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The coordination of technological and financial innovation concepts on the marine economy and its ecological development

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ABSTRACT

This study first constructs an evaluation index system based on the pressure state response model, and assigns weights through entropy method and coefficient of variation method, providing theoretical and methodological support for comprehensive measurement and evaluation. Second, the least squares decision model is introduced and the PVAR model is used to analyze the development level of China's marine economy, ecology, and technological and financial innovation. The results indicated that from 2012 to 2022, the marine economic development level, marine ecological development level, and marine technology and financial innovation development level of 9 coastal provinces in China all showed a certain growth trend. However, in terms of the level of marine ecological development, various provinces had shown a downward trend, with Hebei performing the best, with an average of 0.230. Although various regions have achieved significant development in marine economy, ecology, and technological and financial innovation, the level of development varies among regions, and some regions have relatively low levels of technological innovation. The pressure and challenges between the marine economy and ecological environment protection caused by these real environments remain significant.

1. Introduction

Marine economy (ME) refers to the economic activities that rely on the ocean to utilize and develop marine resources for production, trading, and related services. It covers economic activities in various fields such as marine technology, marine biology, marine energy, marine tourism, and marine culture. The ME carries the livelihoods and well-being of a large portion of the world's population, and is also an important component of the global economic system (Amaral-Zettler et al., 2020; Sarwar, 2022; Cochrane, 2021). With the increasing awareness of marine ecological environment (MEE) issues, the world has entered a stage of coordinated development between ME and MEE. The relationship between technological and financial innovation (TF-I) and the ME is attracting increasing attention. Technological innovation has played a crucial role in the coordinated development of the ME and ecological environment. Promoting the efficient use of marine resources through technological innovation and taking into account the protection of the MEE is an important way to promote the coordinated development of the ME and MEE. In the context of digitization and informatization, the updating, iteration, and implementation of marine technology have stimulated more vitality for the development of the marine economy (MED). Financial innovation provides impetus for the MED from the perspective of capital. Financial innovation has promoted the MED by activating the capital market, guiding and absorbing various aspects of capital to invest in the ME (Zouari-Hadiji, 2023; Nazir et al., 2021; Butler et al., 2021). The research about the ME and its MEE under the linkage of TF-I is an important topic in the current field of marine research. Hence, this study will explore from multiple perspectives how technology and financial innovation can coordinate the MED and MEE, hoping to provide specific and feasible suggestions for it. The first part of this paper proposes the purpose and discusses the coordinated role of TF-I concepts in the MED and its ecology. The second part establishes a measurement and evaluation model. The third part uses models for empirical analysis. The fourth part draws research conclusions.

The contribution of this study lies in the construction of an evaluation index system for marine economy and ecological development based on pressure state response model in terms of technology, and the objective assignment of evaluation index weights through entropy

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method and coefficient of variation method, which is more scientific and objective than traditional subjective weighting methods, providing a new perspective and methodological support for the comprehensive evaluation system of marine economy and ecology. At the same time, the study introduced the least squares decision model and panel vector autoregressive model, which not only evaluated the level of marine economic development, but also quantitatively analyzed the impact of technology and financial innovation, providing important empirical data support for understanding the dynamic relationship and interaction between these three. In terms of society, the results of this study help policymakers to more effectively evaluate and monitor the progress of coastal provinces in marine economy, ecological development, technology and financial innovation, and provide guidance for formulating specific regional development strategies. By revealing the uneven status and possible trends of ecological development, the study also provides the public and relevant stakeholders with a new understanding of the challenges of marine ecological protection and sustainable development in China's coastal areas, which helps to improve public environmental awareness and participation.

2. Related work

For the past few years, many experts have studied the ME and MEE. T. Makkonen et al. explored the complex interaction issues in maritime sector innovation from the perspectives of departmental innovation and technological innovation, using the Ballast Water Treatment System (BWTS) as an example. Research had found that public policies and institutional acceptance had a significant impact on shaping the BWTS market. The research results also validated the feasibility of using the SSI/TIS combination framework for environmental innovation research (Makkonen and Inkinen, 2021). B. Li et al. established an indicator system for evaluating the high-quality growth of China's marine fisheries and used entropy method to evaluate the development level and spatiotemporal evolution patterns between 2000 and 2016. The fisheries were in the initial stage with an upward trend in the development of various provinces, autonomous regions, and municipalities directly under the central government, and the spatial distribution transitioning from single to multipolar (Li and Liu, 2022). F. Zhu constructed a comprehensive evaluation index system (EIS) and used a combination of Analytic Hierarchy Process and Grey System Theory for evaluation. At the same time, a coupling degree model (CDM) was added to measure the CCD, and comprehensive coordination index between China's green finance and MEE. With China's emphasis on green development, the coupling and coordination of the system were gradually strengthening (Zhu, 2020). S. Wang et al. established an indicator system for quantifying the coordinated development of environment and economy (CDoEE), and proposed a Panel Threshold Mediation (PTM) model. Using INEF as an intermediary, an empirical test was conducted on the nonlinear relationship about the CDoEE in 283 cities in China from 2003 to 2018. The results showed that different INEF thresholds had different impacts on the CDoEE. When INEF was below 0.2381, its complete mediating effect had been verified (Wang et al., 2021a). W. Li et al. evaluated the financial innovation priority of renewable energy investors by establishing a new hybrid fuzzy decision-making model. Ensuring customer demand was a key factor in meeting the financial innovation needs of renewable energy investors (Li et al., 2022).

Y. Wang et al. used the Tapio decoupling model to analyze the decoupling relationship among the marine condition, determining factors, and the ME, revealing the inherent relationship and growth trends between the dynamic changes of the ME and the MEE. The marine ecological efficiency of coastal provinces and cities in China had improved, but that of the southern and northern regions was relatively low. In addition, the decoupling connection between the ME and MEE in 11 coastal areas was showing a downward trend, indicating that investment in marine resources not only occupied an essential position in the growth of the ME, but also put pressure on the marine environment (Wang et al., 2021b). Integrated Ocean Management (IOM) is considered a key integrated approach to achieving a sustainable ME. IOM is a comprehensive approach based on ecosystem and knowledge, building on existing departmental governance efforts and integrating them. It aims to ensure the sustainability and resilience of marine ecosystems, while coordinating different marine uses to optimize the overall ME. J. G et al. identified six universal action opportunities for achieving a sustainable ME by discussing examples from the International Organization for Migration in practice (Winther et al., 2020). S. Fu et al. used Qingdao as an example to quantitatively evaluate the evolution of the relationship between urbanization and ecological environment development from 2000 to 2008 by establishing a comprehensive indicator system and applying a coupled coordination model. These two status contributed the most to urbanization and environmental systems. The economic urbanization and response subsystem were important determining factors in the coupling relationship between urbanization and ecological environment (Fu et al., 2020). A. Phelan et al. used a study on the coastal areas of South Sulawesi Province, Indonesia as an example to introduce community-based ecotourism to support the sustainable use of marine resources. This study providef an entry point for low resource coastal communities to participate in the blue economy. Waste management, reception skills, and market access were the three key areas where communities most need multilateral support (Phelan et al., 2020). Y. Kong et al. used system dynamics methods to construct a carbon reduction model for the offshore supply chain. Taking Shanghai Port as an example, an in-depth analysis was conducted on the interaction between enterprises, economy, energy, environment, and policies. Coastal power had enormous emission reduction potential, while emission trading plans had a relatively small impact on emissions reduction and might increase carbon dioxide emissions. Regardless of the emission reduction measures taken, scenario 4 had been proven to be the best alternative to reducing carbon dioxide emissions in the offshore supply chain. Therefore, under allowable conditions, comprehensive utilization of various resources to reduce carbon dioxide emissions was the most effective means (Kong et al., 2023).

In terms of the coordinated development between the ME and the MEE, current research mainly focuses on ballast water treatment systems, high-quality progress of marine fisheries, and the coupling research between green finance and the MEE. In addition, it also includes the CDoEE, and the priority of financial innovation for renewable energy investors. The comprehensive EIS and model established in these studies provide reference and reference for subsequent research in related fields, further expanding theoretical and practical perspectives. However, there is still little literature on the coordinated analysis of TF-I concepts on the ME and its MEE. Therefore, this study will explore the coordination of ME and MEE from this unique perspective. Especially focusing on how to solve the balance problem between ME and MEE through TF-I concepts, and promote sustainable development.

3. The Coordinated relationship between China's ME and MEE Development under TF-I

On the basis of the constructed EIS, this study measures and evaluates the ME and MEE innovation and development level of China through collected data. Moreover, from the perspective of technological innovation, a series of mathematical models are used to study the China's marine CDoEE.

3.1. Measurement and evaluation of the development level of China's ME ecology science and technology finance

The research first sets the following assumptions before designing the model. Firstly, in the entropy method and coefficient of variation method, we assume that the weight relationship between indicators is linear. This means that we assume that the relationship between indicators is uniform and consistent, without considering potential nonlinear interactions, which may limit the explanatory power of the model in certain situations. Secondly, in the design of the PVAR model, we assume that the time series data is stationary. Therefore, we conducted a unit root test on the data. We can only continue the analysis if the data has been tested by LLC, ADF, and PP and proven to be stable. However, this assumption may overlook the structural changes in certain macroeconomic factors or the impact of unexpected events on the marine economy. Finally, ignore potential endogeneity issues arising from model design.

This study constructed an indicator system based on relevant theories such as marine ecosystems and ecological economics, as well as collected data, to measure and evaluate the degree of innovation and development in China's ME, ecology, technology and finance. The study constructed an EIS built on previous literature, using the Pressure State Response (PSR) model as the theoretical basis (Yazbek et al., 2023). This model introduces marine technology and financial innovation as a new element into the marine economic ecosystem and improves on the original PSR model. Therefore, a PSR model can be established to describe the interrelationships between research objects, as shown in Fig. 1.

To objectively evaluate the development level of China's marine economic ecology and marine technological innovation (MTI), the study referred to relevant research and constructed an EIS for marine economic ecological technological innovation. The evaluation system includes three dimensions of development level: ME, MEE, and MTI. To ensure the comparability and accuracy of the data, 9 coastal provinces from 2012 to 2022 were taken as the experimental subjects. The data such as the China Ocean Statistical Yearbook (COSY) and the China Coastal Environmental Quality Bulletin were used for analysis. After formula transformation and processing, a total of 18 indicators were obtained. Table 1 shows the evaluation indicators.

In order to comprehensively evaluate the innovation and development level of China's marine economy (ME) and marine economic ecology (MEE), this study designed an evaluation index system containing multiple key indicators. In the selection of indicators, the multidimensional and dynamic nature of marine ecological economy was comprehensively considered, with special attention paid to indicators that can reflect marine economic activities, ecological environment conditions, and technological and financial innovation levels. These indicators can reflect the health and innovation capacity of the marine economic ecosystem from different dimensions, and are the core of the evaluation system involved in this study. To reduce the subjectivity of weighting, the study adopted the entropy method and coefficient of variation (EM-CV) method in objective weighting to calculate weights. And a least squares decision model was introduced to integrate the weights of the two, giving comprehensive weights to indicators from different mathematical perspectives. Entropy was used in information theory to measure uncertainty. The entropy method judged the weight of indicators based on the size of the entropy value. A smaller entropy value indicates a larger amount of information, and the corresponding weight is also larger. The first step is to select indicators, assuming there are n years and m indicators, where $x_{i,j}$ represents the value of the j-th

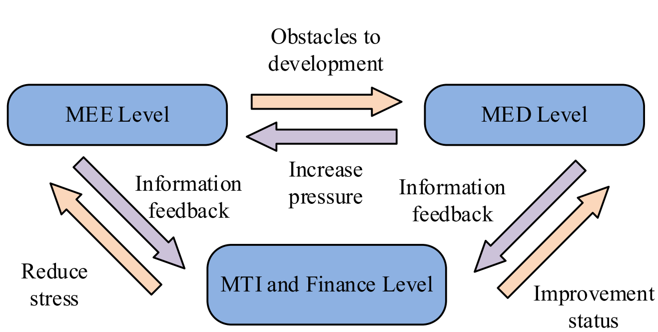

Fig. 1. PSR model relationships.

Table 1
Evaluation index system.

Dimension	Index	Definition and calculation method
	Per capita GMP (10,000 yuan/person)	Gross Marine Product (GMP)/Ending Population of Coastal Areas
MED level	Growth rate of ME (%)	(GMP of the Year - GMP of the Previous Year)/GMP of the Previous Year
	Proportion of marine secondary and tertiary industries (%)	The proportion of the output value of the secondary and tertiary industries in the coastal areas of China
	GMP (100 million yuan)	The proportion of GDP
	Return on Capital of ME (%)	Source: COSY
	Per capita marine fishing volume (tons/10000 people)	Obtained from the COSY
	Industrial solid fuel emissions (tons)	Added Value of Marine Industry/GMP
	Direct discharge of industrial wastewater into the sea (10,000 tons)	Marine fishing volume/year-end population of coastal areas
	Unit aquaculture area seawater aquaculture yield (tons/ha)	Sourced from the COSY
MEE Level	Per capita sea salt production (tons/person)	Obtained from the COSY
	Proportion of Class IV and Inferior Class IV (P&I-CIV) Seawater (%)	Seawater aquaculture yield/area
	Number of marine nature reserves	Sea salt production/year-end population of coastal areas
	Ocean cargo turnover (100 million tons per kilometer)	Obtained from the Environmental Quality Bulletin of China's nearshore waters
	Number of scientific and technological (S&T) projects in marine research institutions (MRI)	Obtained from the COSY
	Average number of researchers in MRI (person/institution)	Obtained from the COSY
MTI and Finance Level	Number of S&T papers written by MRI (items)	Acquired from the COSY
	The proportion of highly educated personnel engaged in S&T activities in MRI (%)	Number of researchers/MRI
	Revenue from recurring expenses of marine scientific research institutions (10,000 yuan)	Gained from the COSY

indicator in the i-th year ($i = 1,\cdots,n, j = 1,\cdots,m$). To meet the principle of comparability, first, standardize each indicator. Due to the different numerical meanings of positive and negative indicators, different processing methods need to be adopted. For positive indicators, the higher the value, the higher the degree of representation. The processing method for positive indicators is Eq. (1).

$$x_{ij}^{'} = \frac{x_{ij} - min\{x_{1j},\cdots,x_{nj}\}}{max\{x_{1j},\cdots,x_{nj}\} - min\{x_{1j},\cdots,x_{nj}\}} \tag{1}$$

The processing method for negative indicators is Eq. (2).

$$x_{ij}^{'} = \frac{max\{x_{1j},\cdots,x_{nj}\} - x_{ij}}{max\{x_{1j},\cdots,x_{nj}\} - min\{x_{1j},\cdots,x_{nj}\}} \tag{2}$$

In the equations above, $x_{ij}^{'}$ is the standardized indicator. $max\{x_{1j},\cdots,x_{nj}\}$ and $min\{x_{1j},\cdots,x_{nj}\}$ are the max and min values of the j-th indicator in each year. The proportion of year i to the j-th indicator is calculated using Eq. (3).

$$p_{ij} = \frac{x_{ij}^{'}}{\sum_{i=n}^{n} x_{ij}^{'}} \quad (3)$$

The entropy value of the j-th indicator is Eq. (4).

$$e_j = -k\sum_{i=1}^{n} p_{ij} ln(p_{ij}) \quad (4)$$

In Eq. (4), $k = \frac{1}{ln(n)} > 0$ satisfies $e_j > 0$. The calculation of information redundancy is Eq. (5).

$$d_j = 1 - e_j \quad (5)$$

The weight values of each indicator are solved as shown in Eq. (6).

$$u_j = \frac{d_j}{\sum_{j=1}^{m} d_j} \quad (6)$$

The coefficient of variation method utilizes the degree of dispersion of various indicators to calculate the weight of the indicators. The coefficient of variation formula for each indicator is Eq. (7).

$$v_j = \frac{\sigma_j}{\overline{x}_j} \quad (7)$$

In Eq. (7), v_j, $\overline{x}_j$ and σ_j are the coefficient of variation, average value and standard deviation of the j-th indicator. The weights of various indicators are shown in Eq. (8).

$$h_j = \frac{v_j}{\sum_{j=1}^{m} v_j} \quad (8)$$

In Eq. (8), h_j is the j-th indicator. To maximize the comprehensive weight and reflect the excellent mathematical properties of EM-CV method, a least squares decision model was established to calculate the comprehensive weight, as shown in Eq. (9).

$$minF(w) = \sum_{j=1}^{m}\sum_{i=1}^{n}\left\{\left[(u_j - w_j)x_{ij}^{'}\right]^2 + \left[(h_j - w_j)x_{ij}^{'}\right]^2\right\} \quad (9)$$

In Eq. (9), $\sum_{j=1}^{n} w_j = 1$ and $w_j \geq 0$.The least squares decision model provides a more comprehensive and objective evaluation method by integrating the weights obtained from the entropy method and the coefficient of variation method. This model not only enhances the evaluation of the importance of various indicators of marine economy and ecology, but also enhances research insights into the marine economic vitality and ecological protection effectiveness of coastal provinces in China. Through this model, the most significant factors affecting the development of ME and MEE in China can be successfully identified, and possible future development trends can be predicted.

The evaluation index for each year is Eq. (10).

$$S_i = \sum_{j=1}^{m} w_j x_{ij}^{'} \quad (10)$$

In Eq. (10), S_i represents the evaluation index of a certain dimension in the i-th year of a certain province. In the process of developing an evaluation index system, multiple indicators related to marine economic activities, ecological environment conditions, and technological and financial innovation levels were considered in the study. In order to reduce subjective bias, we used entropy method and coefficient of variation method to allocate weights. Both of these methods are based on different mathematical theories, and their fusion provides a more objective way of weight allocation. The entropy method is based on the principle of measuring uncertainty in information theory. When the entropy value of an indicator is small, it indicates that it has a large amount of information. Therefore, it should be given greater weight. The coefficient of variation rule uses the degree of dispersion of each indicator to determine the weight, that is, indicators with a higher degree of dispersion have a greater weight because they have a greater impact on data changes. By combining these two methods, these indicators that can comprehensively reflect the health and innovation capacity of the marine economic ecosystem were integrated together, and a highly representative comprehensive evaluation index system was constructed.

In Table 2, the comprehensive weights is utilized to solve various indicators in the EIS of China's ME ecology technology finance

Table 2
Weights of evaluation indicators for China's ME ecology science and technology innovation EIS.

Dimension	Index	Entropy method	Coefficient of variation method	Comprehensive weight
MED level	Per capita GMP (10,000 yuan/ person)	0.0734	0.0224	0.0492
	ME growth rate (%)	0.1244	0.3384	0.2329
	Proportion of marine secondary and tertiary industries (%)	0.0352	0.0505	0.0458
	GMP (100 million yuan)	0.0352	0.0025	0.0192
	Return on Capital of ME (%)	0.0529	0.0048	0.0304
MEE Level	Per capita marine fishing volume (tons/10000 people)	0.0347	0. 0859	0.0606
	Industrial solid fuel emissions (tons)	0.0050	0.0315	0.0184
	Direct discharge of industrial wastewater into the sea (10,000 tons)	0.0438	0.0263	0.0355
	Unit aquaculture area seawater aquaculture yield (tons/ha)	0.0069	0.0230	0.0152
	Per capita sea salt production (tons/ person)	0.0157	0.01 85	0.0174
	P&I-CIV Seawater (%)	0.0199	0.0366	0.0385
	Number of marine nature reserves	0.0258	0.0776	0.0529
	Ocean cargo turnover (100 million tons per kilometer)	0.0070	0.0487	0.0181
MTI and Finance Level	Number of S&T projects in MRI	0.1652	0.0356	0.1023
	Average number of researchers in MRI (person/ institution)	0.0600	0.0385	0.0504
	Number of S&T papers written by MRI (items)	0.1374	0.0562	0.0982
	The proportion of highly educated personnel engaged in S&T activities in MRI (%)	0.0256	0.01 86	0.0225
	Revenue from recurring expenses of scientific MRI (10,000 yuan)	0.1471	0.0358	0.0926

innovation.

In the MED level, the gross domestic product of the ocean is given the highest weight at 0.2329. The weights of other indicators are relatively low and basically similar. The weights of various indicators for the MEE level are not significantly different, so it is possible to generally evaluate the level of MEE development in a region from multiple aspects.

This study focuses on using the "MTI and Finance Level" dimensions in the constructed EIS indicator system to measure the impact of technological and financial innovation on the development of the marine economy. In this dimension, indicators such as' number of scientific and technological projects', 'average number of researchers in research institutions',' number of scientific and technological papers in research institutions', 'proportion of highly educated personnel engaged in scientific research activities', and' regular funding income of research institutions' collectively reflect the overall situation of scientific and technological innovation. At the same time, by comprehensively considering the weights of various indicators on the comprehensive evaluation index of marine economic and ecological technology development, the entropy weight method and coefficient of variation method (EM-CV method) were objectively weighted to further analyze the specific impact of technological innovation on marine economic and ecological development. In addition, the establishment of the PVAR model quantitatively reveals the dynamic relationship and feedback mechanism between technological and financial innovation and marine ecology and marine economy. This model takes into account the characteristics of short-term and cross interval large samples in time series, and fully estimates and analyzes the differences between different individuals, enabling a more accurate and comprehensive evaluation of the role of technological and financial innovation in the development of the marine economy.

3.2. The Dynamic relationship of China's ME ecology S&T financial innovation based on PVAR

This study establishes a PVAR model based on the least squares decision model to verify China's level of MED, ecology, and technological financial innovation in three dimensions. The PVAR model is similar to traditional vector autoregressive (VAR). However, the PVAR model has the advantages of short time series and large cross-section, which can fully solve the problems caused by differences between individuals, and fully consider time and fixed effects to better analyze the dynamic response relationship between variables. The PVAR model is Eq. (11).

$$y_{it} = c_i + \sum_{j=1}^{p} \beta_j y_{i,t-j} + \gamma_i + \varepsilon_{it} \tag{11}$$

In Eq. (11), i and t are region and time. y contains three vectors, namely the MED level, ecology, and TF-I level. β_j represents the coefficient matrix of the panel vector autoregressive model. γ_i is the fixed effect of the individual. ε_{it} represents the residual vector.

The study used LLC test, ADF test, and PP test to detect the stationarity of panel data. The purpose is to verify the rationality of the PVAR model in the interaction between China's ME, ecology, and technological financial innovation, and to test whether there is a pseudo regression phenomenon. Only when the results of these three methods pass the test can time series data be considered stable. To eliminate the impact of heteroscedasticity on testing and subsequent modeling, as shown in Table 3, the data was logarithmized.

In Table 3, the logarithmized sequences can reject the original hypothesis at a significance level of 5%, thus passing the stationarity test of the panel data. After confirming the stationarity of the panel data, it is necessary to select the optimal lag order (OLO) for modeling. Three statistics, MBIC, MAIC, and MQIC, were used to select the OLO. The OLO refers to the order in which the minimum value is taken among these three statistics. Table 4 shows the results of selecting the OLO.

In Table 4, the model selects first-order lag as the optimal choice. Based on the stationarity test of panel data, continue to explore the Granger causality between the three dimensions. This is to verify whether the theoretical assumptions of the PSR model constructed from the perspective of TF-I are reasonable, and will also lay the foundation for subsequent research. Table 5 shows the specific results.

According to the results in Table 5, overall, the ME and MEE are undoubtedly influenced by the MTI. Therefore, from the perspective of technological innovation, the PSR model hypothesis of the interaction between China's marine ecological development level and MED level has been validated.

Although the PVAR model is a powerful statistical tool that can analyze the dynamic interaction relationships between variables, it is not without limitations. For example, the model requires high data stationarity, which may affect the analysis results of non-stationary series; In addition, the PVAR model may not be precise enough when dealing with small sample data, and there may be oversimplification issues in explaining the relationships between variables. Future research can enhance the applicability and explanatory power of models by introducing new methods and techniques, and further refine the complex interaction relationships between variables.

On the basis of conducting stationarity tests on panel data variables, unit circle tests are also needed to confirm the stability of the PVAR model. Only when this stability test is passed can the PVAR model converge, thus making the impulse response meaningful in practice (Nezhadkian et al., 2022). This study selected first-order hysteresis for unit circle testing. The inspection results are shown in Fig. 2.

Fig. 2 shows that all points fall within the unit circle, showing that the PVAR has good stability and fitting performance. Therefore, pulse response can be used to further investigate the dynamic response relationships between these variables.

This study explores the coupling relationship between China's ME, ecology, TF-I by establishing a CDM. Coupling degree is the dynamic correlation between two or more systems, which achieves coordinated development and reflects the strength of mutual constraints and interdependence between systems. From a mathematical perspective, the CDM formula is obtained as shown in Eq. (12).

$$C = 2 \times \left\{ \frac{U_1 \times U_2 \times \cdots \times U_n}{\prod_{i<j} (U_i + U_j)^{\frac{2}{n-1}}} \right\}^{1/n} \tag{12}$$

In Eq. (12), $n \geq 2$, that is, the number of systems should not be less than 2, and $U_i \geq 0$ is used to represent the evaluation index of the i-th system. C is the coupling degree of these n systems. The value range of C is [0,1]. The coupling categories vary among different numerical ranges. The development category with a coupling degree of 0 and 1 are in an

Table 3
Unit root test results of panel data.

Variable	LLC Inspection	ADF Inspection	PP Inspection	Conclusion
P	−1.1527	28.5073*	53.1584***	Unstable
S	−5.1774***	36.4292***	50.7672***	Stable
R	−3.7577***	21.9605	23.8419	Unstable
InP	−2.0008**	28.8864**	53.5602***	Stable
InS	−6.8287***	39.0079***	46.0620***	Stable
InR	−7.0333***	42.8522***	55.0061***	Stable

Note: ***, **, * are significance levels of 1%, 5%, and 10%.

Table 4
Selection of optimal lag order for PVAR.

Lag phase	MBIC	MAIC	MQIC
1	−83.2960*	−29.0980*	−50.0568*
2	−53.1623	−17.0303	−31.0028
3	−30.1900	−12.1240	−19.1103

Note: * represents the optimal hysteresis period.

Table 5
Granger causality test results.

Dependent variable	Explanatory variable	Chi-sq	Prob
Level of Marine Ecological Development in China (lnP)	China's MED level (nS)	0.090	0.764
China's MED Level (InS)	China's level of MTI and development (nR)	4.728**	0.030
China's level of MTI and development (lnR)	ALL	5.463*	0.065
Dependent variable	Development level of marine ecology in China (nP)	0.953	0.329
Level of Marine Ecological Development in China (lnP) China's MED Level (InS)	China's level of MTI and development (nR)	4.168**	0.041
	ALL	4.820*	0.090
China's level of MTI and development (lnR)	Development level of marine ecology in China (nP)	0.482	0.488
	China's MED Level (InS)	5.103**	0.024.
	ALL	5.141*	0.077

Note: ** and * represent significance levels of 5%, and 10%.

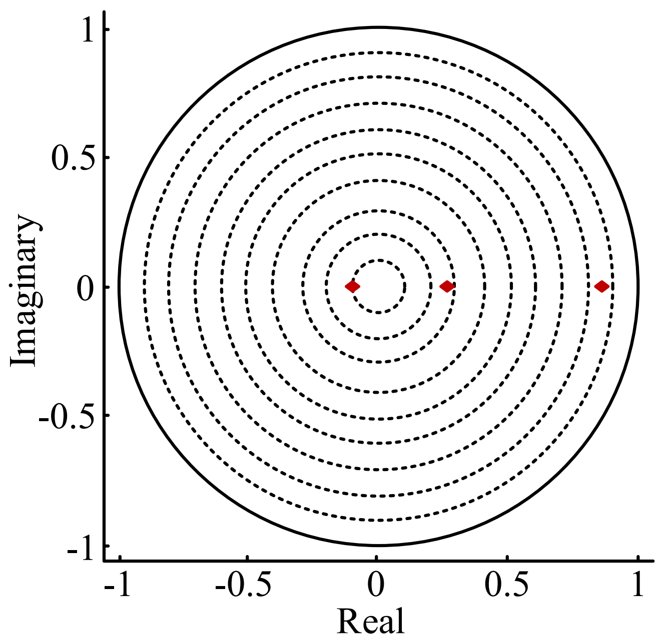

Fig. 2. PVAR model stability test result chart.

unrelated state and benign resonance coupling. The development category of coupling degree in (0,0.3), (0.3,0.5), (0.5,0.8) and (0.8,1) are low-level coupling, antagonistic period, running-in period, and high-level coupling.

This study explores the symbiotic relationship between China's ME and MEE from the perspective of TF-I by establishing a symbiotic evolution model. The ocean is considered a composite system, where economic and ecological attributes are considered as two different populations. Marine technology and financial innovation, as a factor causing changes between the two, can be introduced as environmental capacity. From the aspects of technological innovation, the development levels of China's MEE and ME are set as N_1 and N_2, respectively. Their natural growth rates are r_1 and r_2, respectively. The sum of China's marine S&T innovation level and China's MEE development, as well as the sum of marine S&T innovation and MED level, is set as the environmental capacity $K_1(t)$ and $K_2(t)$ of this symbiotic system. Based on this, the symbiotic evolution function model of the interaction between the two can be represented as Eq. (13).

$$\begin{cases} \dfrac{dN_1(t)}{dt} = r_1(t)\left[1 - \dfrac{N_1(t)}{K_1(T)} + \alpha \cdot N_2(t)\right]N_1(t) \\ \dfrac{dN_2(t)}{dt} = r_2(t)\left[1 - \dfrac{N_2(t)}{K_2(T)} + \beta \cdot N_1(t)\right]N_2(t) \end{cases} \tag{13}$$

In Eq. (13), $N_1(t)$ represents the level of China's MEE development at time t. $N_2(t)$ represents the development level of China's ME at time t. The natural growth rates of both at time t are $r_1(t)$ and $r_2(t)$, respectively. α and β are the coefficients of the symbiotic effect of China's ME on MEE, supported by factors such as TF-I. The positive or negative relationship between the two can determine their symbiotic relationship. To calculate the symbiotic coefficients α and β of the two, it is necessary to calculate the natural growth rates $r_1(t)$ and $r_2(t)$ at time t. Any two adjacent years $[t^T, t^{T+1}]$ are taken as intervals, and the increment of MEE development level in this interval is denoted as ΔN_1^{T+1}, and the average value within the interval is denoted as $averN_1^{T+1}$. The increment of the MED level in this interval is denoted as ΔN_2^{T+1}, and the average value within the interval is denoted as $averN_2^{T+1}$, as shown in Eq. (14).

$$\begin{cases} \Delta N_1^{T+1} = N_1^{T+1} - N_1^T, averN_1^{T+1} = \left(N_1^{T+1} + N_1^T\right)/2 \\ \Delta N_2^{T+1} = N_2^{T+1} - N_2^T, averN_2^{T+1} = \left(N_2^{T+1} + N_2^T\right)/2 \end{cases} \tag{14}$$

The endogenous growth rates $r_1(t)$ and $r_2(t)$ at time t are expressed as eqs. (15).

$$\begin{cases} r_1 = \left| \dfrac{K_1 \Delta N_1^{T+1}}{averN_1^{T+1}\left(K_1 - averN_1^{T+1}\right)} \right| \\ r_2 = \left| \dfrac{K_2 \Delta N_2^{T+1}}{averN_2^{T+1}\left(K_2 - averN_2^{T+1}\right)} \right| \end{cases} \tag{15}$$

To address the shortcomings of this method in terms of construction, taking into account the dynamic response relationship between variables and the possibility of negative endogenous growth rates, the study adopts the method of taking absolute values. This will not affect the qualitative analysis, and the calculation results are still valid.

Regarding the impact of external factors such as globalization, although global economic changes are not directly reflected in the control variables of the model, their impact has been internalized by default in the unobservable error terms of the model. The marine economy is not only influenced by internal factors such as marine technology and financial innovation, but also by subtle changes in the global economic environment that can have profound impacts on it. For example, the development of the global economy will affect the exports of China's coastal provinces, indirectly affecting the overall state of the marine economy and ecology. The technological and financial innovation in the model can reflect the impact of global economic environment changes on the composition of China's marine economy. Therefore, technological and financial innovation has become the core variable of this article. The data from the China Coastal Water Environment Quality Bulletin can reflect the impact of global climate change on the marine environment; The indicators of "number of scientific and technological projects" and "number of scientific and technological papers" reflect the impact of the global economic environment on domestic scientific and technological research and development investment from one side. Therefore, although global factors are not explicitly present in EIS, their impact has been implicit in various indicators.

3.3. *Data sources*

The study collected data from the China Ocean Statistical Yearbook and the China Coastal Environmental Quality Bulletin. These two yearbooks are both published by relevant departments in China, and the data is accurate and reliable. Reliable data provides a solid data foundation for research.

4. Analysis of the coordinated relationship between China's ME and MEE based on TF-I

This study utilized the established EIS for the MED and the analysis system for the coupling degree of ME ecology technology finance innovation. Firstly, the measurement results of China's ME ecology technology finance development level were analyzed. Afterwards, an analysis was conducted on the symbiotic relationship between China's ME and MEE development under TF-I.

4.1. Analysis of the measurement results of the development level of China's ME ecology S&T—F

Based on the weight calculation of evaluation indicators, the study utilized the established EIS for the China's MED level from 2012 to 2022 to solve the problem. Table 6 shows the calculated weight values and corresponding measurement results of each indicator.

In Table 6, from 2012 to 2022, the overall level of MED in the nine coastal provinces of China has shown an rising trend year by year. The average value increased from 0.069 in 2012 to 0.143 in 2022. Among them, Shandong, Fujian, and Guangdong have achieved the greatest improvement in the MED level. Shandong increased from 0.129 in 2012 to 0.244 in 2022, Fujian from 0.094 to 0.200, and Guangdong from 0.100 to 0.301. However, the increase in Liaoning and Guangxi is relatively small. Liaoning increased from 0.062 in 2012 to 0.080 in 2022, and Guangxi increased from 0.025 to 0.043. According to the measurement of the MED level, the average values of Shandong and Guangdong were both greater than 0.15. The construction of the ME in these two provinces started early and the marine industry was relatively mature. The marine economic strength of Liaoning, Jiangsu, Zhejiang, and Fujian was slightly inferior to that of Shandong and Guangdong, with their average values greater than 0.7. Hebei, Guangxi, and Hainan belonged to regions with relatively weak ME. The ME in these three regions started relatively late, with a weak foundation, and a relatively low level of development in the marine industry.

There are also some unexpected findings in data analysis. In provinces with high levels of marine technological innovation, the level of marine ecological development may not necessarily be very high. For example, Jiangsu and Guangdong, although their level of marine technological innovation is relatively high, their level of marine ecological development is not high, indicating that there is not a completely positive correlation between the two. This may be due to the environmental pressure that technological innovation may bring, resulting in the inability to effectively protect and restore the ecological environment while technological innovation is developing rapidly. In provinces with lower levels of marine economic development, such as Hebei and Guangxi, the development level of marine ecological environment is usually also relatively low. But this does not mean that their efforts in environmental protection are insufficient, but may be due to their weak economic foundation and lack of investment and technological innovation funds in environmental protection, which affects the protection and sustainable development of marine ecology.

Based on the weight calculation of evaluation indicators, this study uses the established EIS for MEE development level to solve the problem of China's marine ecological development level from 2012 to 2022. Table 7 shows the weight values and corresponding results of each indicator.

In Table 7, from 2012 to 2022, the overall level of MEE development in 9 coastal provinces and cities in China showed a downward trend, but remained relatively stable. The average remained between 0.180 and 0.195, decreasing from 0.186 in 2012 to 0.184 in 2022, with a relatively small decrease. From a regional perspective, Hebei has the highest level of marine ecology, with an average of 0.230. On the one hand, the economic foundation of Hebei Province is relatively weak. On the other hand, according to the original data, its industrial emissions and degree of exploitation of natural resources are both low, resulting in a higher level of marine ecology. Liaoning, Jiangsu, Guangxi, and Hainan also have high levels of marine ecology. The level of marine ecological development in Shandong, Fujian, and Guangdong is relatively low. These three regions are rich in marine resources and have a high degree of development in marine natural resources. The proportion of its fourth type and inferior fourth type seawater is at a relatively high level, therefore the level of ecological development is relatively low. However, Zhejiang has the lowest level of marine ecology, similar to Shandong, Guangdong, and other places, with a high level of marine natural resources. And the P&I-CIV seawater is also relatively high, so the level of marine ecology is slightly lower than that of other regions.

Based on the weight calculation of evaluation indicators, the EIS for the development level of marine TF-I in China from 2012 to 2022 was used to solve the problem. Table 8 shows the measurement results of each indicator.

In Table 8, from 2012 to 2022, the overall level of marine S&T innovation development in the nine coastal provinces of China has shown an upgraded trend year by year. The average has risen from 0.058 in 2012 to 0.125 in 2022. Liaoning, Shandong, Jiangsu, and Guangdong have achieved the greatest improvement in the level of MTI and development. Liaoning increased from 0.027 in 2012 to 0.107 in 2022, Shandong from 0.131 to 0.240, Jiangsu from 0.101 to 0.182, and Guangdong from 0.120 to 0.336. From a regional perspective, Shandong, Jiangsu, and Guangdong have a relatively high level of MTI, with an average level of over 0.15 in these three provinces. Liaoning, Zhejiang, and Fujian also have strong levels of MTI, with an average level of over 0.05 in these three provinces. However, the innovation level of marine technology in Hebei, Guangxi, and Hainan is relatively weak, with an average level of less than 0.05. The results indicate that China has realized that relying solely on resource investment to pursue marine economic growth in the past can no longer cater for the requirements of sustainable development. Therefore, strengthening the development of marine high-tech and shifting to a marine economic growth model led by technological progress has become a rigid demand.

To display the dynamic response relationship between variables, pulse response functions were used to explore the relationship between the three. In order to fully depict the long-term dynamic impact effect between these three, the Monte Carlo method was used for 200

Table 6
Measurement results of China's MED level.

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Mean value
Hebei	0.046	0.048	0.029	0.043	0.048	0.049	0.050	0.058	0.057	0.056	0.070	0.050
Liaoning	0.062	0.058.	0.061	0.069.	0.083	0.080	0.088	0.093	0.083	0.079	0.080	0.076
Shandong	0.129	0.107	0.111	0.134	0.148	0.162.	0.173	0.200	0.216	0.230	0.244	0.169
Jiangsu	0.072	0.070.	0.078	0.087	0.097	0.101	0.104	0.115	0.122	0.131	0.134	0.101
Zhejiang	0.065	0.070	0.080	0. 085	0.096	0.103	0.109	0.116.	0.131	0.142	0.146	0.104
Fujian	0.094	0.098	0.096	0.107.	0.115	0.117	0.126	0.139	0157	0.172	0.200	0.129.
Guangdong	0.100	0. 122	0.133.	0.158	0.169	0.190	0.201.	0.233	0.250	0.274	0.301	0.194
Guangxi	0.025	0.026.	0.023	0.028	0.026	0.031	0.033	0.036	0.038	0.040	0.043	0.032
Hainan	0.033	0.037	0.034	0.039	0.045	0.048	0.050	0.049	0.055	0.062	0.066	0.047
Mean value	0.069	0.071	0.072	0.083	0.092	0. 098	0.104	0.115	0.123	0.132	0.143	0.103

Table 7
Measurement results of China's MEE development level.

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Mean value
Hebei	0.210	0.217	0.228	0.236	0.235	0. 234	0.238	0.237	0.239	0.226	0.229	0.230
Liaoning	0.203	0.207	0.197	0.210	0.201	0. 204	0.204	0.204	0. 207	0.199	0.210	0. 204
Shandong	0.168	0. 144	0. 163	0.159	0.162	0.161	0.165	0. 154	0.153	0.131	0.134	0. 154
Jiangsu	0.206	0.211	0.211	0.202	0.210	0.212	0.213	0.204	0.209	0.210	0.210	0. 209
Zhejiang	0.149	0. 142	0. 142	0.140	0.138	0. 136	0.132	0.133	0. 133	0.127	0.122	0. 136
Fujian	0.174	0.176	0. 174	0.187	0.175	0. 187	0.182	0.183	0.158	0.151	0.159	0.173
Guangdong	0.139	0.142	0. 139	0.156	0.158	0. 153	0.158	0.153	0.155	0.153	0.140	0. 150
Guangxi	0.209	0.209	0. 209	0.219	0.222	0.225	0.229	0.231	0.232	0.231	0.228	0.222
Hainan	0.219	0.218	0.217	0.223	0.222	0.220	0.221	0.218	0.216	0.214	0.221	0.219
Mean value	0.186	0.185	0.187	0.193	0.191	0.193	0.193	0.191	0. 189	0.182	0.184	0.189

Table 8
Measurement results of the innovation and development level of china's marine S&T—F.

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Mean value
Hebei	0. 042	0.035	0. 040	0.027	0.044	0.042	0.043	0.046	0.044	0.043	0.044	0.041
Liaoning	0.027	0.029	0.049	0.059	0.071	0.075	0.074.	0.077	0.129	0.106.	0.107	0.073
Shandong	0.131	0. 144	0.164	0.166	0.192.	0.216	0.225	0.243	0.236.	0.226	0.240.	0.198
Jiangsu	0.101	0.112	0. 129	0.153	0.171	0.178	0.185	0.206	0.216	0.171	0.182	0.164
Zhejiang	0.044	0.047	0. 064	0. 064	0.075	0.083	0.090	0.091	0.098	0.092	0.098	0.077
Fujian	0.044	0.048	0.058	0.056	0.062	0. 068.	0.068	0.075	0.071	0.072	0.072	0.063
Guangdong	0.120	0.132	0.143	0.160	0.169	0.197	0.217	0.245	0.305	0.291	0.336	0.211
Guangxi	0. 001	0.002	0.016	0.017	0.019	0.018	0.018	0.052	0.058	0.019	0.021	0.022
Hainan	0.009	0.013	0.015	0.017	0.019	0.019	0.020	0.026	0.027	0.031	0.029	0.020
Mean value	0.058	0. 062	0.075	0.080	0.091	0.099	0.104	0.118	0.132	0.117	0.125	0.097

simulations, set at 10 periods. Fig. 3 shows the pulse response functions of these three and themselves. In the figure, the vertical axis represents the direction and degree of response of the variable to the impact, while the horizontal axis represents the number of periods. The solid line in the middle is the curve of the pulse response function. The shaded areas on both sides represent a 95% confidence interval.

In Fig. 3, there is a mutually reinforcing relationship between TF-I, MED, and MEE development. The impact of TF-I on the ME and MEE has both short-term and long-term characteristics, which can promote the MED and industrial upgrading. Moreover, appropriate environmental regulations are needed to protect the MEE.

The specific factors that lead to differences in the level of marine ecological development among different provinces include but are not limited to the industrialization level and pollution emissions of each province, the degree of marine resource development, the strictness and effectiveness of environmental protection policies implemented, and technological innovation capabilities. For example, in some regions, due to active efforts in technological innovation and the transformation of the marine industry, the level of marine ecological development is relatively high. In some regions, although the marine industry started early, it has been relying on traditional heavy industry for a long time and has not been effectively transformed. Once there are deficiencies in

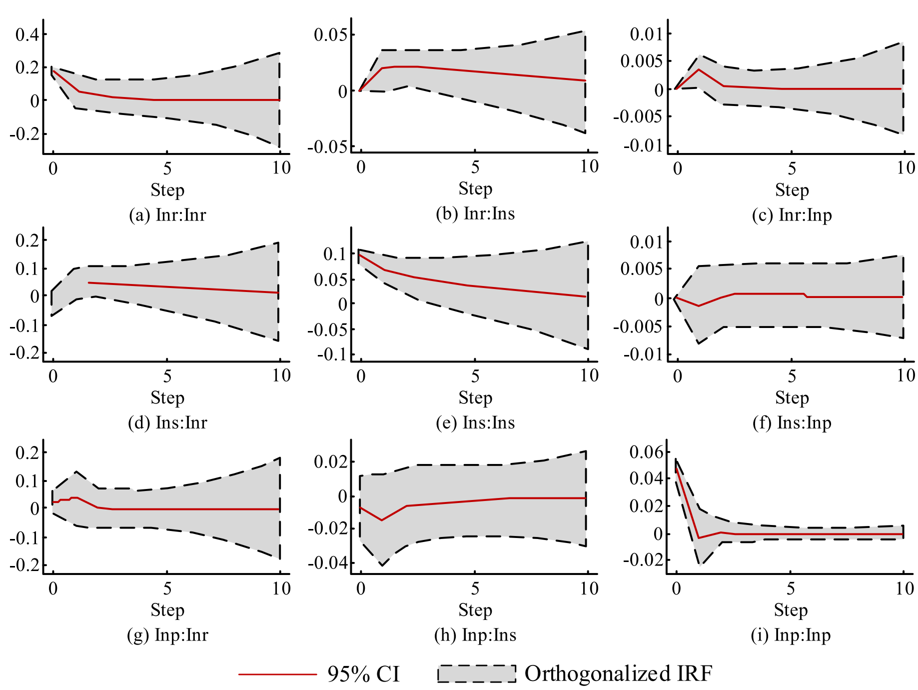

Fig. 3. Pulse response function diagram of the development level of China's ME, ecology, S&T financial innovation.

the industrial configuration and environmental protection measures of the region, the limited improvement of its marine ecological development level will be very limited.

4.2. Analysis of the symbiotic relationship between China's ME and MEE development under TF-I

This study used EM-CV method to measure the level of China's MED, ecology, and technological innovation. On this basis, the measurement results of the coupling degree of ME, ecology, TF-I in China's coastal areas were constructed. Table 9 shows the specific results.

Table 9 shows that between 2012 and 2022, the coupling between the ME and technological innovation in China's coastal areas has basically maintained a high level, but there are regional differences. Shandong, Jiangsu, Zhejiang, Fujian, and Guangdong provinces have maintained a high level of coupling development categories. The coupling degree between Shandong, Jiangsu, and Guangdong has remained above 0.9. Zhejiang and Fujian also maintain a high level of coupling, but due to the low level of technological innovation, the coupling is slightly lower than the first three provinces. Liaoning Province has achieved rapid development in MTI, and the interaction between economy and technological innovation has gradually developed from a period of adjustment to a high-level coupling. Compared with Liaoning Province, the coupling degree in Hebei Province is experiencing adjustment, and although the growth rate is slow, it has been increasing year by year. The coupling degree between Guangxi and Hainan is relatively low, and they are in the transitional stage from low-level coupling to the running-in period and entering the running-in period, respectively. In addition, the extensive MED mode and low-level technological innovation have led to a lack of organic integration between technological innovation and the economic environment, hindering the MED. It has not alleviated the pressure of economic development on ecology, resulting in difficulties in coordinating the MED and MEE.

Based on the calculated index of China's marine ecological development, economic development, and technological innovation development level, substituting it into the formula can calculate the endogenous growth rate for each year from 2013 to 2022. Then, the values of each level and endogenous growth rate are substituted into the formula. The symbiotic effect coefficient of China's ME on MEE and the symbiotic coefficient of China's MEE on ME were obtained from the technological innovation in various regions from 2013 to 2022. Table 10 shows the measurement results of the symbiotic coefficient of marine ecological economic development level in the northern coastal provinces.

Table 10 shows that overall, Hebei and Liaoning provinces in the northern coastal provinces exhibit a reverse symbiotic relationship. Under the investment of technological innovation and capital, the MED will hinder the MEE development. Under the investment of technological innovation and other factors, the MEE development will also hinder the MED. The main reason is that the ME in Hebei Province started relatively late and the development of emerging industries is still in its early stages, thus hindering the MED and ecology. The situation in Liaoning Province is similar. Although the ME started early and marine S&T have been improved, the development model of the ME in Liaoning Province is still relatively extensive due to its leading position in the discharge of marine solids and wastewater. This leads to mutual hindrance between the development of ME and ecology. Shandong Province is in a state of alternating parasitism and mutualism. However, the ME of Shandong Province is still influenced by traditional industries, and the driving force of emerging marine industries has not yet been fully utilized, and the efficiency of scientific research achievements conversion needs to be enhanced. Table 11 shows the measurement results of the symbiotic coefficient of marine ecological economic development level in central coastal provinces.

In Table 11, Jiangsu Province, one of the central coastal provinces, is generally in a transition from parasitic relationships to mutually beneficial symbiosis. The main reason is that the marine industry structure in Jiangsu Province is relatively reasonable. Although Jiangsu Province's ME started relatively late, as a focus area of national strategy, its ME has developed rapidly. Overall, Zhejiang Province belongs to a reverse symbiotic relationship, mainly due to its low ability to innovate in marine technology and the low proportion of emerging marine industries. Moreover, the development model still relies on increasing the development of marine resources as the main means to achieve economic development. In addition, the unfavorable pollution regulation in Zhejiang Province has led to a high P&I-CIV seawater, resulting in an imbalance in the MED and MEE, which hinders each other. Overall, Fujian Province also belongs to a reverse symbiotic relationship. The innovation capacity of marine technology in Fujian Province is relatively low, unable to meet the development needs of emerging marine industries, and traditional industries still dominate. In addition, the intensive aquaculture of seawater in Fujian Province has also led to a high proportion of four types and inferior four types of seawater, affecting aquaculture production and causing disharmony in the development of ME and MEE, both of which hinder each other. Table 12 shows the measurement results of the symbiotic coefficient of marine ecological economic development level in southern coastal provinces.

In Table 12, Guangdong and Shandong provinces in the southern coastal provinces generally belong to a parasitic relationship of economic benefits. The marine industry structure in Guangdong Province is relatively reasonable, but the intensity of industrial structure adjustment is not large enough. Moreover, there is a problem of weak development in emerging industries in Guangdong Province, which hinders the MED and MEE. However, with the emphasis on developing emerging marine industries in the "12th Five Year Plan" and "13th Five Year Plan", Guangdong Province's marine S&T innovation ability continues to improve. The structure of its marine industry is constantly optimizing, and emerging marine industries are also gradually growing. However, there are still issues of imbalanced and insufficient development in the marine industry of Guangdong Province. The MED is still dominated by traditional industries, and the conversion rate of scientific research achievements is relatively low, resulting in some new industries not fully exerting their new driving forces. Overall, Guangxi Zhuang Autonomous Region and Hainan are in a reverse symbiotic relationship. The ME in these two regions started relatively late and the level of technological

Table 9
Measurement results of the coupling degree of ME ecology S&T financial innovation in coastal areas of China.

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Mean value
Hebei	0.739	0.714	0.650	0.633	0.724	0.721	0.724	0.756	0.745	0.753	0.775	0.721
Liaoning	0.713	0.719	0.81 8	0.844	0.895	0.896	0.905	0.913	0.935	0.929	0.920	0.863
Shandong	0.992	0.990	0.984	0.996	0.993	0.990	0.990	0.982	0.983	0.969	0.967	0.985
Jiangsu	0.903	0.903	0.923	0.943	0.951	0.955	0.957	0.965	0.967	0.982	0.983	0.948
Zhejiang	0.865	0.894	0.938	0.942	0.965	0.976	0.985	0.986	0.990	0.984	0.987	0.956
Fujian	0.861	0.875	0.905	0.891	0.917	0.921	0.925	0.937	0.941	0.937	0.918	0.912
Guangdong	0.991	0.998	0.999	0.999	0.999	0.994	0.995	0.981	0.960	0.955	0.923	0.981
Guangxi	0.242	0.275	0.505	0.529	0.534	0.548	0.550	0.707	0.728	0.582	0.608	0.528
Hainan	0.467	0.523	0.535	0.567	0.603	0.612	0.624	0.672	0.694	0.726	0.716	0.613

Table 10
Measurement results of symbiotic coefficient of marine ecological economic development level in northern coastal provinces.

/	/	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Hebei	α	−0.233	−0.392	−0.455	−4.823	−6.509	−0.105	−6.129	−0.042	−5.773	−0.081
	β	−0.008	−3.914	0.061	−0.074	−0.001	−0.005	−0.045	−3.721	−3.654	−0.105
	/	Reverse symbiosis	Reverse symbiosis	Parasitic relationship	Reverse symbiosis	Reverse symbiosis	Reverse symbiosis	Reverse symbiosis	Reverse symbiosis	Reverse symbiosis	Reverse symbiosis
Liaoning	α	−0.110	−4.513	−0.345	−6.485	−0.042	−6.724	−0.009	−0.037	−9.330	−0.115
	β	−3.025	−0.041	−0.054	−0.065	−4.587	−0.016	−0.013	−4.461	−5.855	0.002
	/	Reverse symbiosis	Reverse symbiosis	Reverse symbiosis	Reverse symbiosis	Reverse symbiosis	Reverse symbiosis	Reverse symbiosis	Reverse symbiosis	Reverse symbiosis	Parasitic relationship
Shandong	α	−6.870	−0.019	−9.045	0.001	−7.351	0.013	−6.651	−6.120	−5.514	0.013
	β	−5.979	0.017	0.025	0.025	0.033	0.026	0.047	0.021	0.006	0.006
	/	Reverse symbiosis	Parasitic relationship	Parasitic relationship	Mutual benefit and symbiosis	Parasitic relationship	Mutual benefit and symbiosis	Parasitic relationship	Parasitic relationship	Parasitic relationship	Mutual benefit and symbiosis

Table 11
Measurement results of symbiotic coefficient of marine ecological economic development level in central coastal provinces.

/	/	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Jiangsu	α	−0.054	−0.002	−9.762	−0.032	−0.004	−0.003	−8.945	0.001	0.001	0.001
	β	−5.673	0.062	0.062	0.068	0.027	0.019	0.062	0.043	0.048	0.006
	/	Reverse symbiosis	Parasitic relationship	Parasitic relationship	Parasitic relationship	Parasitic relationship	Parasitic relationship	Parasitic relationship	Mutual benefit and symbiosis	Mutual benefit and symbiosis	Mutual benefit and symbiosis
Zhejiang	α	−7.171	−0.011	−7.746	−7.387	−7.347	−7.380	−0.005	−0.002	−6.521	−5.933
	β	−0.054	−0.129	−0.026	−0.088	−0.035	−0.029	−0.029	−0.073	−0.054	−0.022
	/	Reverse symbiosis	Reverse symbiosis	Reverse symbiosis	Reverse symbiosis	Reverse symbiosis	Reverse symbiosis	Reverse symbiosis	Reverse symbiosis	Reverse symbiosis	Reverse symbiosis
Fujian	α	−0.038	−4.447	−0.195	−4.471	−0.148	−4.628	−0.016	−4.350	−4.021	−0.063
	β	−0.044	−3.778	−0.088	−0.068	−0.013	−0.065	−0.093	−0.119	−0.129	−0.252
	/	Reverse symbiosis	Reverse symbiosis	Reverse symbiosis	Reverse symbiosis	Reverse symbiosis	Reverse symbiosis	Reverse symbiosis	Reverse symbiosis	Reverse symbiosis	Reverse symbiosis

Table 12
Measurement results of symbiotic coefficient of marine ecological economic development level in southern coastal provinces.

/	/	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Jiangsu	α	−0.008	−7.922	−0.007	−0.001	−6.115	0.010	−5.755	0.006	−5.294	−4.744
	β	0.033	0.006	−0.007	0.002	0.012	0.001	0.001	0.002	0.024	0.002
	/	Parasitic relationship	Parasitic relationship	Reverse symbiosis	Parasitic relationship	Parasitic relationship	Mutual benefit and symbiosis	Parasitic relationship	Mutual benefit and symbiosis	Parasitic relationship	Parasitic relationship
Zhejiang	α	−0.681	−0.108	−0.858	−0.369	−0.151	−0.235	−0.129	−0.041	−1.819	−4.027
	β	−0.111	−0.949	−0.122	−3.590	−0.086	−0.044	−0.050	0.029	−0.028	−0.052
	/	Reverse symbiosis	Reverse symbiosis	Reverse symbiosis	Reverse symbiosis	Reverse symbiosis	Reverse symbiosis	Reverse symbiosis	Parasitic relationship	Reverse symbiosis	Reverse symbiosis
Fujian	α	−2.507	−3.050	−0.360	−3.614	−3.523	−0.008	−3.356	−4.481	−4.133	−0.199
	β	−0.157	−2.441	−0.178	−0.152	−0.048	−0.062	−2.585	−0.097	−0.101	−0.052
	/	Reverse symbiosis	Reverse symbiosis	Reverse symbiosis	Reverse symbiosis	Parasitic relationship	Reverse symbiosis	Reverse symbiosis	Reverse symbiosis	Reverse symbiosis	Reverse symbiosis

innovation was low, resulting in the proportion of the marine primary industry always ranking among the top in the country. Its coastal economy still relies mainly on mariculture, fishing, and aquatic product processing, which has led to the development form of mutual obstruction between ME and ecology. The robustness analysis is shown in Table 13.

The robustness analysis of time series at MED, MEE, and MTI levels was conducted using unit root tests (ADF and PP) and KPSS tests, and the *p*-values showed that these sequences were stable at the general significance level. In addition, both cross-sectional correlation tests and tests for different hysteresis periods in the PVAR model indicate that the model results are robust. Therefore, the research model exhibits high reliability under various key tests and can be used to analyze the dynamic relationship of China's marine economic system.

From the result data, it can be seen that there are significant differences in the development level and coupling status of marine economy and marine ecological environment among coastal provinces in China.

Table 13
Measurement results of symbiotic coefficient of marine ecological economic development level in southern coastal provinces.

Inspection method	Select variables/ parameters	Statistics	*P* value	Robustness conclusion
Unit Root Test(ADF)	MED level	−3.5	0.045	Steady
Unit Root Test(PP)	MEE level	−4.2	0.03	Steady
Unit Root Test(KPSS)	MTI level	0.15	0.1	Steady
Cross section correlation test	All variables	1.5	0.12	Steady
PVAR with different hysteresis periods	Lag period 1	−4.5	0.035	Steady
PVAR with different hysteresis periods	Lag period 2	−4.25	0.04	Steady

For example, the innovation level of marine technology and finance in Shandong, Guangdong and other places is relatively high, which may be attributed to a good industrial foundation and technological innovation ability. However, although the development level of marine ecological environment has also improved, the growth rate is relatively slow. This may be due to the lack of effective protection and restoration of the ecological environment while implementing technological innovation. On the other hand, regions like Hebei and Guangxi, due to their late start in marine economy and relatively low investment in technological innovation, have relatively low levels of development in marine ecological environment. Overall, there is not a complete positive correlation between the development of the marine economy and the development of the marine ecological environment. Data from some regions even shows a "reverse symbiotic" relationship between the two, indicating that finding a balance between the development of the marine economy and the protection of the marine ecological environment is still a key issue that coastal provinces need to face.

In the analysis, the development of marine economy and technology in each province is showing a growing trend. The specific factors driving this growth are multifaceted, and the impact on policies is manifested in two levels: the first is the driving effect of policies, and the second is the feedback effect of policies in adjustment. In terms of policy promotion, the government's strategic planning and policy support are important driving forces for the development of marine economy and technology. For example, during the 12th and 13th Five Year Plans, Guangdong Province emphasized the development of emerging marine industries and the enhancement of technological innovation capabilities. Its related policies include financial support, tax reduction, government procurement, and market development measures, which effectively promote the optimization and upgrading of the province's marine industry structure. Especially in the cultivation, technological research and industrialization of high-tech enterprises, policies provide urgently needed financial funds and market environment. In addition, the formation and adjustment of policies reflect the sustained dynamic balance between economic development and ecological protection. For example, the rapid development of the marine economy in Jiangsu Province has benefited from policy attention and investment in emerging industries, resulting in a more reasonable industrial structure and lower P&I-CIV (Ship Pollution and Civil Liability Insurance Agreement) water quality. This indicates that when implementing policies, Jiangsu Province can adjust policies in a timely manner based on the dynamic development of the marine economy, thereby finding a balance between economic growth and environmental protection. When analyzing the interactive impact of economic and technological growth, it was found that technological and financial innovation played a key role in promoting marine economic growth. Specifically, R&D investment has led to the launch of new products and services, which have played an undeniable role in promoting the growth of the marine economy. Taking Zhejiang as an example, although its marine technology innovation capability is relatively low, with the gradual development of marine related industries, it has shown certain vitality in TF-I, especially in the fields of shipbuilding and marine biopharmaceuticals, which have gradually formed strong support for the growth of the marine economy.

In order to address the challenge of combining economic growth with ecological sustainability, based on the analysis of the dynamic relationship between technological and financial innovation and ecological development in this study, it is necessary to first strengthen technological innovation. Improve the application efficiency of ecological and environmental protection technologies, promote industrial structure transformation, and promote environmentally friendly and resource-saving production methods; Secondly, we can improve the financial market system and increase investment and financing support for energy conservation and environmental protection, marine high-tech, and sustainable development; Finally, we can strengthen the supervision of ecological environment and the construction of laws and regulations, formulate and implement stricter environmental protection standards, and ensure that economic activities do not cause irreversible damage to the ecosystem. This can effectively protect and restore the ecological environment while ensuring economic growth, and achieve green and sustainable development.

In the long run, the development of China's marine economy will further shift from scale expansion to quality and efficiency growth, and the high-tech marine industry will become a new driving force for economic development. In terms of marine ecology, by vigorously developing green industries such as marine biomedicine and marine new energy, we will gradually reduce damage to the marine environment and improve marine ecological health. However, if the development of marine resources and the control of land-based pollution are not effectively managed, the resilience of marine ecosystems may be weakened, biodiversity may decline, and the quality of the marine environment may face further threats. Especially in coastal areas, attention should be paid to issues such as overfishing, disorderly expansion of aquaculture in the sea, and blind development of the coastline.

5. Policy recommendations

Based on the results of this study, five developmental policy recommendations are proposed to improve the sustainability of China's oceans.

Firstly, develop a green marine economy. By providing financial and tax incentives to support innovation in marine technology, especially in the fields of new energy and biomedicine, we aim to reduce the negative impact of traditional marine industries on ecology.

Secondly, strengthen maritime management. Develop a cross regional sea area collaborative management mechanism, optimize marine spatial planning, strictly control coastline development, and ensure marine ecological security.

Thirdly, resource protection and restoration. Create marine protected areas, prohibit or restrict the excessive use of marine resources, and encourage projects for the restoration and natural regeneration of marine ecosystems.

Fourthly, strengthen marine environmental monitoring. Utilizing modern technologies such as satellite remote sensing and drone patrols, implementing full time and space monitoring and real-time data analysis to prevent and respond to marine environmental events in a timely manner.

Fifth, enhance public awareness and participation in environmental protection. Intensify publicity and education on marine protection, establish a multi-party network for marine environmental protection, and activate the enthusiasm and creativity of all sectors of society for participation. In addition, considering the uneven development between regions, policy implementation should be tailored to local conditions, giving more attention and resource allocation to areas with lower levels of marine development or fragile marine ecosystems.

In addressing the challenges between marine economic growth and ecological environment protection, the study proposes to first promote international cooperation and exchange. As the ocean has no boundaries, protecting the marine environment requires joint efforts from all countries. We can strengthen international cooperation, share experiences in protecting the marine environment, and jointly promote the development of the marine economy; Secondly, promote scientific research innovation. Encourage and support research institutions and enterprises to conduct scientific research and innovation in marine economy and ecological environment protection, such as developing new environmental protection technologies and marine resource utilization technologies; Strengthen legislation again. Improve relevant laws and regulations on marine environmental protection and rational utilization of marine resources, and impose strict legal sanctions on behaviors that damage the marine environment; Afterwards, promote green consumption. By raising public awareness of environmental protection and promoting the selection of products and services with minimal impact on the environment, enterprises can move towards green development; Finally, establish a long-term mechanism. Especially in areas such as resource utilization and environmental pollution control, a long-term and effective management system and technical support are needed to ensure that policy implementation is not a temporary measure, but a lasting guarantee.

6. International applicability analysis of research

In order to address the challenge of combining economic growth with ecological sustainability, based on the analysis of the dynamic relationship between technological and financial innovation and ecological development in this study, it is necessary to first strengthen technological innovation. Improve the application efficiency of ecological and environmental protection technologies, promote industrial structure transformation, and promote environmentally friendly and resource-saving production methods; Secondly, we can improve the financial market system and increase investment and financing support for energy conservation and environmental protection, marine high-tech, and sustainable development; Finally, we can strengthen the supervision of ecological environment and the construction of laws and regulations, formulate and implement stricter environmental protection standards, and ensure that economic activities do not cause irreversible damage to the ecosystem. This can effectively protect and restore the ecological environment while ensuring economic growth, and achieve green and sustainable development.

7. Suggestions for future research directions

Based on the results of this study, it is suggested that future research should focus on interdisciplinary research, case and comparative studies, innovation in sustainability assessment methods, policy simulation and optimization, and research on ecological compensation mechanisms.

In interdisciplinary research, theories and methods from multiple disciplines such as economics, ecology, oceanography, and sociology should be combined to study the interaction and balance between marine economy and ecological environment from a systems science perspective; In terms of case studies and comparative studies, conduct in-depth case studies on regions where relevant policies have been implemented, and summarize the experiences and lessons learned from successes and failures. At the same time, international comparative research can be conducted to learn from and draw on the advanced experiences and practices of other countries in balancing marine economy and ecological environment; In terms of innovation in sustainability assessment methods, develop and improve the marine economy and ecological environment sustainability assessment system, including methods such as ecological footprint, biodiversity indicators, and ecological service value assessment, to quantitatively analyze the impact of economic activities on the ecological environment; In terms of policy simulation and optimization, computer simulation technology is used to simulate the implementation effects of marine economy and ecological policies, evaluate the long-term impact of different policy combinations, and find the optimal strategy combination; In terms of ecological compensation mechanism research, research and establish an economic compensation mechanism for marine ecological environment protection, including fishery transformation subsidies, marine protected area management compensation, etc., to ensure the implementation of ecological protection through economic incentives.

8. Conclusion

This study constructed an EIS that includes marine technology and financial innovation, and used EM-CV method to calculate the weights. Furthermore, the least squares decision model was introduced for comprehensive weight analysis. Based on this, the level of MED, MEE development, and marine TF-I development in 9 coastal provinces were measured. The results showed that during the inspection period, the MED level of 9 coastal provinces generally increased. Especially in provinces such as Shandong, Fujian, and Guangdong, the performance was relatively outstanding, with average values of 0.244, 0.200, and 0.301, respectively. However, the overall level of ecological development showed a downward trend, maintaining between 0.180 and 0.195. The ecological level of Hebei Province was outstanding, with an average of 0.230, while the ecological level of Zhejiang Province was relatively poor. TF-I was showing an growing trend year by year, with regions such as Shandong, Jiangsu, and Guangdong leading the way in development. In views of the symbiotic relationship between ME and ecological value, some regions such as Jiangsu and Guangdong provinces had transitioned towards mutually beneficial symbiosis. However, there were still some regions, such as Hebei, Liaoning, Zhejiang, etc., that had performed poorly. The issues of disharmony and inadequacy were more obvious. In summary, although China's coastal areas have made certain progress in ME, ecology, and TF-I, there are still regional differences and challenges in the coordinated development of ecology and economy.

The limitation of this study is that due to limited funding and limited data, the research mainly focuses on coastal provinces in China. To achieve wider applicability and universality, future research should expand to more regions and countries, and conduct more research on the interaction of marine ecosystems based on local characteristics, in order to promote the harmonious coexistence of marine economy and ecological development.

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CRediT authorship contribution statement

Yan Sun: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft. **Dongjing Chen:** Funding acquisition, Project administration, Resources, Software, Supervision, Visualization, Writing – review & editing. **Zhaohui Geng:** Data curation, Formal analysis, Software, Validation, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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