{16}$$

In Equation 16, L denotes the classification or partition of factor X, N_h denotes the layer h, and N denotes the total number of cells in the region. δ_h^2 and δ^2 denote the differences in the values of the dependent variable for stratum h and the entire district, respectively. SSW is the aggregate of the variability within a certain stratum, whereas SST refers to the total variance throughout the entire region.

Interaction detection evaluates if the combined effects of several factors amplify or diminish the explanatory capability of the independent variable or if the impacts of this component are autonomous. The method is based on Equation 16 and assumes the existence of two factors, X_1 and X_2. First, determine the Q values for variables X_1 and X_2, denoted as $Q(X_1)$ and $Q(X_2)$ correspondingly. Second, In order to determine the value of Q at the time of interaction, the distribution of new polygons formed by the tangency of the two layers when the variables X_1 and X_2 are superimposed is calculated: $Q(X_1 \cap X_2)$. Finally, The relationship between the independent variables X_1 and X_2 was assessed by comparing the magnitudes of $Q(X_1)$, $Q(X_2)$, and $Q(X_1 \cap X_2)$ values. The interaction relationships and the basis of judgment are shown in Table 3.

Where $Min(Q(X_1), Q(X_2))$ denotes the minimum value in $Q(X_1)$ and $Q(X_2)$, and $Max(Q(X_1), Q(X_2))$ represents the largest value in Q (X_1) and $Q(X_2)$. The expression $Q(X_1) + Q(X_2)$ represents the total obtained by adding $Q(X_1)$ and $Q(X_2)$ together. Therefore, the interaction factor values can explain the multiple influences on the coupled coordinated regional divergence characteristics.

4 Results

4.1 Measurement results of the global entropy method

The research based on the global entropy method (in Table 4) reveals that the Northern marine economic circle demonstrated superior performance in marine ecological governance compared to the other two economic circles throughout the sample period. In this economic circle, Shandong, Hebei, and Liaoning rank higher among coastal provinces in terms of marine ecological governance ratings, indicating their exceptional effectiveness in ecological governance. In contrast, Tianjin exhibits a lower score and consistently ranks behind the coastal provinces in its composite scores over the years. When comparing the Eastern and Southern marine economic circles, their ecological governance levels are approximately equal. Although Jiangsu and Guangdong stand out with better performance, most

TABLE 3 Interaction relationship and basis of judgment.

Interaction Relationship	Basis of Judgment
Nonlinear weakening	$Q(X_1 \cap X_2) < Min(Q(X_1), Q(X_2))$
Single-factor nonlinear weakening	$Min(Q(X_1), Q(X_2)) < Q(X_1 \cap X_2) < Max(Q(X_1), Q(X_2))$
Two-factor enhancement	$Q(X_1 \cap X_2) > Max(Q(X_1), Q(X_2))$
Independent	$Q(X_1 \cap X_2) = Q(X_1) + Q(X_2)$
Nonlinear enhancement	$Q(X_1 \cap X_2) > Q(X_1) + Q(X_2)$

TABLE 4 Measurement results based on the global entropy method.

Region	Province	Marine Ecological Governance			Marine Economy Development		
		2011	2016	2021	2011	2016	2021
Northern marine economic circle	Tianjin	0.383	0.313	0.352	0.456	0.471	0.517
	Hebei	0.596	0.568	0.580	0.361	0.435	0.368
	Liaoning	0.588	0.512	0.563	0.479	0.497	0.464
	Shandong	0.600	0.627	0.678	0.563	0.625	0.528
	Mean Value	0.542	0.505	0.543	0.465	0.507	0.469
Eastern marine economic circle	Shanghai	0.362	0.398	0.360	0.598	0.598	0.529
	Jiangsu	0.579	0.678	0.636	0.397	0.415	0.393
	Zhejiang	0.314	0.436	0.465	0.520	0.551	0.503
	Mean Value	0.418	0.504	0.487	0.505	0.521	0.475
Southern marine economic circle	Fujian	0.385	0.472	0.459	0.552	0.638	0.530
	Guangdong	0.583	0.555	0.574	0.547	0.608	0.482
	Guangxi	0.443	0.411	0.460	0.288	0.365	0.369
	Hainan	0.417	0.451	0.461	0.439	0.478	0.493
	Mean Value	0.457	0.472	0.489	0.456	0.522	0.469

provinces still have low ecological governance scores, indicating regional disparities in ecological governance capacity.

On the other hand, an examination of the aggregate score of the marine economic development system reveals that the Eastern economic circle consistently ranks at the top in terms of average score throughout most years. Furthermore, the scores of the provinces within the circle demonstrate a very equitable distribution. The degree and trajectory of marine economic development in the Northern and Southern marine economic circles show similarities since both go through a transitional phase characterized by an initial rise followed by a subsequent decline. Shandong, Tianjin, Fujian, and Guangdong exhibit more rapid growth in their marine economy inside the circle. However, Hebei and Guangxi are seeing slower progress, which emphasizes the issue of uneven marine economy development in the coastal regions.

4.2 Measurement results of the coupled coordination degree model

This study employed the coupled coordination measurement approach to comprehensively investigate the correlation between marine ecological governance and economic growth in the coastal regions of China. Figure 1 provides a detailed representation of each province's coupling coordination relationship trend throughout the data period.

In 2011, Shandong exhibits the highest degree of coupled coordinated development in the Northern marine economic circle, constantly sustaining a state of high-quality coordination. Meanwhile, the coupled development ties between Hebei and Liaoning have experienced few changes and have consistently maintained a state of good coordination. On the other hand, the coupling coordination development in Tianjin has had a fluctuation phase, marked by an early rise and subsequent drop. The change is due to the ongoing expansion of Tianjin's marine economy. At the same time, the marine ecological governance did not show considerable improvement in the later part of the study period, leading to fluctuations in the level of coordinated growth between the two. During the sample period, Shanghai, Jiangsu, and Zhejiang in the Eastern marine economic circle had good coordinated development. This indicates that these areas can maintain a specific equilibrium between advancing marine economies and ecological governance. For the Southern marine economic circle, Guangdong and Hainan exhibit notable changes. The level of coupling coordination in Guangdong has transitioned from high-quality coordination to good coordination, potentially indicating that the marine economy's rapid development has negatively impacted the local ecological environment. Conversely, the degree of coupled coordination in Hainan substantially increased, transitioning from an intermediate level to a good level of coordination. This indicates the growing importance of Hainan in integrating marine ecological governance and economic development. Meanwhile, the level of coupled coordination in Guangxi remains consistently lowest, while Fujian consistently exhibits a higher level of coupled coordination.

4.3 Theil index decomposition method

To further investigate the degree of differentiation and sources of differences, this study uses the Theil index decomposition method to analyze the differences in coupled and coordinated development levels in different coastal provinces.

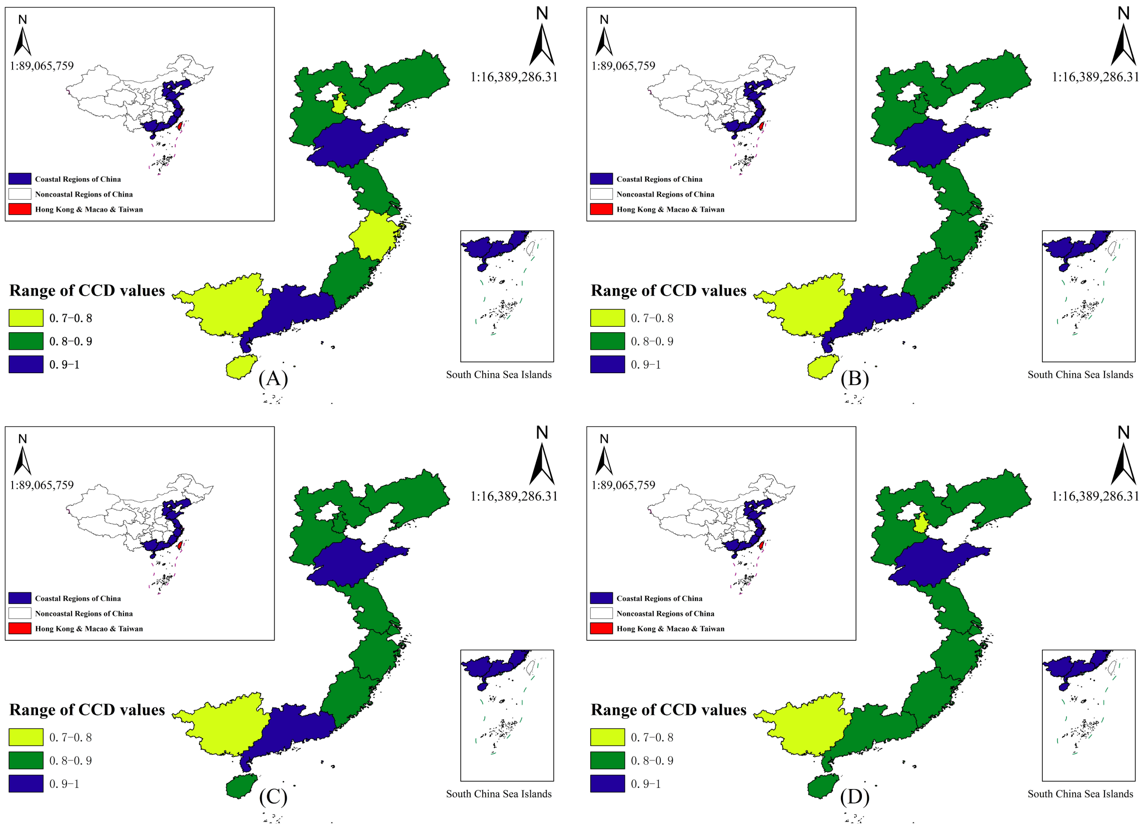

FIGURE 1
Evolutionary trend in the degree coupling coordination of the coastal provinces. **(A)** Year 2011. **(B)** Year 2014. **(C)** Year 2018. **(D)** Year 2021.

Figure 2 shows a downward trend in the overall differentiation for CCD., reaching a peak of 0.0027 in 2013 and declining to a minimum of 0.0013 in 2021. The trend indicates that aligning marine ecological and economic Coordinated development among provinces is progressing favorably. Furthermore, the disparities within regions were far more significant than those between regions, suggesting that the primary source of developmental imbalance stemmed from within the economic circle. More precisely, the intra-regional disparities peaked at 0.0025 in 2016 and subsequently exhibited a fluctuating downward pattern, reaching a low of 0.0012 in 2021. Moreover, the coupled growth patterns within the area align with the general trajectory. Hence, the extent of contact and integration among the regional provinces primarily determines the interdependence between China's marine ecosystem and economy.

The present study further explores the trends in the variation of intra-regional differentiation among the marine economic circles in China. Figure 3 depicts the variations in the contribution of intra-regional disparities among the marine economic circles across different years. Before 2018, the disparities between Southern marine economic circle regions were considerably more significant than those in the Northern and Eastern marine economic circle. From 2018 onwards, there was a significant reduction in the differentiation within the Southern marine economic sphere. On the other hand, the internal developmental differentiation within the Northern marine economic

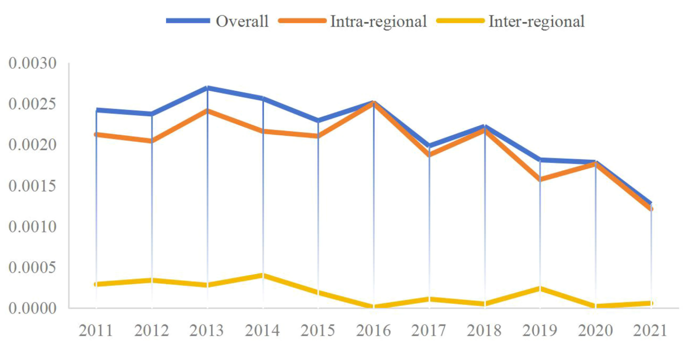

FIGURE 2
Trends in Theil's index of coupling coordination degrees.

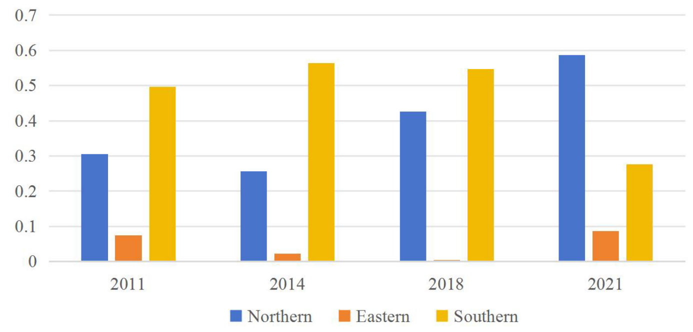

FIGURE 3
Contributions and trends in the Theil Index by region.

circle demonstrates a consistent increase over time. Shandong is progressively aligning marine ecological management with economic growth, whereas Tianjin is notably declining. Late in the sample, the internal disparities within the Northern marine economic circle have taken the lead. For the Eastern marine economic circle, its internal development differences show a more stable trend and remain at a lower level.

4.4 Results of geographic detector

This study examines seven factors that may influence the coordinated development of marine ecology and economy in China's coastal provinces based on existing literature and considering the developmental characteristics of these provinces (Table 5). Given that the chosen indicators are all continuous variables, they were initially transformed into discrete variables using the natural break point approach. This method was employed to classify the indicators into five distinct tiers. Finally, geographic detector were employed to quantify the impact of each indication on the degree of coupling coordination. This analysis yielded the relevant Q and P values provided in Table 6.

TABLE 5 Drivers of differentiation trends of coupled and coordinated development.

Indicator	Measurement Method	Notation
R&D intensity	Internal expenditure on R&D/GDP	X_1
Energy structure	Regional electricity consumption/Total national electricity consumption	X_2
Level of economic development	Real GDP per capita	X_3
Level of technology market development	Technology market turnover/GDP	X_4
Overseas foreign direct investment (OFDI)	(Total foreign direct investment*United States dollar to renminbi exchange rate)/GDP	X_5
Degree of industrial agglomeration	Number of employed persons/ area of administrative division	X_6
Innovation level	Number of Patent Applications Received (pieces) in natural logarithms	X_7

The study's findings indicate that all of the selected indicators achieve a statistically significant level of 1%, confirming the substantial impact of these indicators on the regional differentiation of the coordinated development of marine ecological and economic. Upon doing a more in-depth analysis of the Q-values, we discovered that the Q-values of X_2 (0.55), X_5 (0.40) and X_6 (0.46) surpassed the threshold of 0.4. This suggests that these three indicators significantly contribute to the regional differentiation of coordinated development. In contrast, X_1 (0.37), X_3 (0.38) and X_4 (0.36) have Q-values ranging from 0.3 to 0.4, suggesting a moderate level of impact on regional differences. Meanwhile, X_7 has a Q-value of 0.26, which shows a relatively low influence on regional differentiation. The exhaustive analysis indicates that the energy structure, industrial agglomeration, and the OFDI are the primary influential factors that substantially impact the differentiation of coastal provinces in the coordinated development of marine ecology and economy. On the other hand, factors like the R&D intensity have a less significant effect on this geographical differentiation.

This paper further investigates the drivers of differentiation in coupled coordinated development through interaction detection (in Figure 4). The results of the research demonstrated an enhanced degree of interaction between all the variables. Among them, significant two-factor enhancement interactions are observed between most of the factors. For instance, the interaction results between factor X_1 and its remaining factors are more significant than the Q value of a single factor. Additionally, a few impact factors exhibit nonlinear enhancement interactions, such as the interaction results between factors X_3 and X_7, which surpass the sum of the Q value of the two factors. The most significant interaction coefficients are found for factors X_2 and X_3, with a value of 0.756. In the meantime, most of the coefficients containing X_2 and X_3 are larger than the interaction coefficients of the remaining factors. The study's findings indicate that individual components only partially impact the coordinated development of marine ecology and the economy in coastal provinces. Instead, the powerful synergistic effect of these factors highlights the intricate

TABLE 6 Results of differentiation factor detection.

Variable	X_1	X_2	X_3	X_4	X_5	X_6	X_7
Q-value	0.37	0.55	0.38	0.36	0.40	0.46	0.26
P-value	0.00	0.00	0.00	0.00	0.00	0.04	0.09

and interdependent link among them in the development process. Hence, it is imperative for future research and policy formation to prioritize comprehensiveness and synergy, intending to reduce the disparity between the coordinated development of marine ecology and the economy in provincial areas.

5 Conclusion and recommendation

5.1 Conclusion

This study examines the present state of coordinated marine ecological and economic development in the coastal provinces of China using empirical analysis. The study demonstrates that the ecological governance in the Northern marine economic circle is considerably superior to that in the Eastern and Southern marine economic circles. In contrast, the Eastern marine economic circle exhibits significantly higher levels of marine economic development than the Northern and Southern circles. Shandong, Hebei, Liaoning, Jiangsu, and Guangdong demonstrate superior governance capabilities regarding ecological governance. Shandong, Shanghai, Zhejiang, Fujian, and Guangdong stand out in terms of marine economic growth.

The analysis based on using the CCD model indicates that the provinces in the Eastern marine economic circle consistently exhibit a high level of coupling coordination throughout the study period and reflect their favorable state of synchronized regional growth. At the same time, the coordinated development of the Northern and Southern marine economic circles exhibits an uneven pattern, with Hebei and Guangdong demonstrating superior coupling coordination while Tianjin, Guangxi, and Hainan are falling behind. The overall differentiation in coordinated development within the region remains generally stable throughout the examined period, and the variances within the region are the primary rationale contributing to this differentiation. Additional examination reveals that the energy structure, the level of industrial agglomeration, and overseas foreign direct investment are the primary drivers for coordinated regional development. These factors' optimized configuration and interactions directly dictate the coordination and sustainability of regional marine ecological and economic growth.

The findings of this study are notably consistent with the conclusions drawn from existing scholarly literature. Notably, prior research has indicated that the eastern coastal regions hold a superior position in terms of marine economic resilience structure. This phenomenon is closely associated with the coordinated nature of marine economic policies and practices in these areas (Zhou and Li, 2024). Furthermore, the marine economic resilience structure of the eastern coastal areas has undergone a transition from a "Shandong-Shanghai-Guangdong" dynamic to a "Shandong-Zhejiang-Guangdong" one, reflecting the increasingly significant roles that Shanghai and Zhejiang play in the maritime economic landscape of China. This trend corroborates the results of this paper, further substantiating the advantage of the eastern marine economic circle in terms of coordinated and integrated development (Yu et al., 2024).

Regarding regional differences, the research findings have revealed that while the eastern marine economic region has maintained a relatively low level of internal disparities for most of the studied years, there was a notable increase in 2020, dropping to the last position. This change suggests that despite the eastern marine economic circle's commendable performance in coordinated development, internal regional disparities remain a primary cause of overall disparities (Zhang and Wang, 2024). Concurrently, the differences within the northern and southern marine economic circles have also shown a fluctuating increasing trend. This further emphasizes the significant contribution of internal disparities within the three major marine economic circles to the overall differences (Sun et al., 2018b). These studies collectively substantiate the robustness of the findings presented in this paper.

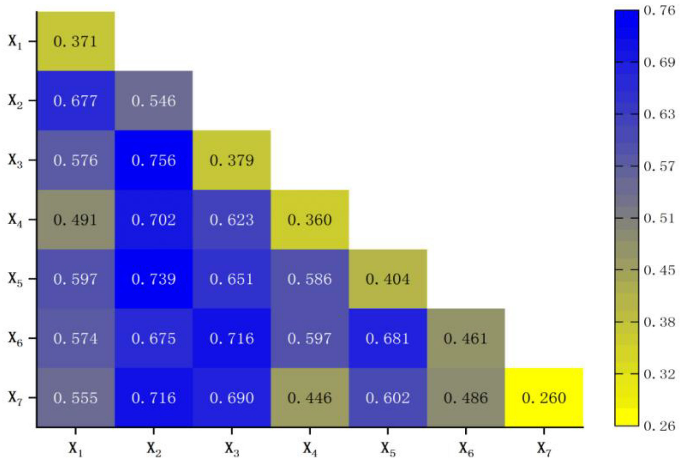

FIGURE 4
Results of interaction detection.

5.2 Recommendation

To achieve the coordinated development of marine ecology and economy in coastal provinces, regions must adopt differentiated strategies based on their unique socio-economic and environmental conditions. In the Northern Marine Economic Circle, particularly in Tianjin, there is a need to enhance the enforcement of marine ecological governance regulations, strictly control the discharge of pollutants, and promote the transformation of the marine economy towards high-tech and clean energy sectors. Hebei and Shandong provinces can leverage their strengths in ecological governance by developing eco-tourism and marine cultural industries, thus converting ecological protection achievements into economic growth drivers. Provinces in the Eastern Marine Economic Circle, such as Shanghai, should continue to lead in marine financial services and technological innovation. In contrast, Jiangsu and Zhejiang provinces should focus on developing high-end marine equipment manufacturing and bio-pharmaceutical industries with a balanced approach to ecological conservation and economic development. In the Southern Marine Economic Circle, Guangdong Province should continue to foster innovative and high-quality marine economic development. In contrast, Guangxi and Hainan provinces must intensify marine environmental governance and develop distinctive marine economies, such as eco-tourism and marine bio-industries, to achieve coordinated and sustainable regional development. By implementing these region-specific policy recommendations, the integrated advancement of marine ecology and economy in China's coastal provinces can be more effectively promoted, reducing regional development disparities and establishing a scientific foundation for realizing a sustainable marine economy in the coastal regions.

In order to promote synchronized growth across the region and narrow the disparity in development across the different coastal economic zones. The first step involves the transfer of the Northern and Southern marine economic circles to a low-carbon energy blend. The government could accelerate the progress of renewable energy projects, such as offshore wind energy, by offering incentives such as tax discounts and financial subsidies. Simultaneously, it is advised that a distinct fund be established to facilitate the R&D and commercialization of low-carbon technologies, thereby guaranteeing a seamless energy structure transformation. Furthermore, the government should improve the investment climate for environmentally sustainable maritime sectors to attract foreign investment and stimulate local economic growth. To encourage the entry of funds and technology and build confidence from foreign sources, it is necessary to adopt measures that make it easier for businesses to access the market and improve the protection of investments, especially regarding safeguarding intellectual property and providing legal assistance. Finally, policy directives should promote consolidating high-tech sectors, including those linked to the maritime economy. Regional cooperation structures are necessary to enhance industries' competitiveness and innovation capability by facilitating the sharing of resources and market information. Moreover, it is necessary to build cross-regional industrial alliances in order to streamline the allocation of resources and foster the flow of information.

This study has unveiled the coordinated relationship between marine ecological governance and economic development among China's coastal provinces, highlighting regional disparities in ecological governance and economic progress and identifying key factors influencing these differences. To further enhance our understanding of this intricate interplay and to provide scientific guidance for achieving a more harmonious and sustainable marine economy, future research may consider the following directions:

1. Regional Integration Strategy Research: Investigate how policy innovation, regional collaboration, and inter-regional governance mechanisms can strengthen the economic and ecological integration among coastal provinces, particularly in ecological compensation, resource sharing, and collaborative environmental management.
2. Development of Ecological-Economic Models: Develop and evaluate novel ecological-economic models that more accurately reflect the value of marine ecosystem services and provide decision support for the sustainable use of marine resources.
3. Risk Management and Adaptation Strategies: Assess the impact of climate change and environmental risks on the coordinated development of marine ecology and economy in coastal provinces and explore effective risk management and adaptation strategies.

Through these research avenues, future studies can offer more specific guidance to policymakers, assisting them in protecting and restoring the health and resilience of marine ecosystems while achieving rapid growth in the marine economy.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: China Statistical Yearbook, China Environmental Statistical Yearbook, China Ocean Statistical Yearbook, the Bulletin on the Ecological and Environmental Status of China's Marine Areas.

Author contributions

ZL: Formal analysis, Methodology, Visualization, Writing – original draft. HL: Data curation, Resources, Writing – review & editing. XZ: Conceptualization, Investigation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2024.1483139/full#supplementary-material

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