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Research on the dynamic co-evolution of the complex system of economy-innovation-environment of the marine industry in China

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Introduction: In the context of accelerating the construction of a marine power, relying on scientific and technological innovation to drive the high-quality growth of the marine economy and paying attention to the protection of the marine ecological environment are the strategic requirements for promoting the sustainable development of the marine industry in China.

Methods: This paper describes the development of marine industry as a complex system of marine economy-innovation-environment, that is, it describes the marine economy, marine innovation and marine environment as a complex system that interacts and restricts each other. Based on the theory of synergetics, a dynamic co-evolution model of the complex system of marine economy-innovation-environment is constructed, and the accelerating genetic algorithm is used to solve the model, so that the contribution degree of each subsystem and interaction effect between them are calculated. This paper uses this model to conduct an empirical study on the current situation of co-evolution of the complex system of marine economy-innovation-environment from 2003 to 2019 in China.

Results: The research results show that: (1) The order degree of the systems of economy, innovation and environment of the marine industry in China is on the rise; (2) At present, the systems of innovation and environment of the marine industry in China are in an evolutionary state, while the system of economy is showing a "recession" trend; (3) There are competition and cooperation between the system of economy-innovation-environment of the marine industry in China at the same time. The system of economy-environment is in a lose-lose state. The system of economy and innovation and the system of innovation and environment are in a win-lose complementary relationship.

Discussion: This result is conducive to the current transformation and development of China's marine industry, adjusting the direction of marine science and technology inputs, optimizing the structure of marine science and technology outputs, enhancing the coordinated development level of regional and even national marine systems, and providing policy reference for promoting multi-objective collaborative governance in marine management department and accelerating the process of high-quality marine development.

KEYWORDS

high-quality development, marine industry, economy-innovation-environment, complex system, co-evolution

Introduction

Under the new normal, China's economy has shifted from the stage of rapid growth to the stage of high-quality development. Since ocean is a strategic place for high-quality development, the marine industry has become a new engine of China's economic growth and plays an increasingly prominent role in the overall economic and social development of China. Statistics show that the total economic output value of the marine industry in China has jumped from more than 6 billion yuan in 1978 to 9038.5 billion yuan in 2021, with a contribution rate of 8% to national economic growth. However, there are many problems worthy of attention in the development of China's marine industry, such as scale-driven development, technical constraints, homogenization of spatial layout and low economic efficiency (Ren et al., 2018; Huo et al., 2020; Ye et al., 2021; Wu and Li, 2022), which indicate that the development mode of Marine industry needs to be transformed and improved to high-quality development. The key to high-quality development of marine industry is to adhere to innovation-driven development and green development, and lies in how to coordinate the relationship between marine economy, marine innovation and marine environment. The change of one of the three factors will bring about, drive and even restrict the development and change of other factors, thus affecting the overall promotion effect of high-quality development of the marine industry. The expansion of scale and efficiency of the marine economy can increase the investment in research and development, but also deepens the threat to the marine ecological environment (Chen and Ma, 2020; Wang Y. et al., 2021). Marine scientific and technological innovation will not only optimize the marine industrial structure and enhance economic vitality, but also provide technical tools for improving marine ecosystem services (Kang et al., 2020; Liu et al., 2021). The deterioration of marine ecological environment will restrict economic activities, and the relevant environmental regulation tools may also stimulate the innovative activities of the economic sector (Liu and Chen, 2022; Sun et al., 2023). In this case, it's urgently required that the three aspects can co-evolve. However, the existing studies mainly examine the coevolutionary relationship between these two factors, and rarely study coevolutionary relationships among the three aspects in a framework. Based on this, this paper depicts the development of marine industry as a complex system composed of the subsystems of marine economy, marine innovation and marine environment, and discusses the dynamic co-evolution of economy, innovation and environment of the marine industry from the perspective of synergetics.

The follow-up arrangement of this paper is as follows: the second part is the literature review, which summarizes the existing literature; the third part is the research method of this paper, which constructs the dynamic co-evolution model of the complex system of economy-innovation-environment of the marine industry in China, and expounds the optimization algorithm of this paper; the fourth part is the research results, which analyzes the empirical results of this paper; the fifth part is the research conclusion of this paper.

Literature review

In recent years, more research has been conducted on the relationship between economy, innovation and environment of marine industry development, but mainly from the correlation and coordination among the marine economy, innovation and environment.

The correlation emphasizes the relating mode or influence degree between the subsystems or elements of economy, innovation and environment in the development process of marine industry. The research on the interaction between marine innovation and marine economic development mainly focuses on exploring the dynamic response mechanism between marine technological innovation and marine economy. Some scholars believe that marine technological innovation can promote the optimization transformation of marine industrial structure, so as to promote the development of marine economy [Xu et al. 2020 (Xu et al., 2020); Wang et al. 2021 (Wang L. et al., 2021); Ren et al. 2021 (Ren and Ji, 2021)]. Shao et al. (2021) (Shao et al., 2021) took the offshore oil and gas industry in the Gulf of Mexico as the research object, discussed the impact of technological innovation on the industrial development, and found that technological innovation not only increases the oil and gas production, but also reduces the production costs. In addition, some scholars examined the coupling relationship between marine technological innovation capability and marine economy from a regional perspective and found that marine technological innovation provides growth impetus for the development of marine ecological economy, and the development of marine ecological economy provides basic guarantee for marine technology [Wang et al., 2020 (Wang et al., 2020); Yu et al., 2020 (Yu and Zou, 2020)]. In addition, some scholars believe that the development of the financial system is also crucial to the development of the marine economy and marine innovation. Su et al. (2021) (Su et al., 2021) found that financial development in China has a certain impact on the growth of the marine economy, but there is regional variability. Song et al. (2020) (Song et al., 2020) showed that there is a threshold effect on the impact of financial development on the growth of the marine economy.

The existing research on the relationship between the marine economy and the marine environment is reflected in the interactive effect between the marine economy and the marine environment [Hao et al., 2020 (Hao et al., 2020)], the green production of the marine economy [wu et al., 2018 (Wu, 2018)] and environmental governance (Gacutian et al., 2022) (Gacutan et al., 2022). The scholars mostly used the SBM model of unexpected output and other methods to regard carbon emission, waste and wastewater discharge as unexpected output, and found that the ecological efficiency of the marine economy will be overestimated if the environmental unexpected output is not considered (Sun, 2020; Du et al., 2021). Yu et al. (2019) (Yu and Bi, 2019) used co-word analysis, word frequency analysis and multi-dimensional scaling (MDS) to analyze the evolution law of marine environmental policies. Dutra et al. (2019) (Dutra et al., 2019) proposed an adaptive framework for marine resource governance under environmental change, and provided a governance system for coral reef fish resource management combined with case assessment. [Jiang et al. 2020 (Jiang et al., 2020)] based on the perspective of stakeholders, established a conceptual model of the relationship between the government, enterprises and non-profit organizations in the comprehensive marine environmental governance, analyzed the internal mechanism of managing the interactions, built a simulation model of the government, enterprises and non-profit organizations with the game theory, and used MATLAB platform to simulate and analyze the correlation between stakeholders and strategy selection. Tuda et al. (2019) (Omondi Tuda et al., 2019) built a framework for adaptive transboundary governance of the marine environment, enabling state and non-state actors to rely on each other to learn from and act on common environmental issues for effective transboundary resource governance.

The relationship between marine technological innovation and the marine environment is mainly reflected in the regulation of marine technology by the marine environment. Qin et al. (2021) (Lingui et al., 2021) discussed the impact of environmental regulation on the green total factor productivity (GTFP) of China's marine economy. Ren et al. (2022) (Ren and Chen, 2022) considered the rigid constraints of resources and negative environmental impacts, and analyzed the impact mechanism of green total factor productivity of China's marine economy. Ye et al. (2022) (Ye et al., 2022) used Tapio decoupling model to analyze the impact mechanism of environmental regulation on the decoupling of marine economic growth and marine environmental pollution. Chen et al. (2020) (Chen and Qian, 2020) compared and analyzed the dual impacts of different types of marine environmental regulations on the upgrading of marine manufacturing industry structure and the transfer of polluting industries based on the panel data of China's coastal areas from 2004 to 2017. Zheng et al. (2020) (Zheng et al., 2020) using the SE-SBM model and the generalized method of moments (GMM) and taking the data of 11 provinces and cities in China's coastal areas as samples, found that there is a Porter hypothesis effect in China's marine economy, and there is a U-shaped relationship between environmental regulation and economic efficiency. Sun et al. (2022) (Sun et al., 2022) used DEA method to discuss whether environmental regulation would promote green output bias. Some scholars examined the impact of marine economic development on marine environmental protection.

In the process of development of marine industry, the economy, innovation and environment are interrelated, and the dynamic coordination among system elements needs to be examined. Tsilimigkas et al. (2018) (Tsilimigkas and Rempis, 2018) analyzed the compatibility between marine economic activities (aquaculture and tourism) and marine protected areas in Crete, Greece and how to enhance the synergies between the two aspects. Zhu et al. (2019) (Zhu et al., 2019) constructed a comprehensive evaluation index system of the population-marine economy-environment system, adopted the coupling coordination degree model to identify the coupling coordination degree of the population-marine economy-environment system, and found that the sustainable development of the population-marine economy-environment system gradually improves as the coupling coordination degree increases. Liu et al. (2022) (Liu et al., 2022) used entropy method, coupling harmonious degree model and Tobit model to measure marine environmental quality, marine fishery economic quality, coordination and factors affecting coordination. Recently, some scholars have extended the research on the coordination between the two aspects to the marine innovation-economy-environment system. For example, the promotion of clean energy technology on islands can not only alleviate the energy shortage in the economic sector, but also greatly reduce the carbon emissions of the marine industry (Hernandez-Delgado, 2015).

In general, the existing research has studied the interaction between marine industrial economy, innovation and environment from the perspective of correlation and coordination, which has accumulated a large number of research results. At the same time, it is shown that the development of marine industry can be characterized as a complex system with coevolutionary characteristics. However, there are still some deficiencies in relevant research. On the one hand, although scholars have analyzed the internal mechanism of the complex system of the marine industry from different angles, they are more limited to the elements of certain two subsystems and lack the overall grasp of the system. On the other hand, their investigation of system coordination also focuses on the coordination of two subsystems, ignoring the complex interaction between the three subsystems, especially the marine environment. Even considering environmental factors, scholars mostly take the three aspects into consideration comparably, without carrying out any theoretical or empirical demonstration of the overall relationship structure of the system in advance, so they are unable to study the evolutionary relationship between competition and cooperation among the three aspects. In view of this, this paper will establish a co-evolution model of the economy-innovation-environment system of the marine industry, and examine its co-evolution status.

Methods and data description

This section explains the research methods and how data were collected and processed.

Synergistic evolutionary analysis of the synergy of marine economy-innovation-environment complex system

The Porter hypothesis states that properly designed environmental protection policies or environmental regulations can stimulate technological innovation while mitigating environmental pollution, commonly referred to as the "weak Porter hypothesis"; later, the "strong Porter hypothesis" was further developed, which points out that technological innovation while offsetting the cost of environmental compliance, it can further improve the profitability and competitiveness of enterprises. It can be seen that marine economy, innovation and environment are the key elements to accelerate the construction of high-quality sustainable development of the marine, and there is a close interaction and interdependence between the three, which can be regarded as a complex and synergistic compound system, namely the marine economy-innovation-environment system (Figure 1).

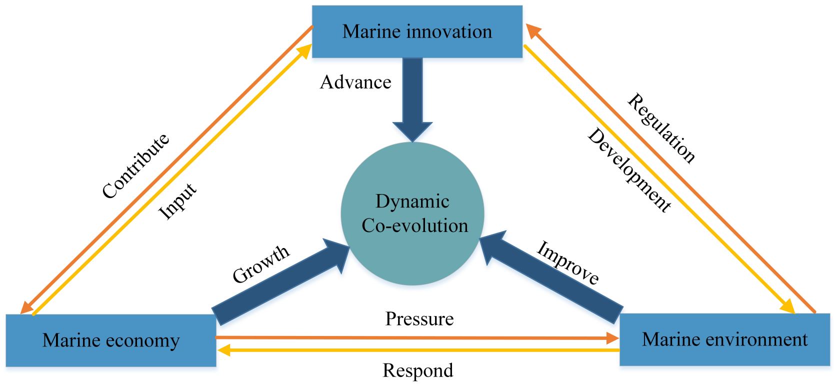

FIGURE 1
Dynamic co-evolution of complex system of economy-innovation-environment of China's marine industry.

In addition, under the theoretical framework of sustainable development, high-quality development of marine economy is the inevitable requirement of sustainable development, marine innovation-driven is the path choice of sustainable development, and high-level protection of marine environment is the goal of sustainable development, and the three are complementary and synergistic with each other. First of all, marine science and technology progress not only provides technical means for marine economic activities, but also provides tools for expanding the use of marine ecological environment services. Furthermore, the growth of marine economy provides more material support for marine science and technology innovation, but also intensifies the exploitation of marine resources and exacerbates the pressure on marine environment. Finally, the deterioration of the marine environment calls for strict regulatory policies to guide the transformation and upgrading of marine science and technology, while also urging the marine economy to respond by shifting to a greener, higher quality growth approach. In order for the marine complex system to develop in a healthier and more orderly direction, harmony and consistency among the system elements is required, that is, the level and trend of development of the three subsystems of marine economy, marine innovation and marine environment are kept in harmony. It can be seen that the marine economy, marine innovation and marine environment have both their opposing and unifying aspects, a relationship between competition and cooperation, and the synergy between them is an intrinsic factor for sustainable and coordinated development. Correctly handle the relationship between the three, make full use of the side of economy, innovation and environment that promote each other, reduce their side that hinder each other, accelerate the synergistic evolution between the three, and promote the high-quality development of marine economy.

Basic model

Synergetics was first established by H Haken. Its outstanding feature is that it can study the phase transition process of the system, so it can be well applied to the development and changes in social and economic systems. There are many subsystems in the whole complex system, and each system has its own self-organization movement. The nonlinear thinking of synergetics can effectively study the internal relationship of the complex system, thus providing help to solve the orderly evolution of the whole complex system. In order to construct the co-evolution model of the complex system of economy-environment-innovation of the marine industry, this paper uses the article of Bai et al. (2018) (Bai et al., 2018) and Sun et al. (2022) (Sun and Hao, 2022)for reference. First, it is assumed that the system evolution follows the Logistic rule and the comprehensive level of external input remains unchanged. Then, the development model of the order degree of a single subsystem is as follows:

$$\frac{dX}{dt} = \alpha X(1 - X) \tag{1}$$

In this equation, X is the order parameter of the system, α is the increment factor, while X on the right of the equation is the dynamic factor, (1-X) is the deceleration factor.

Order degree analysis

Suppose that the variable $\mu_i(i = 1, 2, \cdots, m)$ is the order parameter of the economy, innovation and environment system of the marine industry, and u_{ij} is the jth index of the ith order parameter, whose value is $X_{ij}(j = 1, 2, \cdots, n)$. α_{ij} and β_{ij} are the upper and lower limits of the upper order parameters at the critical point of system stability. In this paper, the maximum and minimum values of the indexes are selected. Then, the contribution coefficient μ_{ij} of economy subsystem, innovation subsystem and environment subsystem to the ordered complex system of marine industry can be expressed as:

$$\mu_{ij} = \begin{cases} (X_{ij} - \beta_{ij})/(\alpha_{ij} - \beta_{ij}), & \mu_{ij} \ \text{is a benefit index} \\ (\alpha_{ij} - X_{ij})/(\alpha_{ij} - \beta_{ij}), & \mu_{ij} \ \text{is a benefit index} \end{cases} \tag{2}$$

In formula (2), μ_{ij} is the contribution of the variable to the complex system of marine industry. The contribution coefficient constructed according to formula (2) has the following characteristics: μ_{ij} reflects the satisfaction degree of each index to achieve the goal, when μ_{ij} approaches 0, it means the most unsatisfactory, and when μ_{ij} approaches 1, it means the most satisfactory, so $0 < \mu_{ij} < 1$. The total contribution of the order degree of each order parameter in the economy subsystem, the innovation subsystem and the environment subsystem can be achieved through the integration method, which generally adopts the geometric average method and the linear weighted sum method:

$$\mu_i = \sum_{j=1}^{m} \lambda_{ij}\mu_{ij}, \sum_{j=1}^{m} \lambda_{ij} = 1 \tag{3}$$

In formula (3), μ_i is the contribution of the subsystem to the order degree of the total system, and λ_{ij} is the weight of each order parameter, which are determined by entropy weight method with reference to the research of Tomal (2021).

On the basis of literature research (Wang J. et al., 2021; Yu and Xing, 2021; Gou et al., 2022; Zhang and Wang, 2022), combined with the development of economy, innovation and environment of China's marine industry, the order parameter system of the dynamic co-evolution of economy-innovation-environment of China's marine industry is constructed, as shown in Table 1.

Co-evolution model of the complex system of marine industry

The basic model of synergetics (1) only considers the equation of a single subsystem, and cannot fully describe the relevant competitive role in the evolution process of the subsystems of economy, innovation and environment in the complex system of marine industry, so this paper attempts to introduce the parameter $\beta_{ij}(i,j = 1, 2, 3)$ to describe the impact effect of system i on system j.

Set F_1, F_2 and F_3 respectively to represent the subsystem of economy, the subsystem of environment and the subsystem of innovation in the complex system of marine industry, so as to obtain the co-evolution model of the economy-environment-innovation complex system:

$$\frac{dX_1}{dt} = f_1(X_1,X_2,X_3) = \gamma_1 = \alpha_1 X_1(1 - X_1 - \beta_{12}X_2 - \beta_{13}X_3) \tag{4}$$

$$\frac{dX_2}{dt} = f_2(X_1,X_2,X_3) = \gamma_2 = \alpha_2 X_2(1 - X_2 - \beta_{21}X_1 - \beta_{23}X_3) \tag{5}$$

$$\frac{dX_3}{dt} = f_3(X_1,X_2,X_3) = \gamma_3 = \alpha_3 X_3(1 - X_3 - \beta_{31}X_1 - \beta_{32}X_2) \tag{6}$$

In the formula (4), (5) and (6), X_1,X_2,X_3 are respectively the development levels of F_1, F_2 and F_3; α_1, α_2 and α_3 are the increment coefficients of the three subsystems, which reflect the development degree of the economy subsystem, the innovation subsystem and the environment subsystem in the whole complex system of marine industry. If $\alpha_i > 0$, it indicates that the subsystem itself is at the level of optimization and improvement, and when $\alpha_i < 0$, the whole subsystem itself is in a deteriorating situation in the whole research range; $\alpha_i = 0$ indicates that there is no change on the whole and it is in a stable or saturated state. One of the three systems not only develops itself in an orderly way, but also influences the other two systems through competitive influence β. $\beta_{ij} > 0$ indicates that the two systems i,j have a competitive relationship, in this case, the benign development of one system will harm the development advantages of the other system, making one system subject to many constraints. $\beta_{ij} < 0$ describes the relationship between system i and system j as a win-win cooperation, in this case, the orderly

TABLE 1 List of order parameters of China's marine economy-innovation-environment complex system.

Subsystem	Dimension	Index name	Code	Index interpretation and calculation	Unit	Direction	Weight
Marine economy	Economic strength(A1)	Marine economic contribution	A11	Marine GDP/regional GDP	%	+	0.0317
		Per capita marine economic scale	A12	Marine GDP/permanent population size	10000 yuan	+	0.0501
		Coastline economic density	A13	Marine GDP/coastline length	100 million yuan/ km	+	0.0529
		Cargo throughput of port	A14	Cargo throughput of ports above designated size (including foreign trade)	10000 tons	+	0.0259
		Foreign exchange income from coastal tourism	A15	International tourism (foreign exchange) income in coastal areas	1 million dollars	+	0.0360
	Economic structure (A2)	Proportion of marine secondary industry	A21	Marine secondary industry GDP/marine GDP	%	-	0.1104
		Proportion of marine tertiary industry	A22	Marine tertiary industry GDP/marine GDP	%	+	0.1271
			A23			+	0.0542

(Continued)

TABLE 1 Continued

Subsystem	Dimension	Index name	Code	Index interpretation and calculation	Unit	Direction	Weight
		Non-fishing industry structure index		Output value of marine secondary and tertiary industries/number of marine employees	10000 yuan/ person		
		Marine industrial structure upgrading index	A24	Calculated according to formula ①	——	+	0.1156
		Marine industrial structure diversification index	A25	Calculated according to formula ②	——	+	0.0327
	Economic vitality (A3)	Marine economic growth rate	A31	Marine GDP growth compared with the previous year	%	+	0.1185
		Elastic coefficient of marine economic growth	A32	Marine GDP growth rate/regional GDP growth rate	—	+	0.1181
		Sea area utilization efficiency	A33	Added value of marine economy/area of sea area confirmed in the current year	%	+	0.0537
		Marine relative labor productivity	A34	The ratio of regional marine labor productivity to the coastal area as a whole	%	+	0.0269
		Comprehensive index of marine infrastructure	A35	Calculated according to formula ③;	——	+	0.0462
Marine innovation	Scientific and technological environment (B1)	Scale of marine scientific research institutions	B11	Number of marine scientific research institutions in coastal areas	1	+	0.0612
		Government support for marine scientific research institutions	B12	Government investment in the construction of marine scientific research institutions	10000 yuan	+	0.1561
		Resources of marine higher education	B13	Number of full-time teachers in marine universities	Person	+	0.0700
		Supply scale of marine talents	B14	Number of graduates with bachelor degree or above in marine major in the current year	Person	+	0.0558
		Supply structure of marine talents	B15	The proportion of graduates with postgraduate degree or above in marine major	%	+	0.0700
	Scientific and technological input (B2)	Personnel scale of marine scientific and technological activities	B21	Number of scientific and technological personnel of marine scientific research institutions	Person	+	0.0512
		Personnel structure of marine scientific and technological activities	B22	The proportion of personnel with postgraduate degree or above in marine scientific and technological activities	%	+	0.0488
		Marine scientific and technological topic	B23	Number of R&D topics	1	+	0.0572
		Scale of marine science and technology funds	B24	Fund income of marine scientific research institutions	10000 yuan	+	0.0471
	Scientific and technological output (B3)	Publication of marine scientific and technological papers	B31	Number of scientific and technological papers published by marine scientific research institutions	Paper	+	0.0482
		Publication of marine scientific and technological works	B32	Number of scientific and technological works published by marine scientific research institutions	Kind	+	0.0473
		Marine patent authorization	B33	Number of patents authorized by marine scientific research institutions	Piece	+	0.0799
		Output of marine scientific research education management service industry	B34	Added value of marine scientific research education management service industry	100 million yuan	+	0.0849

(Continued)

TABLE 1 Continued

Subsystem	Dimension	Index name	Code	Index interpretation and calculation	Unit	Direction	Weight
		Transaction scale of technology market	B35	Turnover of technology market in coastal areas	100 million yuan	+	0.1223
Marine environment	Ecological pressure (C1)	Main pollution sources directly discharged into the sea	C11	CODcr and ammonia nitrogen discharged into the sea per unit discharge outlet	10000 tons	-	0.0809
		Secondary pollution sources directly discharged into the sea	C12	Petroleum and total phosphorus discharged into the sea per unit discharge outlet	ton	-	0.0827
		Marine dumping of marine wastes	C13	Dredged material/sea area	$m3/km^2$	-	0.0690
		Utilization rate of mariculture	C14	Mariculture area/sea area	%	-	0.0815
	Environmental status (C2)	Coastline disaster loss	C21	Marine disaster loss/shoreline length	10000 yuan/ km	-	0.0786
		Tianjin Statistical Yearbook of Offshore Sea Water Quality	C22	Proportion of Class I and II seawater quality in offshore waters	%	+	0.0704
		Sea level rise	C23	Relative changes in sea level over the years	mm	-	0.0803
		Red tide range	C24	——	Km^2	-	0.0772
	Environmental response (C3)	Status of marine protected areas	C31	Area of marine protected area/area of regional sea area	%	+	0.0674
		Wastewater treatment project	C32	Operation cost of industrial wastewater treatment facilities	10000 yuan	+	0.0769
		Solid waste treatment project	C33	Industrial solid waste disposal volume	10000 tons	+	0.0742
		Investment in environmental protection	C34	Total investment in environmental pollution control/GDP	%	+	0.0798
		Regional environmental governance index	C35	Calculate according to formula ④	——	+	0.0810

① = $\sum k_i * h_i$, in the formula, k_i is the proportion of the GDP of the ith industry in the marine GDP, h_i is the industrial height value of the ith industry, which is assigned as 1, 2 and 3 according to the industrial height; ② = $\sum k_i * \ln(1/k_i)$, in the formula, k_i has the same meaning as above; ③ = $\sum w_j' p_j'$, in the formula, j = 1,2,3, which respectively represents the number of docks for production, star-rated hotels and coastal observation stations; p_j' is the data after standardization; w_j' is the index weight;
④ = $\sqrt[3]{Rate\ of\ comprehensive\ utilization\ of\ industrial\ waste * Rate\ of\ centralized\ sewage\ treatment * Rate\ of\ harmless\ disposal\ of\ garbage}$.
"-" indicates that the indicator has a negative impact on the orderliness of the system; "+" indicates that the indicator has a positive impact on the order of the system; "- -" means that there is no dimension; "%" indicates that the dimension of the indicator is a percentage.

development of one system will help the other system improve its own level, so as to realize the coordinated development between the two systems.

In current researches, the maximum likelihood method and the least square method are generally used to solve the parameters of the model. However, the co-evolution model of the economy-innovation-environment complex system of China's marine industry constructed in this paper belongs to a nonlinear model, the two conventional methods mentioned above are not fitted to solve the parameters of this model. Therefore, with reference to other research methods (Wang et al., 2019), this paper uses accelerating genetic algorithm (AGA) to solve the model parameters. Set the optimization function as:

$$Z = min\frac{1}{3}\left[\sum_{i=1}^{14}\left(r_1 - z_1^i\right)^2 + \sum_{i=1}^{14}\left(r_2 - z_1^i\right)^2 + \sum_{i=1}^{14}\left(r_3 - z_1^i\right)^2\right] \quad (7)$$

γ_1^i, γ_2^i and γ_3^i represent the evolution state of system EI, IE and EE in formula (4)-(6), and Z_1^i, Z_2^i and Z_3^i are the interannual variation values of the order degree of each system. The smaller the difference between the evolution state of the system and the interannual variation of its order degree, the higher the reliability of the simulation. In this paper, genetic algorithm is used to solve the above model and calculate relevant parameters in formulas (4)-(6). $i \in [1,14]$ represents the year. Constraint conditions and variable selection rules refer to relevant studies, and the initial intervals of α and β are set as $[-1,1]$ and $[-3,3]$ respectively.

Data description

In view of the availability of data, this paper takes China's marine industry from 2006 to 2019 as the research sample. The original data of marine economy comes from the *China Marine Statistical Yearbook*, *China Port Statistical Yearbook* and *China Tourism Yearbook*. The original data of marine science and technology are mainly from the *China Marine Statistical Yearbook*, and some are from the *China Statistical Yearbook*. The original data of the marine environment are mainly from the *Bulletin of the Environmental Quality of China's Offshore Areas*, the *Bulletin of China's Marine Disaster*, the *Bulletin of China's Sea Level* and the *China Environmental Statistics Yearbook* over the years. The regional and overall indexes such as population and GDP are from *China Statistical Yearbook*.

Results

In this section, the measurement results of the orderliness of the economic-innovation-environmental system of China's marine industry and the coevolutionary relationship between internal subsystems are expounded.

Analysis on the orderliness of the economy-innovation-environment system of China's marine industry

Combining the index system and entropy weight method constructed above, according to the order degree calculation formula (2), the contribution of the order degree of each order parameter in the economy subsystem, innovation subsystem and environment subsystem of China's marine industry can be obtained. Further, the order degree level of the economy subsystem, innovation subsystem and environment subsystem of China's marine industry can be obtained by using the simple weighted average method, as shown in Figure 2. In the sample period, the average order degree level of the economy, innovation and environment of China's marine industry is 0.3898, 0.4472 and 0.5705 respectively, which shows that the order degree level of the economy, innovation and environment of China's marine industry is not high. However, in comparison, the order degree level of the economy subsystem and innovation subsystem of China's marine industry is relatively low, while the order degree level of the marine environment subsystem is relatively high. It shows that since 2006, China has paid more and more attention to the protection of the marine environment, and focused more on "quality" development in the development of the marine industry. In general, in the sample period, the order degree of the economy subsystem, innovation subsystem and environment subsystem of China's marine industry showed an overall upward trend, indicating that the economy, innovation and environmental protection of China's marine industry have achieved considerable development in recent years. Especially after entering 2012, China's marine industry has shown a relatively rapid development level, the main reason of which is that in 2012, China put forward the strategy of becoming a maritime power, and the corresponding policies of adjusting marine industrial structure and optimizing industrial allocation received good results, leading to the rapid development of China's marine industrial economy and reasonable industrial structure.

However, there are great differences in the change track of the order degree of the economy, innovation and environment of China's marine industry. As shown in Figure 2, the order degree curve of the marine economy has multiple "U" shaped stages of change, indicating that the order degree of the economy system of China's marine industry fluctuates greatly and the stability of the system evolution is relatively low; the order degree of marine science and technology has

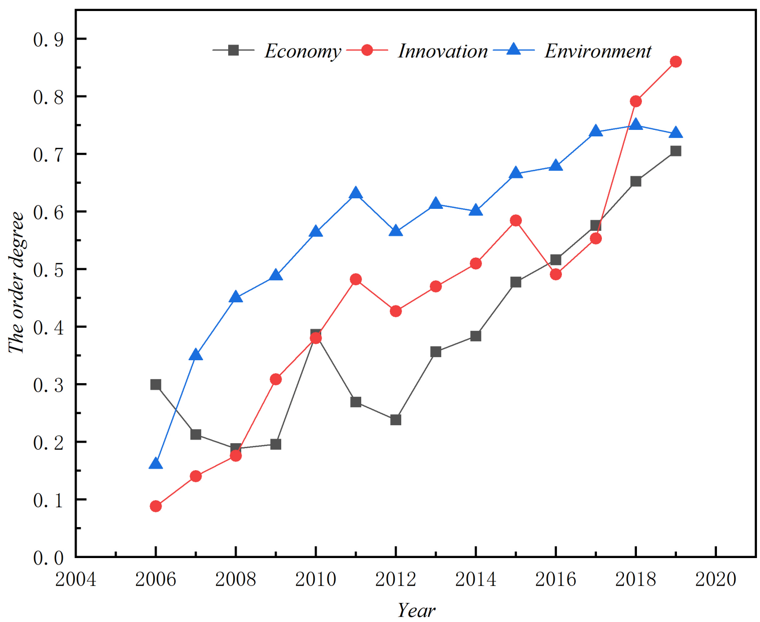

FIGURE 2
Change trend of the order degree of economy-innovation-environment of China's marine industry.

a large growth range and a stable growth trend, with an average annual change rate of 21.57%, indicating that the development of marine science and technology system is highly adaptable. The annual average value of the order degree of environment is the largest, and the annual average growth rate is between that of the economy system and that of the science and technology system, indicating that the evolution of the environment system of China's marine industry is stable and adaptable.

Analysis on the coordination relationship of the subsystems within the economy-innovation-environment system of China's marine industry

In this paper, genetic algorithm is used to solve the economy-innovation-environment co-evolution model of China's marine industry and analyze the coordination relationship between subsystems. The results are shown in Table 2. In Table 2, $\beta_{ij1}(i,j=1,2,3)$ *and* $\beta_{ij2}(i,j=1,2,3)$ denote the influence of two subsystems in the marine industry economic-innovation-environment complex system on another subsystem, respectively, such as row 1 indicates the influence of the marine innovation subsystem and the marine environment subsystem on the ocean. Because $\alpha_1 < 0$, we can find that the economy system of China's marine industry is in a state of decline. The possible reason is that in recent years, China's economic development has entered a new normal, and China's marine economy has entered a transition period from high-speed growth to medium-to-high-speed growth. China's marine industry has implemented the new development concepts in the development process, especially the structural adjustment of China's marine economic industry in 2011. However, $\alpha_2 > \alpha_3 > 0$ indicates that China's marine innovation system and environment system are in the state of evolution, and the innovation system has the fastest evolution speed. This shows that China's marine technology innovation and environmental protection have been in continuous development in recent years. Particularly, in the development of China's marine industry, China's marine technology innovation and environmental protection have always adhered to the concept of "innovation + green". In particular, since 2006, China has taken marine science and technology as one of the strategic deployment priorities of the *National Medium and Long-term Scientific and Technological Development Plan (2006-2020)*, and has continuously increased investment in scientific and technological innovation in the marine field, making China's marine innovation system more orderly. In addition, the Chinese government and local governments continue to attach importance to marine environmental protection, and gradually establish business systems such as marine environmental monitoring, marine oil and gas exploration and development environmental protection, marine dumping management and marine protected area construction. After the 18th National Congress of the Communist Party of China, China has incorporated the construction of marine ecological civilization into the overall layout of marine development, continuously explored top-level design, institutional guarantee, protection and restoration and other aspects, insisted on attaching equal importance to development and protection as well as pollution prevention and ecological restoration, scientifically and rationally developed and utilized marine resources, and maintained the marine natural reproduction capacity, continuously improving China's marine ecological environment

TABLE 2 Parameter calculation results.

Subsystem	α_i	β_{ij1}	β_{ij2}
Economy	-0.0188	0.4554	0.4925
Innovation	0.1235	-1.0866	2.7342
Environment	0.0353	1.4050	-1.7599

From β_{12} and β_{21}, it can be seen that the coordination relationship between the economy system and the innovation system of China's marine industry is not balanced: the improvement of the order degree of the innovation system is conducive to the evolution of the economy system, while the improvement of the order degree of the economy system has a more prominent inhibitory effect on the evolution of the order degree of the innovation system. The coordination relationship between the two systems is "biased towards the innovation system", which indicates that China does not take the economic growth of the marine industry as the only goal, but focuses more on the innovative development.

From β_{13} and β_{31}, it can be seen that the relationship between the economy system and the environment system of China's marine industry is "inhibition", a restrictive relation, that is, within the current structure system of China's marine economy system and environment system, there are two-way constraints between the order degree of the two systems. The development of the economy system hinders the protection of the environment, while the protection of the environment in turn delays the development of the economy system, which is mainly due to the irreplaceable space between the economy system and the environment system of marine industry, as well as the exclusive use and distribution of production factors. The total amount of various production factors in a specific area is limited, in this case, investing a certain quantity of certain resources or a certain amount of funds into the environment system will inevitably form the competition against another system. Although China has formulated a series of marine environmental governance policies to deal with the marine environmental problems caused by the sustainable development of the marine economy, and has made remarkable achievements, the depletion of marine resources, environmental degradation, loss of biodiversity, and increased vulnerability to climate change have become increasingly prominent.

From β_{23} and β_{32}, it can be seen that the coordination relationship between the innovation system and the environment system of China's marine industry is not balanced: the improvement of the order degree of the innovation system contributes to the orderly evolution of the environment system, while the improvement of the order degree of the environment system has a more prominent effect on the inhibition of the orderly evolution of the innovation system. The coordination relationship between the two systems is "biased towards the environment system", which indicates that the current achievements of China's marine technological innovation are widely used in marine environmental protection, promoting the restoration of marine ecology and the improvement of natural protection and environment, and realizing the sustainable use of marine environmental resources.

Conclusion

Based on the synergetics theory, this paper describes the high-quality development of marine industry as a complex system composed of three subsystems of marine economy, marine innovation and marine environment, analyzes the interrelationship between economy, innovation and environment, and establishes the complex co-evolution model of economy-innovation-environment of China's marine industry. In addition, this paper builds an index system on this basis and carries out an empirical study on the current evolution of the complex system of economy-innovation-environment of China's marine industry combined with the accelerating genetic algorithm and by using the data from 2006 to 2019. The main conclusions are as follows:

From the calculation results of the order degree, it can be seen that the order degree of the economy, innovation and environment system of China's marine industry showed an upward trend from 2006 to 2019, which indicates that the economy, innovation and environment of China's marine industry have achieved considerable development in recent years, but there is still a lot of room for improvement to achieve a completely orderly state.

It can be seen from the estimation results of model parameters that the innovation system and environment system of China's marine industry are in an evolutionary state, while the economy system is in a "recession" trend. From further analysis, it can be found that there are competition and cooperation between the economy-innovation-environment system of China's marine industry. The cumulative effect of the three systems shows that at present, China's marine economy-environment system is in a lose-lose situation, and the economy system and innovation system, as well as the innovation system and environment system, are in a win-lose complementary relationship.

The implications for the development of China's marine industry include: first, China's marine industry should focus on improving the recycling supply capacity of the marine system, and broaden the sources of marine science and technology innovation channels by creating larger scale and higher quality of marine economic benefits. Second, investment in marine science and technology should be increased, attention should be paid to the training and introduction of marine scientific research talents. Third, the government should introduce stricter marine ecological protection policies, so as to push back the scientific and technological innovation capacity of sea-related enterprises, such as innovating comprehensive supervision policies for marine ecosystems, establishing a full-coverage, grid-based and fine-grained monitoring system for the marine ecological environment; The Marine Environmental Protection Law and other regulations related to marine ecological protection should be revised and improved, focusing on the management system of outfalls into the sea, the environmental impact assessment mechanism of marine projects, and the dumping system of marine waste. In this way, the efficiency of marine economic growth will be improved, the development system of strategic marine industries will be enhanced, and the transformation of marine economic growth from resource-dependent to green innovation-driven will be promoted.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

WQ and XJ developed the framework of the research. XJ and ZY contributed to the research method. XJ performed the data collection and analysis. WQ and XJ wrote the paper. All authors contributed to the article and approved the submitted version.

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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.

Publisher's note

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