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Evaluation of marine ecological civilization construction and its spatial correlation network in China's coastal province from the perspective of land-sea coordination

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The marine ecological civilization construction (MECC) plays an indispensable role in the development of ecological civilization in China. With the growth of the marine economy, threats to ecological environment have been increasing. From the standpoint of land-sea coordination, this study evaluates the MECC in China's coastal province and employs social network analysis to explore the spatial correlation network structure and radiation capacity. The results show that: (1) The MECC in China's coastal provinces has exhibited a general upward trend with occasional fluctuations. However, the subsystems exhibit disparate developmental trends, with the pressure subsystem exhibiting a slight decline. (2) While the MECC of all coastal provinces has increased, the MECC of China's coastal provinces exhibits considerable variation, with each facing different development challenges. (3) The spatial correlations of the MECC among coastal provinces have become increasingly pronounced, particularly in the regions surrounding Hangzhou Bay and Bohai Bay, while long-distance trans-regional correlations are relatively weaker. (4) There have been notable improvements in the MECC radiation capacity of all provinces, most prominently in Shanghai, Zhejiang, Jiangsu, and Shandong, which currently rank among the highest in the country. Conversely, the MECC radiation capacity of Liaoning, Hebei, Fujian, and Hainan remains relatively underdeveloped. The results indicate that while the MECC has developed, it still encounters obstacles pertaining to regional disparities, subsystem challenges, and spatial correlation development. The study concludes with a series of recommendations aimed at fostering sustainable development of the MECC in China's coastal regions.

KEYWORDS

marine ecological civilization construction (MECC), land-sea coordination, sustainable development, spatial-temporal evolution, spatial correlation network

1 Introduction

In the twenty-first century, the development and utilization of ocean resources have become a significant driving force for the economic development and global engagement of many countries. The overexploitation of marine resources and the marine environment has resulted in an increasing contradiction between economic development and the marine ecological environment. In response, governments around the world have initiated a process of re-examination of their planning for marine development and seek solutions to the ecological crisis. Marine ecological civilization construction (MECC) represents a significant aspect of China's response to environmental challenges and an effective path to the development of a strong maritime nation (Zhang et al., 2019). Since the 17th National Congress of Communist Party of China (CPC) introduced the concept of ecological civilization, the construction and assessment of ecological civilization have been actively implemented in China. However, the current marine ecological and environmental issues remain a significant concern, impeding sustainable coastal economic and social development. In the context of environmental governance, the challenges associated with marine pollution and offshore ecological degradation resulting from land-based sources of pollution and development remain unresolved. From an ecological perspective, the root cause of the issues can be attributed to ecosystem connectivity, feed interdependencies, livelihood interactions, and climate feedback (Cottrell et al., 2018). From an economic perspective, the root cause of the issues can be attributed to the discordance between the objectives and interests of the land and sea sectors (Zhao et al., 2022).

In order to better coordinate the contradictory relationship between land and sea, in 2010, "land-sea coordination" was first written into the National 12th Five-Year Plan, and the report of the 19th CPC further stressed "adhering to land-sea coordination and accelerating the establishment of a robust maritime nation." This grasps the relationship between the oceans and the country's economic and social progress from a broad vision and strategic level. The "Opinions of the Central Committee of the CPC and the State Council on Establishing a Territorial Spatial Planning System and Supervising Its Implementation" issued in 2019 plans the land-sea coordination of territorial space from a top-level design, taking the coastal zone as the core region, and incorporating the two spatial geographic units of the land and the sea into a "single map" (Yue et al., 2023). As noted by Fang et al. (2024) and Wang et al. (2019), land-sea coordination is the plan and design of regional and social development based on the connectivity and interactions between land and sea, and involves a comprehensive consideration of the resources and environmental characteristics of both land and sea. The coordination of economic development and ecological protection in land and sea development represents a significant challenge in China's current territorial spatial planning (Long et al., 2023). Besides, it also presents an effective path for China to achieve the high-quality development of marine economy (Gao et al., 2023). Some coastal provinces in China have fully acknowledged the necessity of land-sea coordination and have achieved certain in the course of practice (Ying et al., 2022).

At the same time, researches have been conducted to gain a comprehensive understanding of land-sea coordination. Wang et al. (2019) employed Lianyungang as a case study to divide the land-sea coordination system into three subsystems: the land-side subsystem, the sea-side subsystem, and the port subsystem, and applied structural equation modeling to screen indicators. Gao et al. (2022a) proposed a four-dimensional indicator system including economic development, resource utilization, ecological environment, and social livelihood, and developed coupling coordination degree model to evaluate the development of land-sea coordination systems in Shanghai and Tianjin. Long et al. (2023) examines policy background of land-sea coordination and concludes the challenges and practical experiences in Chinese provinces, highlighting the importance of the definition of land-sea boundaries, the composite system perspective, and the coordinated spatial utilization. The relationship between land and sea, the content of land-sea coordination, and construction of indicator system for land-sea coordination have been thoroughly examined. In addition, some scholars have attempted to incorporate the concept of land-sea coordination into other research themes, such as land-sea ecological security (Gao et al., 2023), coastal sustainable development (Yan et al., 2023), port accessibility (Guo et al., 2022a), land-sea human relations (Nieuwhof et al., 2019), territorial space conflict (Zhou et al., 2024). These studies further provide a sufficient theoretical basis for this paper to integrate the concept of land-sea coordination into MECC.

Similarly, substantial research has been conducted regarding ecological civilization, mainly focused on its connotation (Hansen et al., 2018; Fu and Nielsen, 2023), evaluation (Dong et al., 2021; Meng et al., 2021; Chen and Shi, 2022; Xiao et al., 2023), policy impact (Bai et al., 2023; Li and Xie, 2023; Zhang and Fu, 2023), and other ecological civilization-related factors. Despite initial findings indicating that China's economic expansion had exceeded the environmental carrying capacity, recent studies have demonstrated that China's ecological civilization has made notable advancements, particularly in economic and social systems. However, these improvements have not been fully reflected in ecological systems, and the discrepancy between ecological and economic development persists, along with a significant disparity in regional development. Similar scenario can be observed in the marine ecological civilization, yet comprehensive research on MECC remains lacking. Some scholars studied marine ecological civilization demonstration zones and investigated its influences on the marine ecological efficiency (Gao et al., 2024), green development level of marine economy (Ren et al., 2024), coastal zone environment (Wei et al., 2023), etc. Other scholars evaluated MECC to identify problems and enhancement paths in the construction of marine ecological civilization. In the assessment of MECC, scholars constructed marine ecological construction evaluation indicators and used empirical analysis methods to comprehensively analyze degree of marine ecosystem development in a specific region (Guo et al., 2022b). For example, Zhang et al. (2023) established index system of MECC model based on pressure-state-response model. Wang and Li (2021) divided the MECC system into four subsystems: environment, economy, society, and culture, and analyzed the synergy state with marine science and technology innovation system. Miao et al. (2020) built evaluation system from the aspects of natural resources, environment, economy and technology. Lin et al. (2022) constructed index system based on six subsystems of society, economy, governance, culture, resource, and ecology, and evaluated marine civilization construction performance in Zhejiang Province. Among the evaluation methods, the BP neural network (Hu, 2022; Zhang et al., 2023), principal component analysis, entropy weighting method (Gao et al., 2022b), and the Analytic Hierarchical Process (AHP) (Yang et al., 2021; Guo and Liu, 2023) are primarily included. In terms of the regional scale of the study, existing study covers a range of geographical areas, including estuaries (Lin et al., 2023), islands (Zhang et al., 2023), cities (Guo and Liu, 2023; Hu, 2022), and provinces (Jiang et al., 2020).

In summary, the existing studies are of great significance in guiding the assessment of the level of MECC. However, the majority of studies fail to consider the dynamic linkages between subsystems, land-sea ecological processes, and cross-system threats, thus are not conducive for the government to develop policy to control ecological threats from land-based sources. Furthermore, the advancement of technology has facilitated the formation of increasingly robust connections between disparate regions. The majority of existing studies are based on individual state attributes, which fail to consider the interprovincial radiation effect and also lack an analysis of the overall linkage structure of MECC. Additionally, most studies that have evaluated ecological civilization have a limited research scope, focusing on estuaries, islands, and cities, which is less effective in reflecting the overall situation of macro-scale construction. Accordingly, this paper first introduces the perspective of land-sea coordination to construct an index system for MECC. Secondly, this paper conducts a comprehensive evaluation of MECC in China's coastal provinces based on the data from 2006 to 2021, and analyzes their temporal and spatial characteristics. Finally, this paper employs social network analysis to examine the network characteristics and radiation capacity of MECC in China's coastal provinces, thus deepening the understanding of the spatial effect and regional transmission of ecological civilization construction from a geographic perspective.

2 Materials and methods

Currently, the academia does not yet have a consistent methodology for assessing the ecological civilization construction. There are two evaluation methods: the characteristic index and indicator system methods. The characteristic index method is derived from the transformation of single indicators, and the overall assessment results are simple and clear but have a certain one-sidedness. Considering that ecological civilization construction has rich connotations, a single indicator cannot reflect the whole situation. In addition, this method is not conducive to tracing the causes of ecological civilization problems, and the explanatory power of the overall significance of ecological civilization is poor. Therefore, this study first constructs an evaluation index system of marine ecological civilization according to the PSR model, with comprehensive reference to relevant literature. Second, the AHP and entropy weight method is adopted to comprehensively ascertain the indicator weights. Third, the level of MECC is calculated and classified into groups using Jenks Natural Breaks classification method. Finally, based on the evaluation results, spatial networks are constructed with a view to exploring the regional network influence mechanism in terms of both network structure and spatial radiation effect.

2.1 Study area and data sources

China's coastal provinces and municipalities are situated in the eastern and southern coastal regions of the country (Figure 1). Collectively, these regions contain fourteen provinces and municipalities. However, due to the limited data availability of Hong Kong, Macao, and Taiwan, this paper focuses on eleven coastal provinces and cities, from north to south, namely: Liaoning, Hebei, Tianjin, and Shandong (Northern marine economic circle), Jiangsu, Shanghai, and Zhejiang (Eastern marine economic circle), and Fujian, Guangdong, Guangxi, and Hainan (Southern marine economic area). These coastal provinces cover a total area of approximately 1,334,000 square kilometers, accounting for 14 per cent of China's land area (Cheng et al., 2023). Furthermore, the seventh population census bulletin published by the Chinese government indicates that the region's population represents 44.93% of the country's total population, which suggests that it has a substantial population carrying capacity. Besides, it is the most economically developed region in China. According to the 2023 gross domestic product (GDP) data for China, the total GDP value of the region is approximately 665.7 billion Chinese Yuan (CNY), representing 52.8% of the country's total GDP. In the context of land-sea coordination, it is of great importance to evaluate MECC in China's coastal provinces and identify potential issues for improvement. This will facilitate the execution of the role of land-sea coordination and promotion of sustainable development of the marine economy.

In consideration of the availability and accuracy of data, this paper has selected the interval from 2006 to 2021 as the period for study. The data utilized in this study are predominantly obtained from "China Marine Statistical Yearbook", "China Marine Economic Statistics Bulletin", "China Marine ecological environment Bulletin", and "China Environmental Statistical Yearbook". Missing data are filled in using linear interpolation method. The spherical distances between the provinces were calculated using the ArcGIS software.

2.2 MECC indicator system construction

Based on definition of ecological civilization proposed by Xue et al. (2023), we define MECC as civilization achievements developed by human beings in the marine domain, particularly in relation to the relationship between society and nature. It is a complex system that includes a multitude of interrelated factors, including economic development, social culture, ecological environment, and the government policies. The integration of systematic promotion and pivotal breakthroughs represents a pivotal approach to the development of ecological civilization. The emergence of ecological problems attributed to the confluence of numerous subjective and objective factors,

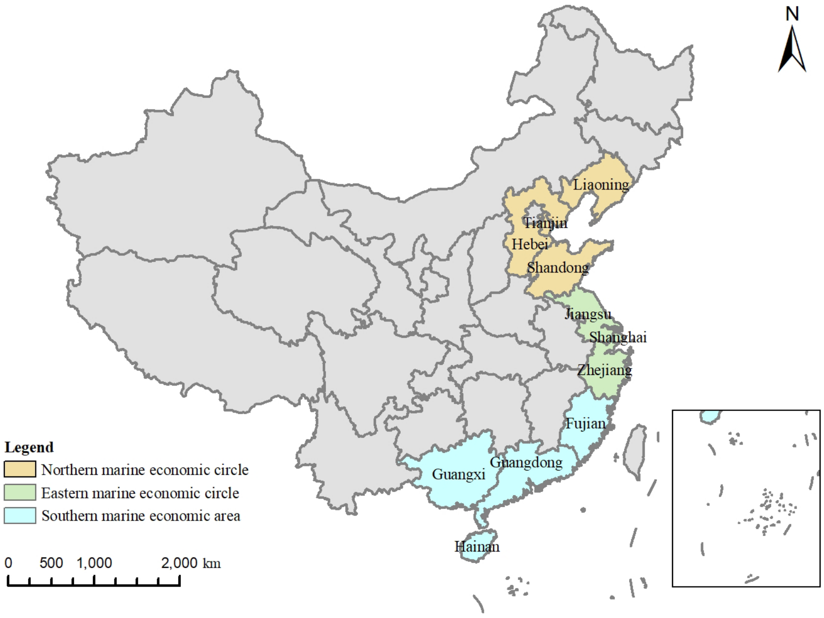

FIGURE 1
Coastal provinces of China.

including geographic history, ecological awareness, production methodologies, and living habits. This necessitates the adherence to the perspective of universal connection in the process of ecological civilization construction. It is thus imperative that the impact of land-based sources be taken into account in the MECC. However, in the analysis of MECC, most current researches ignore the logical relationship between the interactions between subsystems and the interaction between the ecological and economic systems of the land and sea (Jiang et al., 2020). For a considerable period of time, the land and the sea have been regarded as two distinct units. Marine ecosystems are regarded as waste disposal sites because of their self-recovery and mobility. Various kinds of household wastes, agricultural surface pollutants, industrial solid wastes, etc. are discharged into the sea, causing serious damage to the marine ecological environment. However, the land and sea are not independent but are interdependent and interrelated. The suppression of the sea by the land eventually feeds back to the land through atmospheric, hydrological, geological, and biological cycles (Ramesh et al., 2015). For example, Greenhouse gas emissions and inappropriate coastal development lead to global warming and sea level rise, exacerbating storm surges and red tides, subsurface saltwater intrusion, coastal erosion, and degradation of coastal wetlands (Xu et al., 2016). Heavy metals and toxic chemicals in the seas can form acid rain through precipitation, causing damage to terrestrial vegetation and soils. The mismatch between marine ecological conservation and economic development can, in turn, result in ecological constraints on the development terrestrial economies and society (Zhou et al., 2024). These include the financial burden of marine ecological restoration, the influence of marine resource supply on industrial chains, and the impact of marine environmental degradation on the living environment of inhabitants and the movement of talents. In addition to ecological interactions and constraints, land-sea interactions are also reflected in the process of economic and social development. For instance, the expansion of the marine economy into terrestrial areas will also facilitate the continuous growth of coastal cities and accelerate rural urbanization through the aggregation of population and industry, thereby stimulating economic growth and enhance the quality of social development across the land area (Li et al., 2021; Shao et al., 2021). Therefore, it is imperative to comprehensively acknowledge, scientifically harness, and effectively regulate the interconnections between the land and the sea in terms of material, energy, and information flows, and to promote marine ecological civilization based on the principle of land-sea coordination.

In summary, this study developed a MECC evaluation system based on the concept of land-sea coordination, utilizing the PSR model, which consists of three systems: pressure, state, and response. The pressure subsystem refers to the impact of disparate economic and social practices on the surrounding environment. The state subsystem characterizes the current state of the environment and the environmental changes that occur at a specific point in time. The response subsystem represents the process by which entities adapt to and cope with the environmental state. In short, the construction of a marine ecological civilization can be conceptualized as a dynamic process of "pressure–state–response". Specifically, it is a series of ecological civilization responses designed to alleviate the contradiction between marine ecological conservation and its economic and social levels, as well as to improve the health of marine ecosystems under pressure from human activities, the economy, land-based pollution, and resource depletion. Figure 2 depicts a conceptual model of the indicator system, which reflects the degree of MECC in terms of the interaction of the three subsystems.

According to PSR framework, combined with previous research results, the evaluation indicators of Construction of the National Marine Ecological Civilization Demonstration Zone, and the actual situation, this study constructed an evaluation index system including one target layer, three system layers, 11 factor layers, and 29 indicator layers, as shown in Table 1. The pressure subsystem characterizes the driving effect on the MECC and mainly includes social pressure, land-based pollution pressure, and resource consumption pressure. The state subsystem is the status of a particular period under the action of the pressure system, including the ecological environment, resource status, industrial structure, and living conditions. The response subsystem reflects the reaction of the government and other relevant actors to the prevailing circumstances, including the four aspects of scientific and technological levels, ecological governance, ecological management, and ecological culture.

2.3 Methodology

2.3.1 Weight determining method

The combination weight method considers the decision-maker's preference for indices and reduces the arbitrariness of the subjective weight method, thus making decision-making processes and results more reliable (Du and Gao, 2020). In this study, combined subjective and objective weights were used. Subjective weights were obtained using the AHP method; the objective weights were obtained using the entropy value method.

The AHP method is suitable for decision-making in complex systems that are difficult to fully quantify. According to the overall objective, AHP classifies the indicators to different levels, and a four-level hierarchical structure model is established, including "target level – system level – factor level – indicator level." Furthermore, we invited eight experts to score the importance of all indicators at the same level relative to an element at the previous level and constructed a two-by-two comparison matrix from the scoring results to conduct a consistency test and obtain the subjective weight of each index, w_j^a.

The entropy method is an objective weighting method that describes the degree of data dispersion. The smaller the information entropy of the index, the greater the degree of dispersion of the data and the larger the weight of the index. The steps of the associated calculations are as follows:

(1) Normalization of data.

To eliminate dimensional influences among the evaluation indices, the min-max normalization method was first used to perform a linear transformation of raw data to present them in the range between 0 and 1.

For a positive index:

$$X_{ij}=\frac{x_{ij}-Min(x_{ij})}{Max(x_{ij})-Min(x_{ij})} \tag{1}$$

For a negative index:

$$X_{ij}=\frac{Max(x_{ij})-x_{ij}}{Max(x_{ij})-Min(x_{ij})} \tag{2}$$

Where X_{ij} represents the normalized value of the j-th index in region i and x_{ij} represent the true value of the j-th index in region i.

(2) Calculate the information entropy of the index j.

$$e_j=-\frac{1}{ln\,(n)}\sum_{i=1}^{n}\left(\frac{X_{ij}}{\sum_{i=1}^{n}X_{ij}}ln\frac{X_{ij}}{\sum_{i=1}^{n}X_{ij}}\right) \tag{3}$$

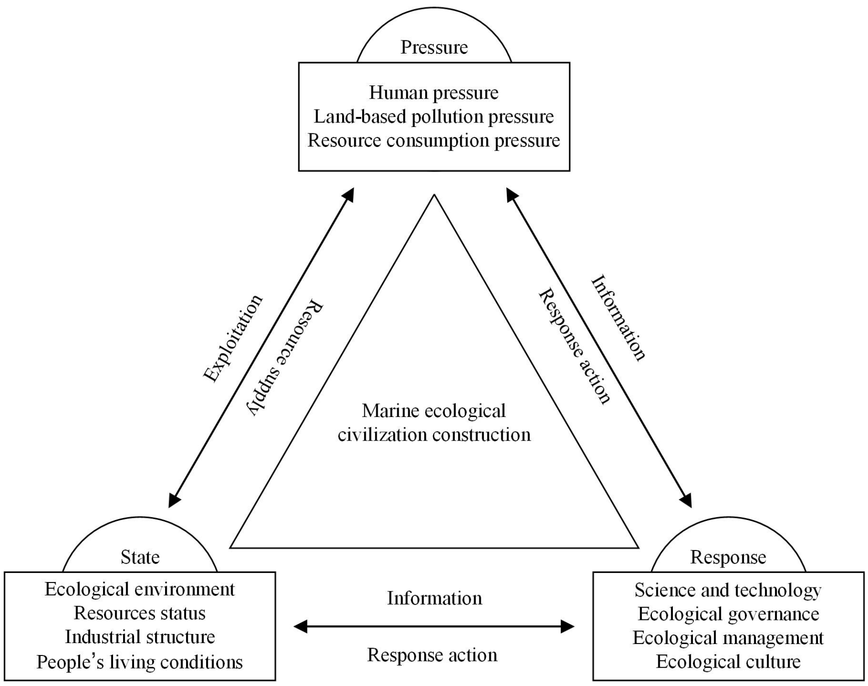

FIGURE 2
PSR conceptual model of MECC.

TABLE 1 Weights and index system for MECC.

Target layers	System layers	Factor layers	Indicator layers	Unit	Weight		
					AHP	Entropy	Combined
Marine Ecology Civilization Construction Level	Pressure	Social pressure	Population density	People/km^2	0.01	0.04	0.03
			Urbanization rate	%	0.02	0.03	0.02
		Land-based pollution pressure	Wastewater discharged directly into the sea	10k tonnes	0.04	0.03	0.04
			Industrial solid waste generation	10k tonnes	0.09	0.04	0.06
			Direct marine discharges of petroleum products	10k tonnes	0.02	0.01	0.02
		Resource consumption pressure	Mariculture area	10k hm^2	0.02	0.04	0.03
			Marine capture production	10k tonnes	0.01	0.08	0.04
	State	Ecological environment	Proportion of sea area with class I or II water quality	%	0.02	0.02	0.02
			Number of red tide occurrences with a maximum area exciding 100 square kilometers	freq	0.01	0.01	0.01
			Economic losses from storm surge	CNY	0.01	0.01	0.01
		Resources status	Composite index of marine water quality[1]	–	0.04	0.02	0.03
		Industrial structure	Share of marine tertiary industry	%	0.03	0.03	0.03
			Share of marine secondary industry	%	0.02	0.03	0.02
			Agglomeration of marine tertiary industry	%	0.04	0.03	0.04
		living conditions	Engel's coefficient	–	0.01	0.04	0.03
			Gross ocean product per capita	10,000 CNY /people	0.01	0.03	0.02
	Response	Scientific and technological levels	Number of marine scientific research institutions	–	0.04	0.02	0.03
			Number of employees of marine scientific research institutions	people	0.07	0.04	0.05
			Number of patents in marine scientific research institutions	–	0.17	0.05	0.11
		Ecological governance	Total investment in industrial wastewater treatment	CNY	0.05	0.04	0.04
			Industrial solid waste utilization rate	%	0.09	0.02	0.05
			Total environmental protection investment as a share of GDP	%	0.04	0.02	0.03
		Ecological management	Authorized sea areas	hm^2	0.01	0.03	0.02
			Area of marine nature reserve	km^2	0.04	0.13	0.09
			Sea use charges	CNY	0.02	0.04	0.03
				km^2	0.01	0.04	0.03

(Continued)

TABLE 1 Continued

Target layers	System layers	Factor layers	Indicator layers	Unit	Weight		
					AHP	Entropy	Combined
			Number of marine observation stations				
		Ecological culture	Fiscal expenditure on education as a share of regional GDP	%	0.04	0.02	0.03
			Per capita cultural and recreational expenditures of urban and rural residents as a proportion of consumer expenditures	%	0.01	0.03	0.02
			Public books per 10,000 people	–	0.01	0.04	0.03

[1]Composite index of marine water quality = percentage of high-quality waters * 100 + percentage of moderate waters * 60 + percentage of poor waters * 20

(3) Calculate the information utility value of the index j.

$$d_j = 1 - e_j \tag{4}$$

(4) Calculate the objective weight w_j^e of the index j.

$$w_j^e = \frac{d_j}{\sum_{j=1}^{n} d_j} \tag{5}$$

This study asserts that subjective and objective weighting methods are equally important in evaluating the level of MECC (p = 0.5). Therefore, we took the average of the two methods of calculating the weights and added them to obtain the comprehensive weights of each indicator using Equation 6, as listed in Table 1.

$$w_j = p w_j^a + (1-p) w_j^e \tag{6}$$

2.3.2 Calculation of the comprehensive index of MECC

The comprehensive index method was applied to calculate the level of MECC through the linear weight summation of the combination weights obtained by Equation 6, with normalization of the indices obtained by Equations 1, 2.

$$MECC_i = \sum_{j=1}^{n} w_j \times X_{ij} \tag{7}$$

Where the comprehensive index *MECC* is the comprehensive evaluation value of MECC in region i. The larger the value of the comprehensive index, the higher the level of MECC.

2.3.3 Jenks Natural Breaks classification method

The level of MECC was determined with the Jenks Natural Breaks classification method using the calculated results for cluster analysis. This method considers that the data have their own breakpoints that can be used for classification (Bai et al., 2022). Based on the data distribution, they were classified according to the rules of maximum intergroup and minimum intragroup variances. Therefore, the calculated results were divided into four groups using the Jenks Natural Breaks classification method.

2.3.4 MECC network analysis

Social network analysis (SNA) is a method that employs network theory to identify network participants and their characteristics, to examine how these participants engage with each other, and to ascertain how these interactions influence group functioning (Wojcik et al., 2021). It has been applied to research fields such as environmental protection (Zhu et al., 2024), green innovation efficiency (Li et al., 2024), spatial planning (Liu et al., 2024), etc. In the process of MECC, each province is not an isolated individual. Rather, complex spatial interactions are formed between different administrative subjects through various links, including cross-regional transmission of pollutants, trade exchanges, and information transfer. The MECC in the coastal provinces will also demonstrate complex networked interactions. Consequently, based on the evaluation of MECC and with reference to relevant literature, this paper constructs the gravity model to develop the MECC spatial network (Equation 8).

$$G_{ij} = K_{ij} \cdot \frac{MECC_i \cdot MECC_j}{D_{ij}^2}, \; K_{ij} = \frac{MECC_i}{MECC_i + MECC_j} \tag{8}$$

Where G_{ij} is spatial correlation strength of MECC between provinces i and j. D_{ij} is the distance between province i and j. K_{ij} refers to the gravitational coefficient, which indicates the contribution rate of MECC between province i and j.

In order to further analyze the spatial correlation effect of MECC, this paper employs the concept of social network analysis and related literature to construct a model of the spatial radiation capacity of provinces. The model is based on the idea of centrality, whereby a higher centrality value indicates a stronger radiation ability (Equation 9).

$$F_i = \sum_{j=1}^{m} G_{ij} (n_i / N_i) \tag{9}$$

Where F_i is the spatial radiation capacity of province i. n_i is the number of provinces that are directly correlated with the province. N_i is the total number of provinces.

3 Results and discussion

3.1 Temporal evolution characteristics of MECC

Based on the above evaluation indexes of MECC and methodology, the average values of comprehensive index of MECC in coastal provinces from 2006 to 2021 are shown in Figure 3. Overall, with the development of marine industry and the promotion of MECC, the comprehensive MECC level in China's coastal provinces shows a fluctuating upward trend. Over the study period, the average value for the MECC was 0.4359, rising from 0.4070 in 2006 to 0.4997 in 2021, with an improvement rate of 22.80%. Further, development of MECC in provinces shows different dynamics in different years and presents periodic features.

Specifically, from 2006 to 2008, the levels of MECC in China's coastal provinces remained relatively stable, with a generally slow upward trend. At this time, the development of the marine economy in most provinces in China was still in its initial stages, the scale of the marine industry was small, and the contradiction between the development of marine economy and the marine ecological environment was not significant. At the same time, since China hosted the Beijing Olympic Games in 2008, the Beijing Organizing Committee of the Olympic Games was "Green Olympics" as the slogan to vigorously promote the construction of the ecological environment. Existing studies have shown that hosting the Beijing Olympic Games had a positive effect on the ecological environment (He et al., 2016; Long et al., 2018; Wu et al., 2023). Although not all coastal provinces were a host nor a co-organizer of the Olympic Games, local coastal governments had attached importance to the protection and management of the marine ecological environment during the Green Olympics. However, the lack of robust scientific and educational capacity in the coastal provinces proved an obstacle to the advancement of MECC.

From 2009 to 2011, the levels of MECC in China's coastal provinces were fluctuated and differentiated. In this period, only five coastal provinces (Shandong, Shanghai, Jiangsu, Zhejiang, Guangdong) demonstrated an enhancement in their levels of MECC, and most changes were within 4%. While the concept of ecological civilization was launched in 2007, at that time it was not given due consideration. Development of marine economy is the main theme in this phase. Land-sea transportation links and infrastructure construction have been continuously improved. Coastal ports, together with land railroads, highways, inland waterways, civil aviation, and other facilities, collectively constitute the national comprehensive transportation and traffic network, which has contributed to the rapid development of the national economy. However, the unregulated and rapid expansion of industry has resulted in the domination of land-based and marine industries by secondary industries, generating a large amount of industrial waste that was discharged into the nearshore sea. For example, development of the marine shipping industry led to an increase in heavy metals and toxic substances in seawater, affecting the quality of seawater and biological habitats in near-shore waters (Liu et al., 2020b). Increasing ecological pressure, coupled with the occasional occurrence of natural disasters, resulted in a bleak situation for the marine ecological environment and resources in the coastal provinces. Furthermore, the essence of land-sea coordination is the comprehensive planning of land and sea areas from the national level across sectors and administrative divisions. However, the relevant legal and regulatory system had not yet been perfected during that period, resulting in a lack of a

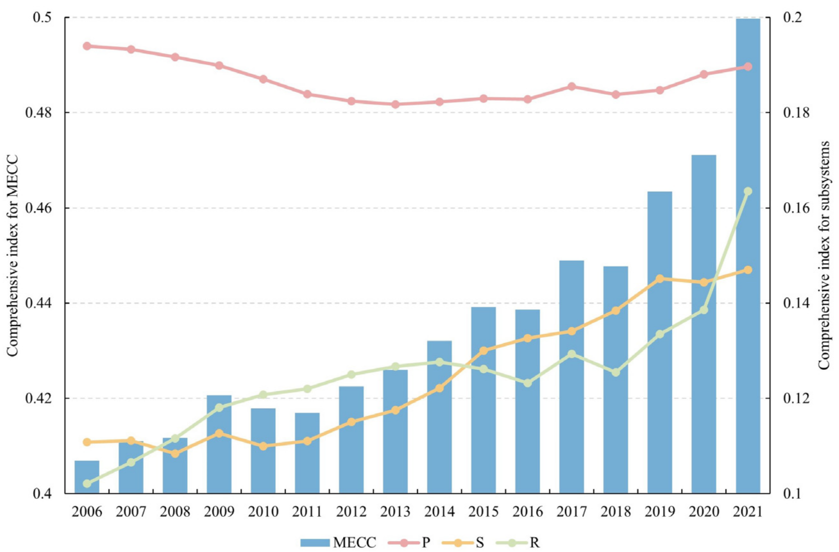

FIGURE 3
Time-changing trends of average values of MECC level in coastal provinces.

clear legal basis and safeguards for the implementation process. For instance, the absence of guidance from the relevant institutional framework has resulted in the limitation of pollution control efforts in the watershed to the coastal zone, with insufficient attention devoted to the regulation of pollution sources. Therefore, land-based pollution source control, pollution reprocessing, and other environmental protection initiatives had not yet shown positive results, further increasing the pressure on the marine ecological environment in the coastal provinces. Besides, the onset of the global financial crisis in 2009 compelled the central government to reorient its priorities towards economic advancement, rather than environmental protection.

Since 2012, the development of MECC entered a period of accelerated growth and expansion. All coastal provinces achieved noteworthy improvement in MECC, with an average increase of 20%. Since the 18th National Congress of the Communist Party of China, the central government has taken comprehensive measures to accelerate the development of a top-level design and a system of institutions for ecological civilization in order to promote the construction of an ecological civilization and reverse the trend of ecological and environmental deterioration. Chinese government has issued "Integrated Reform Plan for Promoting Ecological Civilization", "Thirteenth Five-Year Ecological Environmental Protection Plan", "Water Pollution Prevention Action Plan", "Comprehensive Establishment and Implementation of the Marine Ecological Red Line System" and a series of other policy documents, providing guidance for coastal areas to accelerate the MECC. Furthermore, policies such as "Action Plan for the Battle against Agricultural and Rural Pollution", "Outline of the National Territorial Planning Program (2016-2030)", and "Guiding Opinions on Further Strengthening Agricultural and Rural Ecosystems" provide additional guidance and guarantees from the perspective of land and sea coordination. However, due to the different enforcement efforts of policy implementation, the temporal lag in policy effects, and the inherent differences in the fundamental conditions prevailing in each province, the pace of MECC level varies significantly across different provinces. Comparatively, the MECC growth of Hebei and Guangdong has exhibited a more pronounced improvement, whereas that of Jiangsu has demonstrated a less pronounced improvement.

As shown in Figure 3, the average value for the evaluation indexes of pressure subsystem was 0.1864, decreasing from 0.1940 in the base year to 0.1896 at the end of the period, with a decline rate of 2.26%. The level of pressure subsystem in the coastal provinces demonstrates a U-shaped trend of decline and recovery, with a slight decline. This suggests that the expansion of marine ecological pressure has been relatively well-managed. On the other hand, however, the majority of coastal provinces shows only modest improvement in pressure subsystem, while five provinces (Hebei, Liaoning, Shandong, Fujian, Guangxi) exhibited deterioration during the study period. In terms of the underlying causes of the pressure subsystem problem, land-based pollution pressure factor layer remains a significant concern, as all coastal provinces have witnessed a reduction in the land-based pollution layer. Despite the implementation of numerous pollution control measures at the provincial and national level, land-based pollution pressure continues to pose a significant threat to the development of MECC. A land-sea coordination approach to pollution management and environmental management would prove an effective strategy. The issue of resource exploitation represents a further challenge for the pressure subsystem. However, there have been some improvements in recent years, with the introduction of policies such as fishing quota, reduction of ships and production and marine ranching, which have contributed to a reversal of the downward trend.

As shown in Figure 3, the average value for the response subsystem was 0.1224, rising from 0.1108 in 2006 to 0.1470 in 2021, with an improvement rate of 32.71%. The evaluation indexes of state subsystem of MECC in the coastal provinces in China has a fluctuating upward trend from 2006-2021, which is largely aligned with the trend observed in the MECC. The large improvements of the state subsystem, which, although mainly due to the initial stage's relatively low status, indicates that the MECC has gain certain achievements. Overall, the majority of indicators have shown positive advancement, with the most notable improvements observed in the industrial structure and people's living conditions of residents, indicating the considerable achievement of economic transformation and enhancement of social welfare in the coastal provinces. Whereas, progress in the ecological environment and the resources status has been relatively limited, restricting further improvement of the state subsystem. From one perspective, the efficacy of ecological response measures is often constrained when the underlying ecological pressures have not yet been effectively addressed. The excessive discharge of wastewater and waste can result in adverse effects on the marine ecosystem, including eutrophication, deterioration of water quality, and reduction in resources, which makes the restoration of marine ecosystem more difficult. Furthermore, the enhancement of the ecological environment is a long-term process. Despite the fact that provinces have implemented responsive measures to restore marine ecological environment since China commenced its promotion of ecological civilization, the efficacy of these measures is frequently constrained by a lag.

As shown in Figure 3, the average value for the response subsystem was 0.1250, rising from 0.1021 in 2006 to 0.1635 in 2021, with an improvement rate of 60.11%. The evaluation index of response subsystem of MECC in the coastal provinces in China demonstrated a clear upward trend from 2006 to 2021, especially in Shandong and Guangdong. The accelerated growth of the marine economy in coastal provinces has facilitated the rapid development of scientific and technological capabilities, educational opportunities, and cultural enrichment. These developments have prompted effective improvements to the response system. However, it is noteworthy that not all indicators in response subsystem have experienced satisfactory enhancements. For instance, the indicators in the ecological governance factor layer still present numerous challenges that have hindered the development of the response subsystem. More than half of the coastal provinces experienced a decline in the level of ecological governance during the study period. This is mainly due to the fact the pursuit of economic growth leads to an extrusion effect with regard to environmental protection (Liu et al., 2020a). The expansion of the marine economy

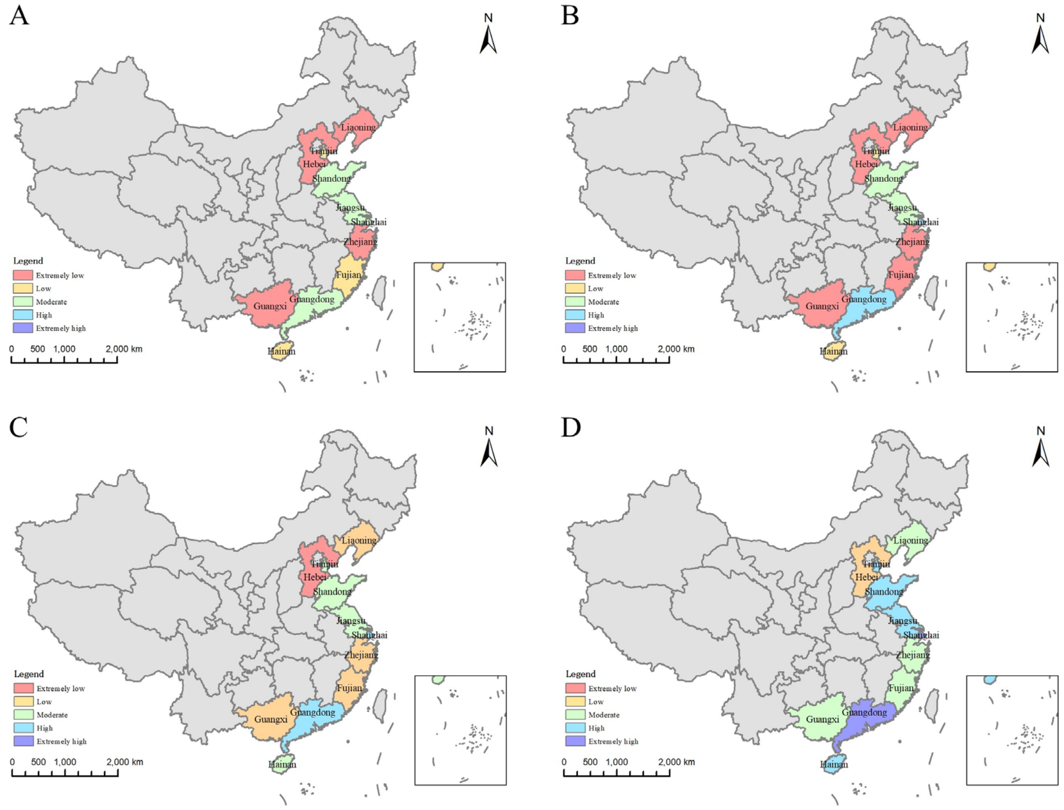

FIGURE 4
Spatial distribution of MECC for coastal provinces in China. **(A)** 2006. **(B)** 2011. **(C)** 2016. **(D)** 2021.

failed to stimulate investment in environmental protection and restoration. In addition, the existing management systems for land and sea are largely independent, with land and sea construction and management departments and agencies working separately. The delineation of responsibilities among these main governance bodies is often unclear, leading to conflicts and inefficiencies in the utilization of resources, which further impairs the effectiveness of inputs for marine protection. Consequently, the discrepancy between economic growth and the rate of investment in environmental protection resulted in a gradual increase in investment in environmental treatment. However, this growth is insufficient to address the mounting challenge of industrial wastewater and solid waste management, which can constrain the potential for further improvement of MECC. Additionally, this may also be an essential contributing factor to the relatively slow growth of the pressure subsystem.

3.2 Spatial distribution characteristics of MECC

To further analyze the spatial distribution characteristics of MECC in coastal provinces in China, this study selected four typical time points (2006, 2011, 2016, 2021), and applied the Jenks Natural Breaks classification method to divide MECC in five groups.

Figure 4 shows the level of MECC for the coastal provinces in China. While all coastal provinces have made some progress in promoting MECC, the results show that there is are clear disparities in the MECC of coastal provinces. While Guangdong, Hainan, and Shandong have demonstrated exemplary performance in advancing the level of MECC, occupying a superior position with favorable developmental trends. Hebei province, which only reached low status by 2021, has demonstrated a relatively lower level of ecological construction and a slower pace of development. In the process of Hebei's development, traditional land-based industries are always given priority, which has not only led to the relative backwardness of the development of marine industries, but also hindered MECC (Xia et al., 2019). The slow pace of construction may also have contributed to Hebei being the only province other than municipality without a national marine ecological civilization demonstration zone. In addition to interprovincial differences, the results of the study also demonstrate clear geographical characteristics. Provinces in the northern marine economic circle, Liaoning and Hebei, exhibit relatively weak performance on the MECC. Shandong and Tianjin rely on the developed marine industry and robust marine scientific research capability to withstand the challenge inherent to the region and to distinguish themselves from other provinces in the northern marine economic circle. In contrast, provinces in the southern marine economic circle show a more favorable overall performance on the MECC, as all provinces have reached moderate or above status in 2021, including Hainan, which has reached the status level, and Guangdong, which has reached the extremely high status. Such geographical differences can be attributed to both natural environmental factors and anthropogenic influences. The marine ecological conditions in the northern marine economic circle are less favorable than in other regions. As a semi-enclosed inland sea, the Bohai Sea has limited seawater exchange capacity, fragile marine ecosystems, and is significantly impacted by pollution from inland rivers, resulting in the highest percentage of non-excellent quality among the four major seas in China (Zhou et al., 2021). Furthermore, with regard to the pollution of rivers that discharge into the sea, only the water quality of rivers in the Bohai Rim has been classified as polluted (Chen et al., 2023b). Additionally, the northern marine economic circle is economically weaker than those in the south. These provinces are more constrained by financial pressures that limit their ability to invest in science, technology, and ecological management, particularly in comparison to their southern counterparts. Furthermore, the absence of an efficacious land-sea industrial linkage mechanism has resulted in a lack of proximity between the inland and marine economies (An et al., 2022). Consequently, the marine economy has been unable to establish an effective coordination with inland industries, leading to suboptimal resource utilization. Additionally, the requisite raw materials and technical support for the marine industry may not be readily accessible from the land, potentially impeding its operations. However, with the continuous promotion of MECC, disparities between regions have been diminishing.

Figure 5 shows the level of pressure subsystem for the coastal province in China. Despite the fact that all provinces have made some efforts in the promotion of MECC, the pressure state of the majority of provinces has not undergone a notable improvement, but rather a decline. The provinces within northern economic circle exhibits exhibit a comparatively weaker performance, as multiple provinces are in the low or extremely low status during the study period. In particular, the pressure subsystem in Hebei experienced a reduction of over 15% between 2006 and 2021, indicating a pressing need for pollution control measures in the province. Intensified pollution and exploitation pressure from land are the primary factors hindering the improvement of pressure subsystem in these provinces. Accelerated economic expansion has occurred at the cost of the ecological environment, to a certain extent. The coastal areas around the northern marine economic circle are not only among the most densely populated regions in China, but also an important manufacturing, industrial, and agriculture base for the country. Escalation in the overall quantity of diverse pollutant emissions, largely attributable to the scale effect of industrial manufacturing throughout its developmental trajectory (Li and Wu, 2023). Besides, while the high population density has effectively contributed to the development of the northern marine economic circle, it has also resulted in a significant amount of pollution and uncontrolled exploitation of marine resources (Yu et al., 2021). In the contrast,

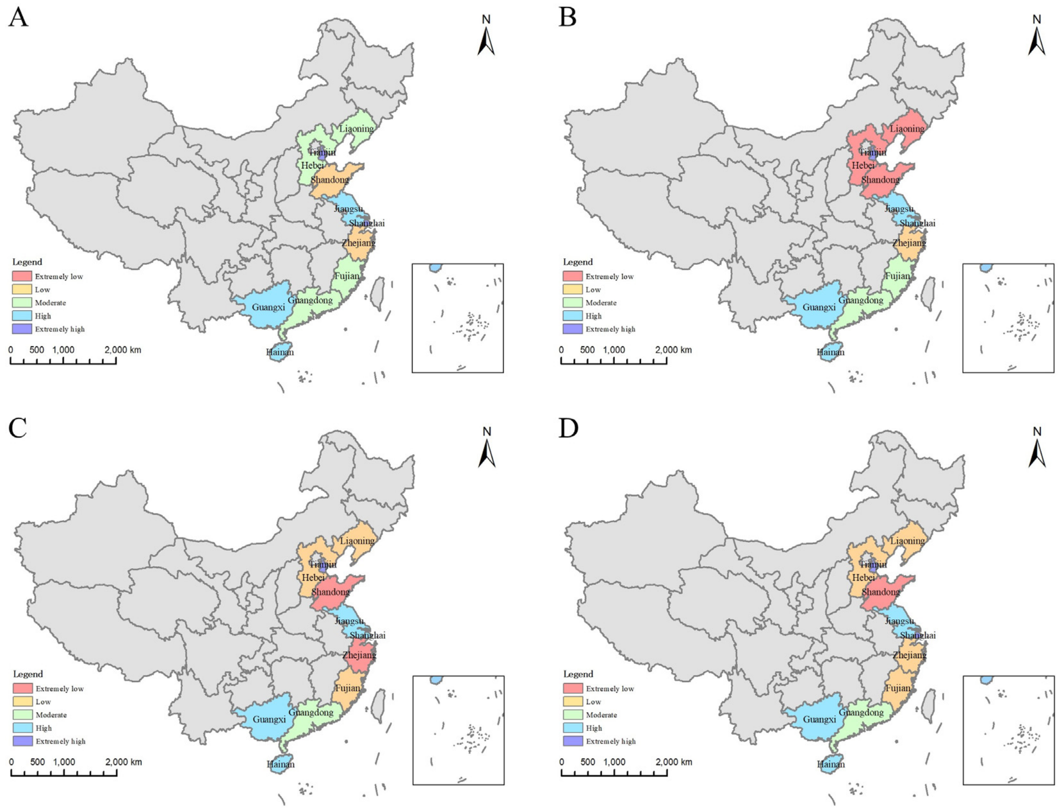

FIGURE 5
Spatial distribution of pressure subsystems for coastal provinces in China. **(A)** 2006. **(B)** 2011. **(C)** 2016. **(D)** 2021.

the pressure subsystems in Tianjin, Jiangsu, Shanghai, Guangxi, and Hainan consistently remain at high level during the study period. Due to low population density and relatively slow pace of industrial development, Guangxi and Hainan face lower land-based pollution and resource consumption pressures, which presents an effective guarantee for the development of pressure subsystems. Tianjin, Jiangsu and Shanghai ensure the stability of the pressure subsystem through rational control to regulate the generation of marine pollution and exploitation of marine resources.

Figure 6 shows the level of state subsystem for the coastal province in China. Despite effects of ecological pressure, the state subsystems of the coastal provinces all have been steadily improved during the study period, largely due to the provinces' promotion of MECC. While only 2 provinces reached high status in 2006, by 2021, nine provinces have achieved high or extremely high status. However, Tianjin and Hebei, which are located in the innermost part of the Bohai Sea, have relatively weak performance on the state subsystem, mainly due to their high difficulty in promoting the state subsystem. As mentioned above, the Bohai is subjected to great high pressure from land-based sources of pollution, and as a semi-enclosed sea it has a weak purification capacity, leading to its own compromised ecological condition. In addition to geographical factors, although the proportion of marine secondary industries in Hebei and Tianjin continued to improve during the study period, the overall economic development of the two provinces is still dominated by industrial development. While the industrial sector is a key driver of economic growth, it also represents a significant source of environmental pollution. This not only constrains the further development of the provinces and cities but also poses a significant challenge to the pursuit of MECC (Xiao et al., 2023). Besides, the high intensity of coastal development in the adjacent provinces of Shandong and Liaoning has led to the unfavorable status of the state subsystem. Considering the openness and connectivity of marine ecosystem, there is close interaction and energy transfer between organisms and materials in adjacent seas. Marine ecological problems in neighboring provinces, such as marine pollution, can be transmitted to each other and affect the state of marine ecology. Therefore, Promoting the co-construction of MECC with neighboring provinces on the basis of land-sea coordination will be an effective way to improve the state subsystem.

Figure 7 shows the level of response subsystem for the coastal province in China. As economic and technological levels continue to rise, most response subsystems for coastal provinces in China have also undergone significant and rapid upgrades during the study period. However, there are huge differences between provinces on the response subsystem. Shandong, Guangdong, Shanghai, and Zhejiang demonstrated accelerated progress and superior performance in the response subsystem, all achieving above high status. The results indicates that these provinces have developed an effective marine ecological response system to address marine ecological pressures. These provinces have both robust foundation for marine development and strong economic and scientific infrastructure, and they have effectively leveraged their

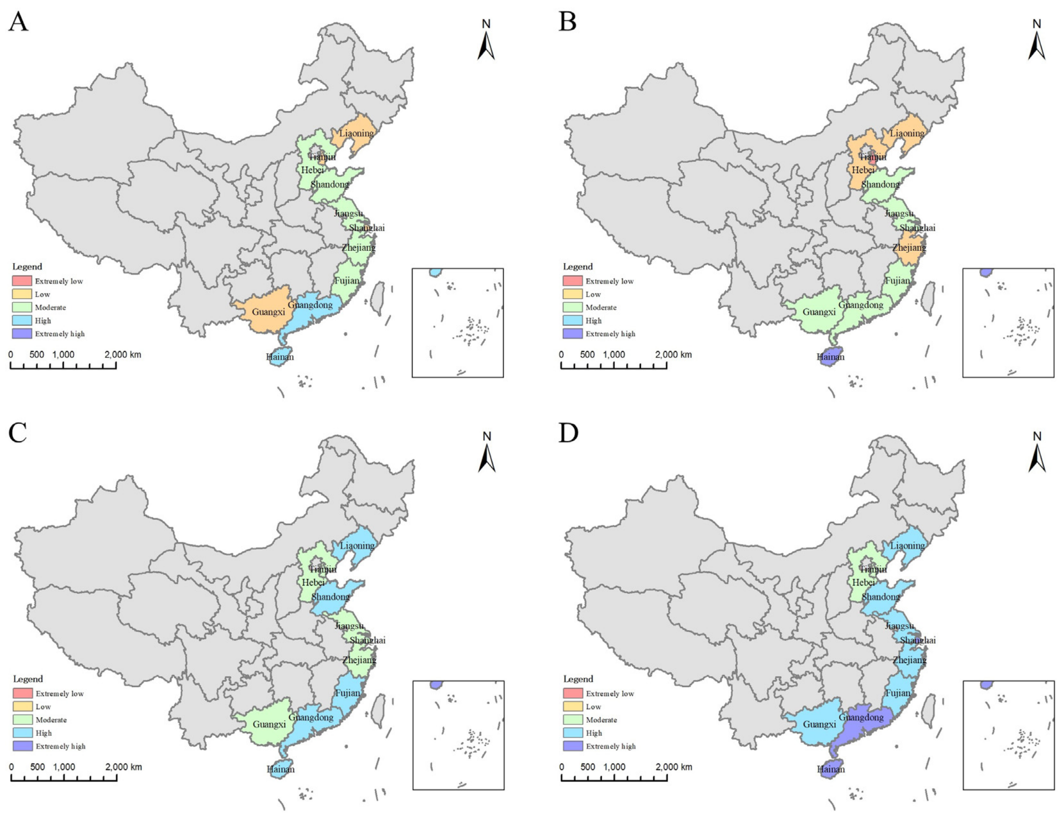

FIGURE 6
Spatial distribution of state subsystems for coastal provinces in China. **(A)** 2006. **(B)** 2011. **(C)** 2016. **(D)** 2021.

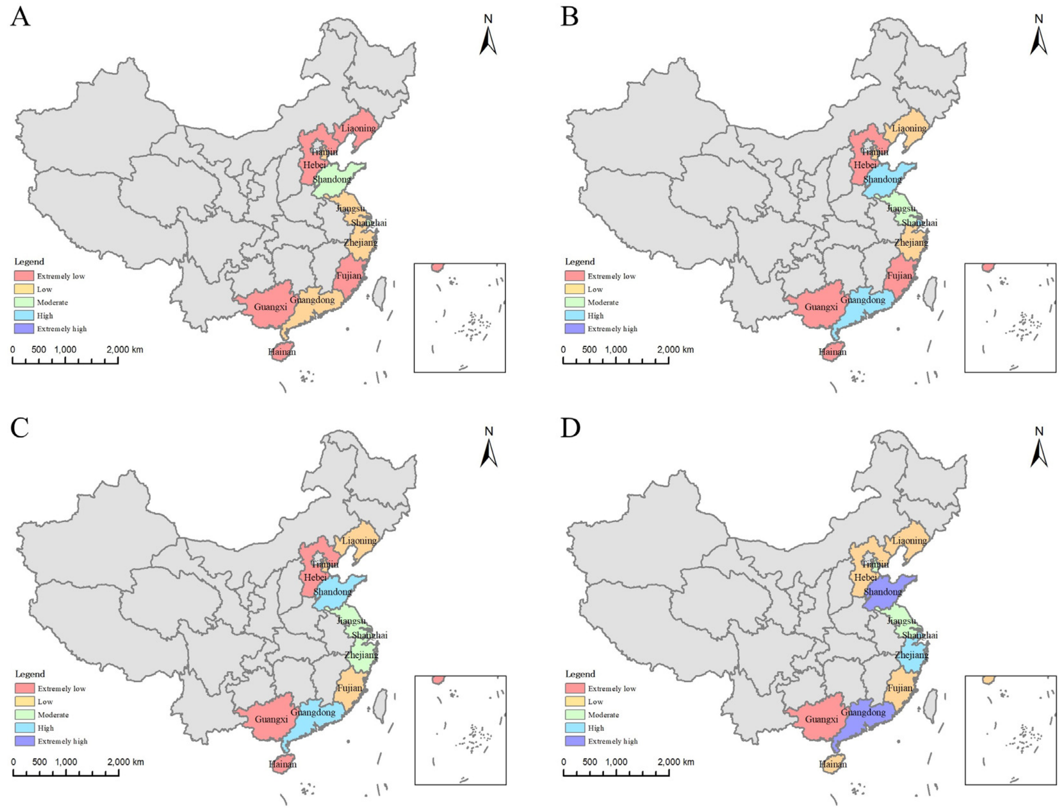

FIGURE 7
Spatial distribution of response subsystems for coastal provinces in China. **(A)** 2006. **(B)** 2011. **(C)** 2016. **(D)** 2021.

economic and scientific advancement to propel improvement of the response subsystem. In contrast, the response subsystem performance of Guangxi, Hebei, Liaoning, Fujian, and Hainan is below average, with low or extremely low status. These provinces typically lack of sufficient economic or technological resources to provide adequate support to the response system. In particular, although Liaoning has relatively favorable conditions for marine technology, due to its greater emphasis on land-based development and the lack of a unified policy support and coordination mechanism, it is unable to form an effective synergy even when it has sufficient inputs of marine technological and economic resources, resulting in a waste of resources and affecting the efficiency of the response subsystem. In addition, some provinces, such as Hebei and Guangxi, have a short history of marine development, less developed marine industry, and shortage of marine talents. A defective response subsystem may impede effective management of marine ecological pressures, which could ultimately hinder the development of the MECC.

3.3 Spatial correlation network characteristics of MECC

The MECC spatial correlation network maps with values in 2006, 2011, 2016, and 2021 for the coastal provinces in China are produced using ArcGIS, and the spatial correlation strength is divided into four levels using Jenks Natural Breaks classification method. As shown in Figure 8, during the study period, there were clear spatial correlations in MECC among coastal provinces, with channels becoming intertwined and different nodes coexisting with neighboring channels and jumping channels. The spatial network shows a trend towards increasing complexity and densification. With the promotion of MECC in China, the strength of spatial correlations among provinces also shows notable enhancement. For instance, the spatial correlations of MECC between Liaoning and Hebei, Shandong and Shanghai, Shanghai and Fujian, Jiangsu and Fujian have all been effective enhanced, indicating a growing level of interactions and cooperations of MECC in these provinces. While some of these provinces are not neighboring, their spatial correlations of MECC have been markedly reinforced during the study period. The increase in the spatial correlations of MECC between Shanghai and Shandong, and Shanghai and Fujian can be attributed to the following reasons. Firstly, Shanghai not only has the geographical location advantage of bridge the north to the south, but also has the largest airport and port in China, as well as a comprehensive transportation network comprising railways, highways, and pipelines, which facilitates collaboration of MECC with non-adjacent provinces (Huo et al., 2022). Except for neighboring provinces, Shandong and Fujian are geographically closest to Shanghai, which helps to the formation of a spatial correlation network. Secondly, the "Outline of the National Territorial Planning Program (2016-2030)" indicates that

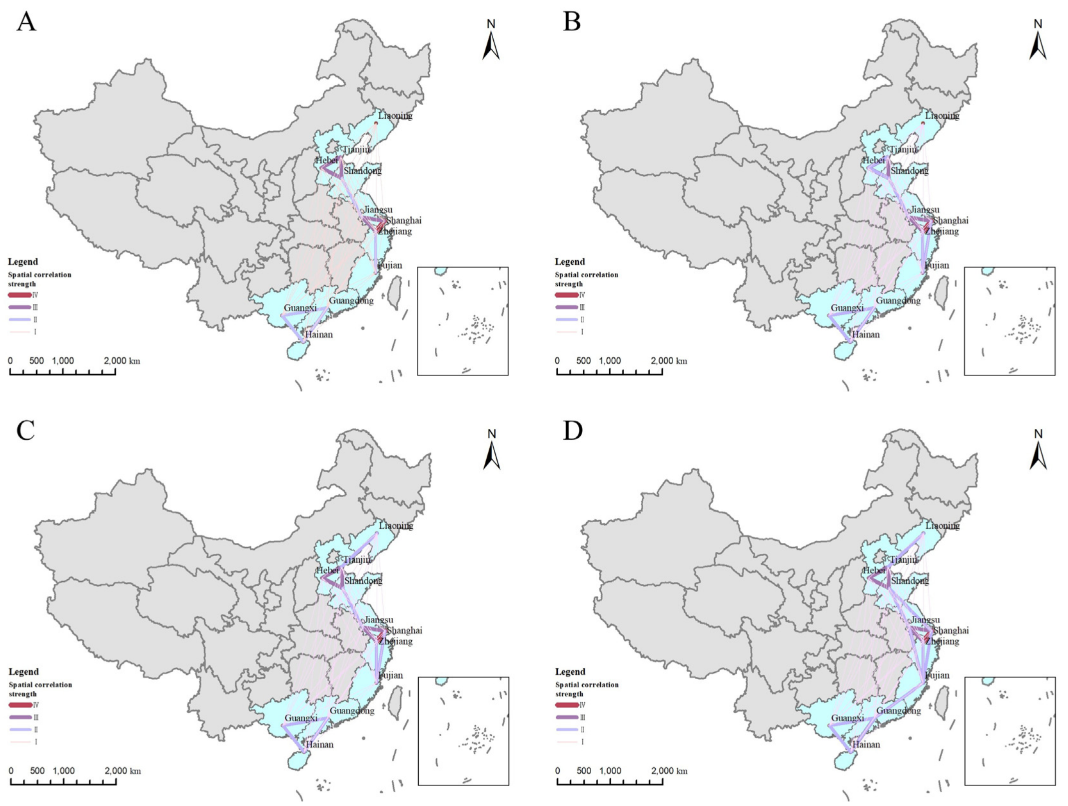

FIGURE 8
Spatial correlation network of MECC for coastal provinces. **(A)** 2006. **(B)** 2011. **(C)** 2016. **(D)** 2021.

Shanghai and other megacities should optimize their comprehensive functions of serving the entire country and engaging with the global community, improve their international influence and competitiveness, and lead the development of whole country. MECC in Shanghai is not only contingent upon the city's own sustainable development, but also has a leading role in China. Thirdly, both Shandong and Shanghai have robust marine technology and economy, which facilitates greater exchanges and flows in related fields. Shanghai and Fujian are both situated on the East China Sea, and have signed "Shanghai-Fujian Science and Technology Innovation Cooperation Framework Agreement", which provides the basis for the strengthening of spatial correlations. With regard to the enhanced spatial correlation between Jiangsu and Fujian, the main reasons are as follows. First of all, in 2017, the "13th Five-Year Plan for National Marine Economic Development" positions Jiangsu as a pivotal nexus of the 21st Century Maritime Silk Road, with Fujian designated as the core area for its construction. The two provinces exhibit similar developmental orientations, and under the promotion of relevant policies, there is a more expansive space and opportunity for collaboration between the two in the marine development. Besides, both provinces are located along the eastern coast of China, facilitating convenient transportation and fostering strong economic strength and close interaction (Fan and Xiao, 2021), which collectively contribute to the formation of a robust spatial correlation. However, the spatial correlation between the majority of coastal provinces on the MECC still needs to be strengthened. The results suggest that the distance dependence of provincial trajectory MECC spatial flows is more pronounced, indicating that the majority of spatial flows associated with MECC occur between neighboring provinces. The reason is that the spatial proximity of provinces reduces the costs of time and distance for cooperation and linkages in economic, social, and other fields, promoting the allocation of resources and the flow of factors between provinces. This, in turn, strengthens economic cooperation and complementarities, facilitating the spatial linkages of the MECC. Furthermore, the ecosystems of neighboring provinces are more closely interconnected and possess greater incentives to engage in collaborative cross-provincial pollution management.

In terms of spatial characteristics, the spatial correlations of MECC are stronger in the eastern marine economic circle and northern marine economic circle, while weaker in the southern marine economic circle. The results demonstrate that the two-way mutual feedback intensity of the spatial flow of MECC among provinces in these two regions is greater than that observed in the southern marine economic circle. The provinces in the northern and eastern marine circles are located in the Bohai Bay and the Yangtze River Delta Economic Circle, which have historically demonstrated a high degree of interconnectivity in the process of China's marine development. The promotion of the cooperative development plan for the Bohai Rim and the strategy of the Great Bay Area around Hangzhou Bay further erode the boundary of provincial and municipal jurisdiction in these regions. This has

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facilitated the establishment of more effective coordination mechanisms, the internal integration of urban agglomerations, infrastructure connectivity, and coordinated ecological governance, which collectively laid the foundation for the co-development of MECC. In contrast, the provinces in the southern marine economic circle have been developed largely in isolation, and the spatial correlations between their internal provinces are weak. Furthermore, the spatial correlation between the provinces in the southern marine economic circle and provinces outside it is even weaker due to the influence of spatial distance.

3.4 Spatial radiation capacity of MECC

As shown in Figure 9, While there have been some fluctuations in the radiative capacity of the provinces in the MECC network, the overall radiative capacity of the provinces has nevertheless been enhanced to a certain extent. By 2021, provinces in similar radiation capacity levels demonstrate a more pronounced spatial aggregation. Among them, Shanghai, Zhejiang, and Jiangsu in the eastern marine economic circle and Shandong and Tianjin in the northern marine economic circle demonstrate strong radiation capacity, indicating their significant role in promoting MECC through spatial radiation effect. In contrast, Liaoning, Fujian, Guangxi, and Hainan exhibit comparatively diminished radiating capacity, positioning them in marginal locations of spatial network. This renders it challenging for these provinces to exert influence over other areas. The majority of these provinces exhibit a relatively low level of ecological civilization construction, underscoring the urgent need to enhance marine ecological civilization construction through a multi-pronged approach that integrates the problems identified in the previous section, and at the same time take advantage of the radiation capacity and advance development of the surrounding provinces to facilitate their development. The disadvantage of location faced by Hainan and Guangxi is such that it is more challenging to establish a robust regional linkage effect with neighboring provinces. This is due to the fact that other provinces are less able to act as a source of radiation to drive the development of these two regions. Consequently, there is a greater need for the central government to facilitate cooperation between developed and underdeveloped regions through regional strategic adjustments.

Match the results with MECC levels, provinces with higher levels of MECC tend to have stronger radiation capabilities. Furthermore, excellent performance levels can create stronger spatial connected effects with neighboring provinces, which in turn can drive their development of MECC. In particular, Guangdong has low radiation capacity despite the high level of MECC, indicating that Guangdong's influence on other provinces is relatively limited. The primary reasons are as follows. Firstly, Guangdong is geographically distant from the northern and eastern coastal provinces, especially when traversing the sea, which makes it more challenging to engage in cooperations with them. Consequently, Guangdong's spatial connections are primarily

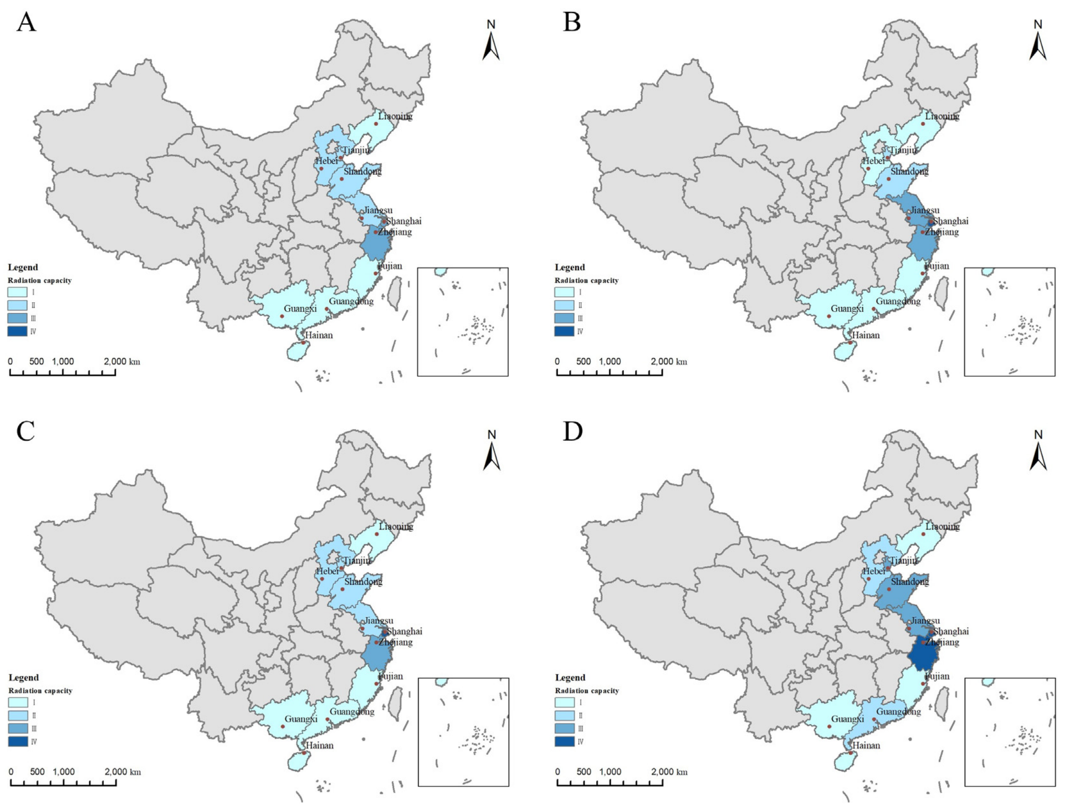

FIGURE 9
Spatial radiation capacity of MECC for coastal provinces. **(A)** 2006. **(B)** 2011. **(C)** 2016. **(D)** 2021.

with neighboring provinces. Secondly, Guangdong boasts a significantly stronger economic and technological prowess than its neighboring provinces, leading to a diminished inclination to collaborate with them. Currently, Guangdong is more focused on collaborate with Hong Kong and Macao to establish the Guangdong-Hong Kong-Macao Greater Bay Area, and has already established close ties in the domains of industry, innovation, and logistics (Wang et al., 2024). Related literature also indicates that the strong linkages are primarily concentrated among the cities in the eastern Pearl River Delta, while the network connectivity with the cities in western part of Guangdong is relatively weak (Chen et al., 2023a; Wang et al., 2024). Thirdly, there are evident regional disparities in Guangdong's internal development. The concentration of development remains in the Pearl River Delta region. The outlying regions of Guangdong are characterized by a relatively low population density, low levels of socio-economic development, and a lack of robust infrastructure (Liao and Zhang, 2022), which hinder the potential for exchange of products, capital and labor with other provinces (Li et al., 2024). Therefore, while promoting the development of its own MECC, Guangdong should also enhance its radiation effect through construction of regional infrastructure, establishment collaborative innovation platform, cross-regional ecological governance, and industrial integration.

4 Conclusions and implications

4.1 Conclusions

This paper introduces the concept of land-sea coordination into the theoretical framework of MECC. Based on the quantitative evaluation of MECC in the coastal provinces from 2006 to 2021, this paper employs gravity model to construct a MECC spatial correlation network and analyze the network structure and radiation capacity to determine the spatial influence of provinces in the MECC. The main conclusions are as follows:

1. In terms of temporal characteristics, the comprehensive index of MECC for the coastal provinces shows a fluctuating upward trend from 2006 to 2021, with a decline in the pressure subsystem and an evident increase in the state and response subsystem.
2. In terms of spatial characteristics, there is considerable variation in the performance of MECC across different provinces over the study period. While provinces within southern marine economic circle demonstrate a relatively stronger performance on the MECC, particularly Guangdong, those within northern economic circle exhibit a relatively weaker performance, particularly Hebei.
3. Despite the fact that the interprovincial MECC spatial network is becoming increasingly interconnected, the strong spatial correlations are primarily concentrated between provinces situated in close geographical proximity, particularly in the vicinity of Bohai Bay and Hangzhou Bay.
4. During the study period, there has been improvements in the MECC radiation capacity across all provinces. There is a correlation between the MECC radiation capacity and the MECC level, with the exception of Guangdong, where the majority of provinces with a higher MECC level also demonstrates a stronger radiation capacity.

4.2 Policy implications

Based on the above conclusions, this study puts forward the following suggestions for further strengthening the MECC:

1. The implementation of rigorous measures to prevent and control land-based pollution is essential to mitigate the impact of development pressure. Despite the implementation of several policies aimed at fostering ecological civilization in China, the underlying pressure subsystem has yet to undergo substantial improvement. In particular, land-based pollution represents a significant obstacle to the development of marine ecological civilization. It is imperative that the relevant governmental departments implement a comprehensive prohibition on the discharge of untreated and substandard waste by industrial enterprises. Furthermore, they must implement rigorous monitoring and enforcement of penalties for key polluting industries in key industrial areas, such as chemicals and paper-making. Concurrently, when reforms are implemented in pivotal industries, the government should provide suitable subsidies to enterprises to encourage clean production, facilitate effective acceptance and implementation, and strive to serve as a model for green practices to enhance the demonstration effect.
2. It is imperative to optimize the structure of the marine industry and enhance the efficiency of resource utilization. On the one hand, the transformation and upgrading of traditional marine industries should be promoted, while the development of strategic emerging marine industries should be strengthened. In addition, marine efficient fisheries, marine renewable energy utilization, desalination and comprehensive utilization of seawater, and marine pharmaceuticals and other marine strategic emerging industries should be cultivated and grown. Besides, in order to ensure the efficient use of marine resources, it is essential to reinforce the management of the total amount of marine resources, comprehensive conservation and recycling, and the efficient allocation of resources. Furthermore, the government should facilitate

the advancement of marine monitoring and evaluation technology, marine pollution treatment technology, and marine ecological restoration technology. This will contribute to an increase in the total amount of marine resources and an enhancement in the quality and stability of marine ecosystems.

3. It is essential to recognize the discrepancies and inconsistencies inherent to the construction of marine ecological civilization. It is recommended that each province formulate its own MECC enhancement strategy and guarantee mechanism according to local conditions. This approach would allow provinces to leverage their unique advantages and address any shortcomings within their respective regions. For instance, provinces such as Shandong, Hebei, Liaoning, and Zhejiang face elevated ecological pressures, while Hebei and Tianjin are experiencing marine ecological degradation and resource depletion. Additionally, Guangxi, Hainan, and Fujian, have limited technological resources to support further development of MECC.
4. It is crucial to focus on the spatial correlation of inter-provincial MECC, aiming to expand the spatial spillover channels of MECC on a global scale, transcend administrative boundaries, and reinforce the resilience and proximity of the spatial correlation of MECC. It is recommended that the radiation capacity of provinces with high MECC levels be fully utilized. The frequency of inter-provincial MECC spatial connections should be increased, and provinces with weak MECC levels should be encouraged to fully leverage the learning effect and exchange mechanism, thereby facilitating their own development through the radiation-driven drole of neighboring provinces. In particular, Guangdong needs to strengthen its capacity to facilitate the development of MECC in neighboring provinces, thereby assuming a leading role in the southern marine economic circle. Furthermore, while stabilizing the MECC spatial correlations of neighboring provinces, it is essential to prioritize the expansion of long-distance interregional MECC spatial correlations. The advancement of cross-regional economic, scientific, and technological collaboration, coupled with the establishment of a cross-regional ecological common governance platform, will facilitate the realization of a coordinated development of the MECC in China as a whole.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

KG: Conceptualization, Data curation, Methodology, Writing – original draft. LY: Methodology, Validation, Writing – review & editing.

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Conflict of interest

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

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The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

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