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EDITED BY
Junjie Wang,
Nanjing University of Aeronautics and Astronautics, China

REVIEWED BY
Yuan-Wei Du,
Yunnan University, China
Lu Zhai,
Shanghai Ocean University, China

*CORRESPONDENCE
Yanwei Wang
wyw2952648592@163.com

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Research on the measurement and spatiotemporal evolution characteristics of new quality productive forces in China's marine economy

Xue Jin[1,2], Yanwei Wang[1,2]* and Kedong Yin[1,2]

[1]School of Management Science and Engineering, Shandong University of Finance and Economics, Jinan, China, [2]Institute of Marine Economics and Management, Shandong University of Finance and Economics, Jinan, China

The marine economy's new quality productive forces is an important driving force to promote the high-quality development of the marine economy. Exploring the level of marine economy's new quality productive forces and its spatiotemporal evolution law will help to provide solid theoretical support and empirical basis for formulating scientific strategies to promote the accelerated development of marine economy. Based on panel data from 11 coastal provinces and cities from 2010 to 2022, this study applies the entropy value method to measure the level of marine economy's new quality productive forces, and then uses the Dagum Gini coefficient and its decomposition, kernel density estimation method and spatial Markov chain model to reveal its regional differences and spatiotemporal evolution characteristics. The results of the study showed that: (1) The level of marine economy's new quality productive forces in China and the three major marine economic circles (northern, eastern and southern) have grown annually, but regional imbalances are increasing. Among the constituent elements, scientific and technological productive forces exhibited the strongest growth momentum, while the development of green productive forces relatively lagged behind. (2) The level of marine economy's new quality productive forces in individual provinces deviates significantly from the national average, resulting in supervariable density becoming the main source of spatial differentiation of marine economy's new quality productive forces level. (3) Except for the eastern marine economic circle, other regions generally show obvious polarization, which not only limits the effective allocation of resources, but also affects the rational flow and transfer of new quality productive forces levels between different regions. In this regard, relevant policy recommendations are put forward: (1) The implementation of differentiated strategies promotes the regional adaptive

development of marine economy's new quality productive forces. (2) Strengthening internal and external linkage mechanisms to release the spillover effect of the marine economy's new quality productive forces. (3) Science and technology drive green development and enhance the green content of marine economy's new quality productive forces.

KEYWORDS

marine economy's new quality productive forces, marine economic circles, level measurement, regional disparities, spatiotemporal evolution

1 Introduction

The concept of "new quality productive forces" was first clearly proposed by General Secretary Xi Jinping during his inspection visit to Heilongjiang Province in September 2023, and gave in-depth interpretation and high emphasis in many subsequent important meetings. From the perspective of basic theory, new quality productive forces centers on innovation as the core driver of development, abandoning the shackles of the traditional economic growth model, and opening a new path for productive forces development. It is characterized by high technology, high efficiency, and high quality (Yi and Zheng ,2024), aligning with the new era's development, and representing the latest embodiment of advanced productive forces. As the forefront of the modernization and transformation of the productive forces, the new quality productive forces not only comply with the requirements of the new development concept, but also inject strong impetus into the high-quality economic development in the new era (Ren, 2024). The deep understanding of its dimensions needs to focus on the dual dimensions of "new" and "quality". "New" is reflected in the profound reform and upgrading of the basic components of productivity, including the improvement of the quality of workers (the transformation from simple and repeated labor to knowledge-intensive labor), innovation of labor materials (integrated into the Internet, intelligent equipment and other emerging technology infrastructure), the expansion of labor objects (covering non-material form resources such as data), and the comprehensive innovation of production form (the disruptive reshaping of technology, industry and forms of business). "Quality" emphasizes the fundamental transformation of the productivity operation mechanism, involving the optimization of the operation path, the improvement of the quality and efficiency of the operation results, the intelligent and green transformation of the operation carrier (Ding and Li, 2024). These changes go beyond the traditional mode of productive forces relying solely on quantitative expansion, and realize a qualitative leap in the essential attributes of productive forces. While pursuing economic benefits, the new quality productive forces also attach great importance to ecological benefits, which reflects the unremitting pursuit of resource conservation and efficient utilization. Through the introduction of advanced technology to transform the production process, and through the practice of the concept of green and sustainable development, the new quality productive forces effectively reduces the negative impact on the ecological environment, thus being in line with the concept of green productive forces. Through the introduction of advanced technology to transform the production process, and through the practice of the concept of green and sustainable development, the new quality productive forces effectively reduces the negative impact on the ecological environment, thus being in line with the concept of green productive forces in essence.

The proposal of new quality productive forces has established a clear strategic orientation for promoting the high-quality transformation and development of China's Marine economy. Marine economy, as the key engine of economic growth in the new era, not only carries the important task of promoting new growth drivers, but also leads the optimization and upgrading of economic structure and the exploration of new development model (Chen and Di, 2023), opens up a new dimension of economic expansion and becomes a solid foundation of the strategic blueprint of building a maritime power. Since the beginning of the 21st century, China's marine economy has stepped into the fast lane of rapid development. By 2023, its economic aggregate has jumped to 99,097 billion yuan, compared with 951.84 billion yuan in 2001, it has achieved a leap growth of nearly ten times, highlighting the strong driving role of Marine economy on the economic growth of coastal areas and even the whole country (Yin et al., 2016). The focus of the national marine economic policy has gradually shifted from the previous growth model that focuses on speed to the high-quality development model that pays equal attention to quality and efficiency, and paid more attention to innovation-driven, structural optimization, green, low-carbon and open and win-win results (Jin et al., 2021). In 2017, the "*13th Five-Year Plan for the Development of the National Marine Economy*" proposed to further improve the quality and efficiency of the marine economy. In 2018, the "*Implementation Opinions on Promoting the High-quality Development of the Marine Economy*" focused on supporting the transformation and upgrading of traditional marine industries, and in 2021, the "14th Five-Year Plan" for the development of the marine economy proposed to "accelerate the construction of a

marine power". At present, although the marine economy shows a vigorous development, there are still problems such as serious marine environmental pollution, excessive exploitation of marine resources, imperfect marine industrial structure, excessive regional differences, marine technology "bottleneck" and other need to be solved by (Lu and Yao, 2024). Therefore, given the above challenges, it is particularly important and urgent to accelerate the construction and formation of new qualitative productive forces in the marine field. The cultivation of new quality productive forces is not only the innovation and transcendence of the traditional marine economy development model, but also the only way to cope with the current difficulties and realize the high-quality development of marine economy (Sun and Song, 2021). It requires us to make breakthroughs in marine environmental protection, sustainable utilization of resources, optimization and upgrading of industrial structure, coordinated regional development and independent research and development of key technologies, so as to build a more green, efficient, coordinated and open new marine economy system.

At present, the academic circle has set off the upsurge of research on new quality productive forces, mainly focusing on the connotation interpretation of new quality productive forces (Ding and Li, 2024; Ren, 2024), research status and prospect (Guan et al., 2024; Yang, 2024), level measurement (Han et al., 2024; Liu and He, 2024; Lu et al., 2024; Zhu et al., 2024), cultivation path (Chen and Liu, 2024) and so on aspects. Some scholars have also explored the new quality productive forces in specific fields. For example, Gao and Ma (2024) interpreted the new agricultural productive forces from the perspective of political economy, Zhang and Wang (2024) proposed the improvement path after analyzing the new agricultural productive forces; Dong (2024) proposed to explore the new quality productive forces of grass industry; Deng et al. (2024) analyzed the basic framework of the new quality productive forces in the industrial field. However, there is a great shortage of research on new quality productive forces in the marine field. Xie and Li (2024) mentioned to accelerate the development of new quality productive forces in the marine field. Ye et al. (2024) measured the level of China's new marine quality productive forces. Liang et al. (2024) explored how the new quality productive forces can empower the high-quality development of the marine economy. Yu et al. (2024) analyzed the characteristic connotation and development path of the new marine quality productive forces. In view of the important growth pole of marine economy in China's economic system, in-depth exploration of the new quality productive forces of marine economy is not only an expansion of the existing research framework, but also an internal

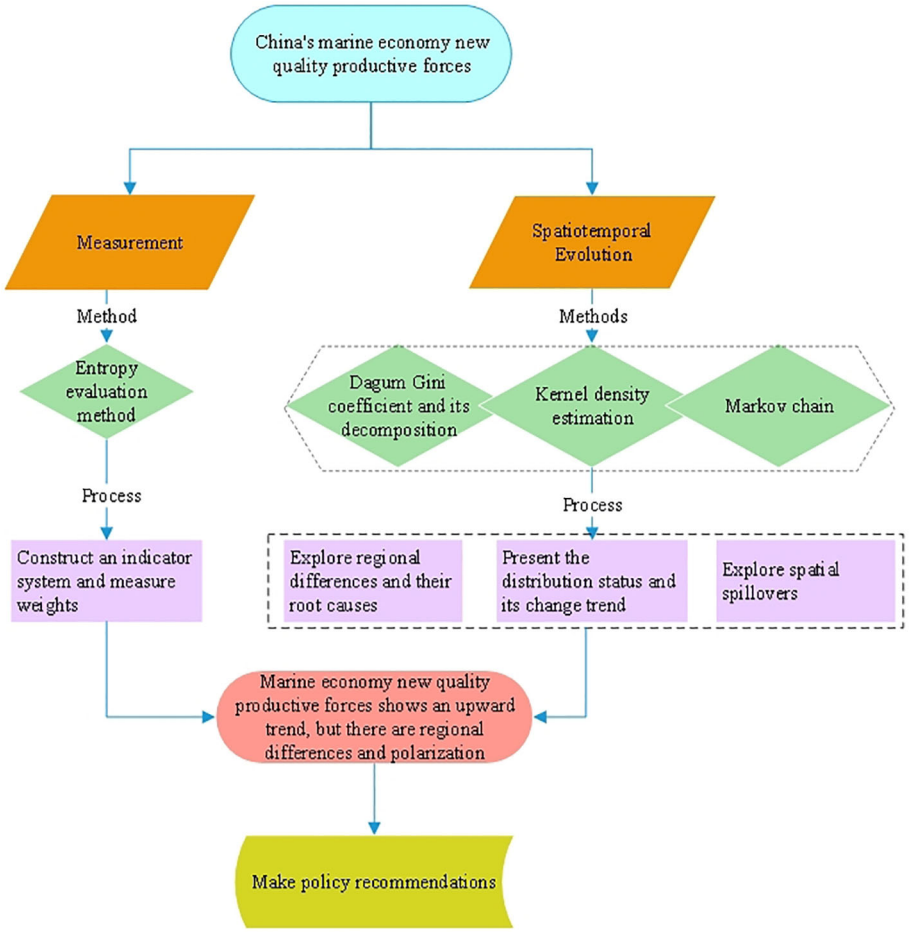

FIGURE 1
Research framework.

requirement to promote the high-quality development of marine economy. In analyzing the marine economy's new quality productive forces, it is necessary to not only adopt the general theoretical framework of new quality productive forces, but also fully consider the uniqueness and complexity of marine production activities, so as to provide strong theoretical support and practical guidance for the sustainable development of marine economy.

From the perspective of the research status, the quantitative evaluation system of the marine economy's new quality productive forces is still in the initial stage of construction and improvement, and in-depth research needs to be conducted from the perspective of time dimension and spatial difference. Based on this, according to the research framework of Figure 1, this paper constructs the index system of marine economy's new quality productive forces, and calculates the level of marine economy's new quality productive forces in 11 coastal provinces and autonomous regions in 2010-2022. Through the regional division strategy, the research area is divided into three marine economic circles(the northern marine economic circle includes Liaoning, Tianjin, Hebei and Shandong, the eastern marine economic circle includes Jiangsu, Shanghai and Zhejiang, and the southern marine economic circle includes Fujian, Guangdong, Guangxi and Hainan), exploring the differences in the level of marine economy's new quality productive forces within different regions and between regions, and using the technology of nuclear density estimation to depict the distribution pattern and change trend of marine economy at different time points. At the same time, combining with the spatial Markov chain analysis method, it deeply analyzes the spatial dynamic process and the spatial spillover effect of the marine economy's new quality productive forces, which has important theoretical value and practical significance for promoting the balanced and sustainable development of marine economy.

2 Research methods and data sources

2.1 Construction of an index system for marine economy's new quality productive forces

The marine economy's new quality productive forces, as the specific mapping of the new quality productive forces in the marine dimension, strictly follows the theoretical logical framework, core connotation characteristics, systematic construction path and its realization strategy of the new quality productive forces. It is rooted in the basis of strengthening human ability to conquer and transform nature endowed by scientific and technological progress, and represents the leap of productive forces led by scientific and technological innovation in the marine field (Liu, 2024). At present, the global new scientific and technological revolution and the wave of industrial transformation have had a profound impact on the evolution of the marine economy, and have given birth to a number of breakthrough scientific and technological achievements (Feng et al., 2024), highlighting the position of science and technology as the core driving force for the current and future growth of China's marine economy. Digital economy, as a direct product of scientific and technological progress, has begun to take shape and deeply integrate into the national economic system. Its positive incentive effect on marine economy is significant (Fu et al., 2022), indicating a strong engine for the development of marine economy's new quality productive forces in the future. At the same time, the marine economy's new quality productive forces contains the characteristics of green productive forces, which is committed to realizing the harmonious coexistence between economic and social development and marine resources and environmental protection (He et al., 2023), and leading the marine economy to the direction of high quality and sustainable. In summary, the marine economy's new quality productive forces is a comprehensive system integrating science and technology, digital and green elements.

In view of the above analysis and relying on the existing research basis of the theory of new quality productive forces, an evaluation system for the development level of marine economy's new quality productive forces is constructed. This system considers scientific and technological, digital, and green productive forces as the first-level evaluation dimension. Further refinement shows that scientific and technological productive forces covers the two sub-dimensions of marine innovation productive forces and marine technological productive forces. Digital productive forces is decomposed into digital industrial productive forces and industrial digital productive forces. Green productive force includes marine environment-friendly productive forces and marine resource-saving productive forces (see Table 1).

General Secretary Xi Jinping's concept that "talent is the foundation of innovation, and the core of innovation-driven is talent-driven," highlights the essential role of talent resources in promoting innovation activities. In the field of marine economy, the assessment of marine innovation productive forces needs to focus on the scale and quality of marine researchers and the marine research results they produce. Specifically, the quantitative index of the number of researchers is set as the number of employees in the field of marine research, while the quality level is reflected by the proportion of high-quality talents in the marine field (i. e., talents with master's degree or above degree in marine majors), which directly reflects the overall quality and potential of the marine research team. The measurement of marine scientific research achievements covers the number of patents granted, the number of scientific papers published and the performance of research and development (R&D) projects in marine scientific research institutions. Collectively, these indicators constitute the direct output and influence of marine scientific research innovation activities. As a bridge connecting scientific knowledge and production practice, technology is the core driving force and key element of productivity development. In the category of marine economy, the evaluation of technical productive forces focuses on the actual results in improving production efficiency, optimizing the utilization mode of means of production and improving the quality of labor objects. This paper selects the marine industry robot penetration density as a key index of the intelligent marine industry process. Its calculation method draws lessons from the research of Kang and Lin (Acemoglu and Restrepo, 2020), combining the International Federation of Robotics (IRF)

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TABLE 1 Evaluation index system for the development level of marine economy's new quality productive forces.

Level 1 indicators	Level 2 indicators	Level 3 indicators	Quantification method	Nature
Scientific and technological productive forces	Marine innovation productive forces	Training of high-quality personnel in the marine field	Number of master's degree or above in marine major/Number of graduate students	Positive
		Marine researchers are invested	Number of people engaged in marine scientific research	Positive
		Patent research and development of marine scientific research institutions	Number of patents granted by marine scientific research institutions	Positive
		Marine scientific research and development topics	Number of R & D projects	Positive
		Research results in the marine field	Number of scientific and technological papers in marine scientific research institutions	Positive
	Marine technology productive forces	The penetration density of marine industry robots	Proportion of marine industry personnel * Robot installation volume	Positive
		Marine labor productivity	Total output value of marine economy/Number of marine employees	Positive
		Marine monitoring level	Number of seaside observation stations in coastal areas	Positive
		Port production level	International standard container throughput of coastal ports	Positive
Digital productive forces	Digital industry productive forces	Telecom business scale	Total telecom business	Positive
		Telecom communication level	Mobile phone penetration rate	Positive
		Software maintenance	Software business revenue	Positive
		Information technology services	Information technology service revenue	Positive
	Industrial digital productive forces	The breadth of Internet popularization	Number of Internet broadband access users	Positive
		Depth of enterprise digital application	The number of websites per 100 enterprises	Positive
		E-commerce economic scale	E-commerce sales volume	Positive
		Communication infrastructure density	Optical cable line length/ Regional area	Positive
Green productive forces	Marine environment-friendly productive forces	Industrial wastewater is discharged directly into the sea	Direct discharge amount of industrial waste water in coastal areas	Negative
		Industrial exhaust gas emission intensity	Industrial SO2 emissions/Gross marine product	Negative
		Industrial solid waste resource utilization	Comprehensive utilization of industrial solid waste/Industrial solid waste discharge	Negative
		Fishing boat use	Number of motorized boats/Total number of fishing boats	Negative
		Environmental protection degree	Environmental protection expenditure/Central fiscal expenditure	Positive
	Marine resources conservation type productive forces	The proportion of traditional marine fishermen	Number of traditional marine fishermen/Marine fishery population	Negative
		Port development and utilization		Negative

(Continued)

TABLE 1 Continued

Level 1 indicators	Level 2 indicators	Level 3 indicators	Quantification method	Nature
			Number of wharf berths used for production in coastal ports above the designated scale	
		Economy of energy consumption	Energy consumption/GDP	Negative
		Production capacity per unit of mariculture area	Mariculture yield/Mariculture area	Negative
		Marine industrial structure	The proportion of the marine and tertiary industry	Positive

industrial robot installation data and China's coastal provinces marine employment population proportion, using the formula "industrial robot installation quantity of marine industry percentage" to construct a quantitative index. Additionally, the improvement effect of marine technological productive forces on labor efficiency is measured by marine labor productive forces, while the development level of marine monitoring technology is indirectly reflected by the number of coastal observatories in coastal areas. This index reflects the application effectiveness of marine science and technology in environmental monitoring and protection. Advances in marine technological productive force also significantly affect the operational efficiency and production capacity of critical infrastructure such as ports. With the continuous innovating and upgrading of marine technology, the international standard container throughput of coastal ports has become an important dynamic index to measure the port operation efficiency and internationalization level. This index intuitively shows the driving role of marine technological progress in the optimizing of port logistics systems and improving throughput.

The measure of digital productive forces can be subdivided into two major dimensions: digital industrial productive forces and industrial digital productive forces. Digital industrial productive forces focuses on the use of modern information technology to catalyze the formation and development of digital industry. Its quantitative index system covers telecom business scale (telecom business total measure), telecom communication level (e. g., mobile phone penetration), and the economic contribution of the software and information technology service industry (reflected by software business income and information technology service income respectively). Industrial digital productive forces emphasizes the penetration of traditional industries and transformation and upgrading effect, the evaluation framework including internet popularization breadth (such as Internet broadband access users), the depth of digital application in enterprises (such as the number of each hundred enterprises, with websites per hundred), the economic scale (e-commerce sales), and the intensity of communication infrastructure density (cable line length and coverage). These indicators reflect the impact of digital technology on industrial production efficiency and structure optimization.

The marine environmental-friendly goal of productive forces of green productive forces is to reduce the pollution load to the marine environment and promote the healthy and sustainable development of the marine ecosystem (Liu et al., 2024). Its quantitative assessment focuses on the environmental externalities of coastal industrial activities, including the mass of industrial waste water directly discharged, the intensity of industrial waste gas emissions (measured by industrial SO_2 emissions and the ratio of gross marine product), and industrial solid waste resource utilization level (the ratio of comprehensive utilization of industrial solid waste and emissions).Additionally, the assessment considers the environmental impact of marine fishing activities, the trade-off between motorized fishing efficiency and environmental protection, and the role of government expenditure on marine environmental protection. Marine resource-saving efforts focuses on improving the utilization efficiency of marine resources to achieve the sustainable development of the marine economy through optimized resource allocation. The efficiency of the traditional fishery production mode limitation, the efficient development and utilization of port resources (marked by the number of wharf berths at coastal ports), energy consumption efficiency (energy consumption per unit of GDP), intensive management of mariculture space (production per unit area), and marine tertiary industry (such as coastal tourism, marine research education) of dependence on marine resources, together constitute the assessment of marine resources conservation productive forces multi-dimensional perspective. These analyses not only reveal the current status quo and potential of marine resources utilization, but also provide an important basis for formulating scientific and effective marine resources management policies.

2.2 Study methods

2.2.1 Entropy evaluation method

The entropy method adopts an objective way of empowerment to avoid the interference of subjective thinking and objectively reflecting the importance of each evaluation index to the system. When the data of an evaluation index shows a large degree of dispersion, it means that the change of the index has a more significant impact on the overall evaluation results. The calculation steps were performed as follows:

First, the data were standardized using by the range method to eliminate the dimensional differences between the different evaluation indicators:

Positive indicators:

$$p_{ij} = \frac{x_{ij} - min(x_{ij})}{max(x_{ij}) - min(x_{ij})} \quad (1)$$

Negative indicators:

$$p_{ij} = \frac{max(x_{ij}) - x_{ij}}{max(x_{ij}) - min(x_{ij})} \quad (2)$$

Second, we calculated the feature weight y of the jth index for the ith sample:

$$y_{ij} = \frac{p_{ij}}{\sum_{i=1}^{m} p_{ij}} \quad (3)$$

Third, the entropy value of the jth index was calculated:

$$e_j = -\frac{1}{\ln m} \times \sum_{i=1}^{m} y_{ij} \times \ln y_{ij} \quad (4)$$

Subsequently, the redundancy of the g_j of the information entropy e_j and the weight coefficient w_j were calculated as follows:

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

$$w_j = \frac{g_i}{\sum_{j=1}^{n} g_i} \quad (6)$$

Finally, the linear weighting method was used to calculate the marine economy's new quality productive forces:

$$U_i = \sum_{j=1}^{m} w_j p_{ij} \quad (7)$$

Where, m is the number of years evaluated.

2.2.2 The Dagum Gini coefficient and its decomposition

Compared to other methods used for measuring regional disparities, the Dagum Gini coefficient has the advantage of addressing the issue of the overlapping phenomenon in the survey data and can better identify the source of the regional gap. The Dagum Gini coefficient can be decomposed into three components: the within-group coefficient G_w, between-group coefficient G_{nb}, and hypervariable density G_t, expressed as

$G = G_w + G_{nb} + G_t$.

$$G = \frac{\sum_{j=1}^{k}\sum_{h=1}^{k}\sum_{i=1}^{n_j}\sum_{r=1}^{n_h}\left|Y_{ji} - Y_{hr}\right|}{2n^2\bar{Y}} \quad (8)$$

$$G_{jj} = \frac{\sum_{i=1}^{n_j}\sum_{r=1}^{n_h}\left|Y_{ji} - Y_{jr}\right|}{2\bar{Y}n_j^2} \quad (9)$$

$$G_{jh} = \frac{\sum_{i=1}^{n_j}\sum_{r=1}^{n_h}\left|Y_{ji} - Y_{hr}\right|}{n_j n_h(\overline{Y_j} + \overline{Y_h})} \quad (10)$$

$$G_w = \sum_{j=1}^{k} G_{jj} p_j s_j \quad (11)$$

$$G_{nb} = \sum_{j=2}^{k}\sum_{h=1}^{j-1} G_{jh}(p_j s_h + p_h s_j) D_{jh} \quad (12)$$

$$G_t = \sum_{j=2}^{k}\sum_{h=1}^{j-1} G_{jh}(p_j s_h + p_h s_j)(1 - D_{jh}) \quad (13)$$

$$p_j = \frac{n_j}{n} \quad (14)$$

$$s_j = \frac{n_j \overline{Y_j}}{nY} \quad (15)$$

$$D_{jh} = \frac{d_{jh} - q_{jh}}{d_{jh} + q_{jh}} \quad (16)$$

Where G represents the overall Gini coefficient, G_{jj} represents the Gini coefficient within j regions, G_{jh} represents the Gini coefficient between j and h regions, Y_{ji} (Y_{hr}) represents the level of marine economy's new quality productive forces in $i(r)$ provinces within j (h) regions, D_{jh} represents the relative impact of the marine economy's new quality productive forces level between j and h regions, d_{jh} represents the difference in the marine economy's new quality productive forces between j and h regions, q_{jh} represents the variable first order moment, k represents the number of divided regions, n represents the number of provinces, $n_j(n_h)$ represents the number of provinces within the j (h) region, $\bar{Y}$ represents the average level of the marine economy's new quality productive forces in all provinces, and $\overline{Y_j}$ ($\overline{Y_h}$) represents the average value of marine economy's new quality productive forces levels in the j (h) region.

2.2.3 Kernel density estimation

Kernel Density Estimation (KDE) can describes the distribution and difference sources of the marine economy's new quality productive forces. This study selected Gaussian nuclear function to estimate the dynamic evolution law of the marine economy's new quality productive forces in 11 coastal provinces and autonomous regions and the three major marine economic circles.

$$f(x) = \frac{1}{Nh}\sum_{i=1}^{N} K\left(\frac{X_i - \bar{X}}{h}\right) \quad (17)$$

$$K(x) = \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} \quad (18)$$

Where N represents the number of observations, X_i is the independent and equally distributed observations, $\bar{X}$ is the mean of the observations, $K(\cdot)$ is the Gaussian kernel, and h is the bandwidth.

2.2.4 Markov chain

Based on the results of the KDE, Markov chain was introduced to further analyze the spatial and temporal evolution characteristics of marine economy's new quality productive forces in China. Markov chain is divided into a traditional Markov chain and spatial Markov chain. The spatial Markov chain fully considers the spatial spillover effect of neighboring units on the target unit. The traditional Markov chain constructs a transition probability matrix of $k \times k$ expressed as follows:

$$P_{ij} = \frac{n_{ij}}{n_i} \quad (19)$$

$$P_{ij} = \begin{bmatrix} n_{11} & \cdots & n_{1j} \\ \vdots & \ddots & \vdots \\ n_{i1} & \cdots & n_{ij} \end{bmatrix}_{k \times k} \quad (20)$$

Where n_{ij} indicates the total number of provinces with the marine economy's new quality productive forces level during the study period from level i in T to level j in $T + 1$ year, and n_i indicates the number of provinces with the marine economy's new quality productive forces in level i during the study period.

2.3 Data sources

Time-series cross-sectional data from 11 coastal provinces, municipalities and autonomous regions between 2010 and 2022 were selected as the basis for empirical analysis. The data were obtained from diverse and authoritative sources, including but not limited to the official statistics released by the National Bureau of Statistics, regional fishery data released by the International Fishery Resources Organization (IFO), the "*China Statistical Yearbook*" provides comprehensive data of macro economic and social development, the "*China Marine Statistical Yearbook*" with detailed records of marine economic activities, the "*China Environmental Statistical Yearbook*" with an overview of environmental quality and protection efforts, the "*China Fishery Statistical Yearbook*" on fishery production, trade, and resources, the "*Communiqué on the Status of China's Marine Ecology and Environment Marine Ecological Environment*" on marine ecological quality, and the "*Statistical Bulletin of China's National Economic and Social Development*", summarizing annual economic and social progress.

3 Results and analysis

3.1 Analysis of the measurement results of the marine economy's new quality productive forces

3.1.1 Sub-regional analysis

The results of the entropy method for the marine economy's new quality productive forces are shown in Table 2.

Overall, from 2010 to 2022, the mean value of the national marine economy's new quality productive forces steadily increased from 0.164 to 0.378, though the growth rate remained slow and the overall level was still low. At the level of each marine economic circle, despite brief declines in the northern marine economic circle in 2016 and 2019, all the marine economic circles— northern, eastern and southern—showed an increasing trend year by year. Specifically, the northern marine economic circle increased from 0.155 to 0.322, while the eastern marine economic circle significantly increased from 0.207 to 0.470, becoming the region with the most substantial growth. The southern marine economic circle also increased from 0.140 to 0.364.

Figure 2 visually shows the dynamic changes in the average value of the marine economy's new quality productive forces in each economic circle. The eastern marine economic circle stands out with a significant average advantage, which is significantly higher than the national average level, and has further expanded its leading position with a stronger growth rate after 2016. In contrast, the development trajectory of the northern marine economic circle is more bumpy. In the early stage of the study (2010-2015), it was surpassed by the latter since 2015, and the gap between the two has expanded since 2018. Notably, the northern marine economic circle's average value was relatively consistent with the national level between 2010 and 2013, but then gradually fell behind, reaching its largest gap from the national level in 2020. Although the average value of the southern marine economic circle has long been below the national average, the gap has gradually narrowed. Especially between 2018 and 2020, the average values of the two nearly converged, showing the strong catch-up momentum in the southern marine economic circle.

From the perspective of regional situation, the mean value of the marine economy's new quality productive forces in provinces, cities, and autonomous regions exhibited significant heterogeneity characteristics. During the study period, the mean value of each region showed great dispersion, with Guangdong Province (mean 0.460), significantly higher than those of the other regions. It was followed by Shandong Province (0.368), Jiangsu Province (0.345) and Shanghai City (0.321). Together, these provinces constitute the highlands of the marine economy's new quality productive forces. Zhejiang Province and Fujian Province fell into the sub-high range, with the averages hovering between 0.2 and 0.3, while the remaining provinces (cities and autonomous regions) generally showed lower levels, with the averages between 0.1 and 0.2. Examining the cross-sectional data for 2022 (Figure 3), the regional distribution pattern of the marine economy's new quality productive forces becomes clearer. Guangdong Province stands out with a value above 0.7, showing an absolute lead; Shandong Province follows with a value above the threshold of 0.5, and Jiangsu Province and Shanghai City both have values above 0.4. The overall ranking from highest to lowest is Guangdong, Shandong, Shanghai, Jiangsu, Zhejiang, Fujian, Tianjin, Guangxi, Liaoning, Hebei and Hainan. This ranking is consistent with the average research results and reveals a "W"-shaped geographical distribution pattern from north to south, highlighting the imbalance in the marine economy's new quality productive forces across different regions.

In terms of the average annual growth rate, the performance of provinces, cities and autonomous regions showed a "left low and right high, stable in the middle" trend. Specifically, Liaoning Province, located in the northernmost part of the study area, is relatively backward, while the southernmost province shows strong growth momentum and is the highest. For other provinces (cities and autonomous regions), the annual growth rate shows a relatively stable fluctuation trend without significant signs of acceleration or deceleration. This distribution characteristic of the growth rate further deepens our understanding of the regional differences and dynamic changes in the marine economy's new quality productive forces.

The distribution pattern of the marine economy's new quality productive forces is shaped by multiple factors, including unique

TABLE 2 Level of marine economy's new quality productive forces in coastal provinces, cities and autonomous regions from 2010 to 2022.

Marine economic circle	Province	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Mean value
Northern marine economic circle	Liaoning Province	0.133	0.133	0.151	0.164	0.192	0.225	0.178	0.189	0.193	0.198	0.200	0.214	0.227	0.184
	Hebei Province	0.090	0.093	0.097	0.104	0.114	0.128	0.132	0.147	0.185	0.198	0.205	0.214	0.217	0.148
	Tianjin Municipality	0.136	0.148	0.160	0.207	0.181	0.190	0.184	0.202	0.203	0.236	0.226	0.256	0.259	0.199
	Shandong Province	0.262	0.262	0.306	0.270	0.286	0.303	0.313	0.340	0.411	0.431	0.468	0.524	0.585	0.368
	Mean value	0.155	0.155	0.179	0.186	0.193	0.211	0.202	0.220	0.248	0.266	0.275	0.302	0.322	0.225
Eastern marine economic circle	Jiangsu Province	0.232	0.241	0.258	0.270	0.292	0.314	0.323	0.347	0.393	0.424	0.447	0.451	0.489	0.345
	Shanghai Municipality	0.234	0.239	0.243	0.258	0.298	0.312	0.283	0.302	0.320	0.327	0.405	0.452	0.504	0.321
	Zhejiang Province	0.155	0.155	0.165	0.182	0.209	0.232	0.238	0.262	0.300	0.337	0.361	0.375	0.415	0.261
	Mean value	0.207	0.211	0.222	0.237	0.266	0.286	0.281	0.304	0.337	0.363	0.404	0.426	0.470	0.309
Southern marine economic circle	Fujian Province	0.133	0.133	0.145	0.163	0.176	0.190	0.198	0.214	0.242	0.263	0.261	0.292	0.314	0.209
	Guangdong Province	0.246	0.242	0.268	0.287	0.321	0.391	0.416	0.487	0.569	0.641	0.679	0.688	0.750	0.460
	Guangxi Zhuang Autonomous Region	0.102	0.103	0.105	0.108	0.120	0.124	0.121	0.128	0.160	0.182	0.206	0.217	0.231	0.147
	Hainan Province	0.079	0.077	0.078	0.085	0.089	0.093	0.097	0.098	0.120	0.130	0.134	0.149	0.161	0.107
	Mean value	0.140	0.139	0.149	0.161	0.176	0.200	0.208	0.232	0.273	0.304	0.320	0.337	0.364	0.231

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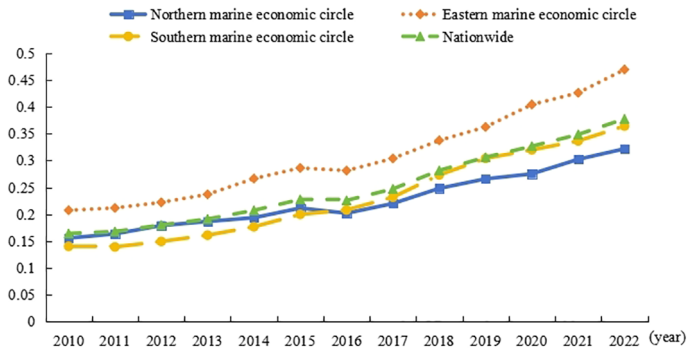

FIGURE 2
Changes in the average level of marine economy's new quality productive forces of the three major marine economic circles and the nationwide from 2010 to 2022.

marine resource endowment, differentiated marine industrial structures, specific geographical locations, and capabilities in scientific and technological innovation. Specifically, provinces in the eastern and southern marine economic circles, with their solid economic foundations, effectively allocate resources to support the development of the marine science and technology innovation ecosystem. This includes cultivating high-end talents, advancing research and development in marine intelligent technology and equipment, and promoting the continuous improvement of marine technology level. This series of measures has laid a solid foundation for the comprehensive upgrading of the marine economy's new quality productive forces—such as workers, labor materials and labor objects—thus promoting the significant enhancement of productive forces. The provinces in the eastern marine economic circle not only have a high level of development in marine economy's new quality productive forces, but also the internal differences are relatively small, showing a high degree of balance, which makes them play the leading role in the development of marine economy's new quality productive forces in the whole country.

The development paths of the marine economy in Shandong and Guangdong provinces each have their own characteristics and have achieved remarkable results. Shandong Province leverages its leading marine equipment industry, including equipment for oil and gas exploration, ship and marine engineering equipment, and new marine energy technologies. Through continuous technological innovation, Shandong Province promotes the optimization and upgrading of its industrial structure and expands the international scope and cooperation space of the marine economy. Guangdong Province, as a leader of the national marine economy, has built an increasingly sophisticated marine economic system by leveraging rich marine biological resources, marine mineral resources, unique marine culture and prosperous coastal tourism, combined with the implementation of major strategies such as "The Belt and Road Initiative", the Guangdong-Hong Kong-Macao Greater Bay Area and the National Free Trade Zone. Importantly, Guangdong Province is also taking the lead in the protection and governance of marine ecological environment, actively exploring ways to balance industrial development, realizing a win-win situation between marine protection and resource utilization, and setting a model for the sustainable development of marine economy. By contrast, Hainan province, Liaoning province, Hebei province, the natural resources, space resources, port resources and fishery resources are relatively scarce, combined with the marine scientific research strength is weak, lead to marine economic structure imbalance, especially the emerging marine industry development lag, these factors jointly restricted the marine

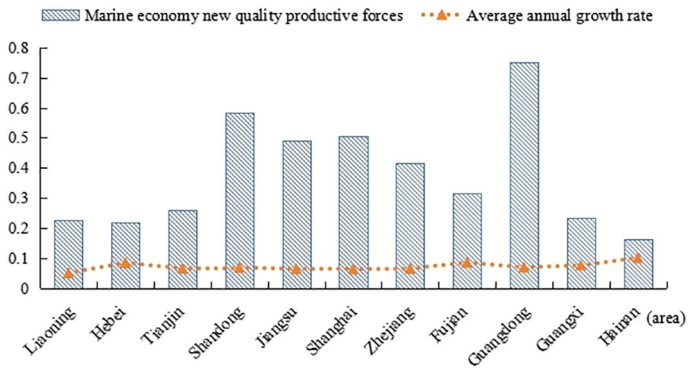

FIGURE 3
Level of marine economy's new quality productive forces in coastal provinces, cities, and autonomous regions in 2022.

TABLE 3 Overall level of marine economy's new quality productive forces from 2010 to 2022.

Year	marine economy new quality productive forces	Scientific and technological productive forces	Digital productive forces	Green productive forces
2010	0.300	0.315	0.203	0.383
2011	0.307	0.336	0.206	0.380
2012	0.329	0.359	0.241	0.388
2013	0.350	0.413	0.246	0.391
2014	0.380	0.458	0.288	0.393
2015	0.417	0.511	0.334	0.406
2016	0.414	0.473	0.367	0.401
2017	0.453	0.526	0.432	0.401
2018	0.516	0.608	0.540	0.400
2019	0.561	0.636	0.633	0.414
2020	0.599	0.693	0.711	0.393
2021	0.639	0.897	0.629	0.391
2022	0.692	0.980	0.719	0.379

economy's new quality productive forces, need to focus on in the future development and strategic adjustment.

3.1.2 Dimensional analysis

According to the calculations, the scores of each level were obtained, and the overall level of the marine economy's new quality productive forces from 2010 to 2022 was calculated (Table 3).

As shown in Table 3, the level of the marine economy's new quality productive forces shows a steady upward trend. In 2016, as a turning point, it experienced a short correction and then entered a new round of growth cycle. After 13 years, its overall level significantly increased by approximately 130% compared to the starting point. Since the strategy of building a maritime power was introduced and implemented, the marine economy has gained unprecedented attention and resource allocation. This strategic goal has guided China's marine economy onto a fast track of high-quality development, driving the continuous improvement of level of the marine economy's new quality productive forces.

In the new elements of the marine economy's new quality productive forces, scientific and technological productive forces is particularly prominent, with its index doubling from 0.315 in 2010 to 0.98 in 2022. In addition, its growth rate was the fastest among all productive force types, approaching a the threshold of 1. This achievement deeply reflects the strong vitality and remarkable results of China's scientific and technological innovation system, marking the leapfrog progress and development in the field of marine science and technology. At the same time, although digital productive forces started at a low level, it has been ranked second by 2022, achieving a significant increase of approximately 250%. This transformation is mainly due to the rapid change of digital technology and its extensive application and deep integration in the field of marine economy, which effectively promoted the intelligent and efficient transformation of marine economic activities. In contrast, although green productive forces showed a slow growth trend in the initial stage of the study, it then entered a fluctuating period. By 2022, its level was lower than the initial year, becoming the most sluggish link among the three, and the gap with the other productive forces widened. This phenomenon suggests that while pursuing the rapid development of marine economy, we should pay more attention to the protection and sustainable development of the ecological environment, so as to balance the relationship between economic development and environmental protection.

According to the changing trend of productive forces (Figure 4), in the early stages of observation from 2010 to 2012, green productive forces dominated among scientific and technological productive forces, digital productive forces and green productive forces, showing the highest productive forces level. However, in the following years, scientific and technological productive forces experienced a significant acceleration, gradually surpassing and consolidating its position as the leader of the three productive forces. Especially between 2021 and 2022, when the growth of the other two productive forces slowed or even stagnated, scientific and technological productive forces still maintained its fastest growth momentum, reaching the highest growth rate during this period.

On the other hand, digital productive forces has shown strong growth momentum since 2017, not only successfully surpassing green productive forces but also rapidly breaking the 0.5 threshold in the following year. From 2018 to 2020, digital productive forces continued to narrow the gap with scientific and technological productive forces, and in 2020 achieved a short surpass of scientific and technological productive forces, showing its great development potential and change power. However, from 2021 to 2022, digital productive forces suffered a temporary setback and a slight decline, likely due to changes in the external environment, technological bottlenecks, or policy adjustments.

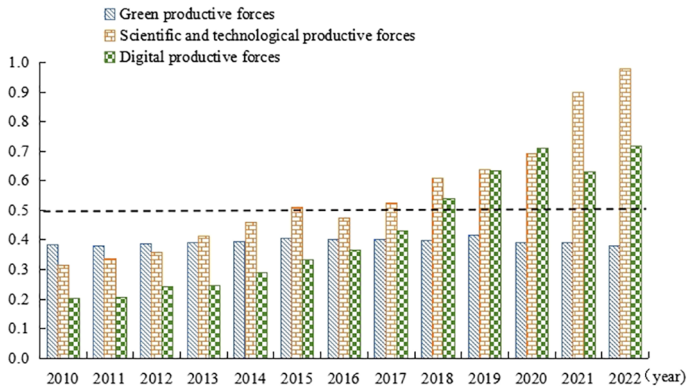

FIGURE 4
The trend of changes in the constituent elements of marine economy's new quality productive forces from 2010 to 2022.

On the contrary, green productive forces failed to surpass the 0.5 threshold during the entire observation period. Since 2017, it has been surpassed by scientific and technological productive forces and digital productive forces, gradually becoming the lowest level of the three. This phenomenon may, to a certain extent, restrict the overall improvement of the marine economy's new quality productive forces, which suggests that we must strengthen the attention and investment of green productive forces while pursuing rapid economic development, so as to achieve a win-win situation between economic growth and environmental protection. Therefore, the development strategy of marine economy in the future should pay more attention to the deep integration of scientific and technological innovation and green transformation, take science and technology as the lead, take green as the background color, and jointly promote the continuous improvement of marine economy's new quality productive forces.

3.2 Regional differences in the development level of the marine economy's new quality productive forces

Using the Dagum Gini coefficient and its decomposition method (Ni et al., 2024) as an analytical tool, we deeply explored

TABLE 4 Dagum Gini coefficient decomposition results of the level of marine economy's new quality productive forces.

Yesr	Overall Gini coefficient	Regional internal Gini coefficient			Gini coefficient between regions			Contribution rate (%)		
		Northern marine economic circle	Eastern marine economic circle	Southern marine economic circle	Northern-eastern	Northern-southern	Eastern-southern	Regional differences	Inter-regional differences	Hypermutation density
2010	0.217	0.209	0.085	0.238	0.219	0.235	0.249	28.0	38.72	33.23
2011	0.222	0.219	0.090	0.236	0.219	0.248	0.251	28.17	40.99	30.83
2012	0.229	0.223	0.093	0.256	0.213	0.263	0.259	28.72	37.51	33.78
2013	0.207	0.182	0.083	0.257	0.168	0.241	0.254	28.79	40.20	31.01
2014	0.212	0.170	0.074	0.266	0.187	0.241	0.265	27.39	41.79	30.83
2015	0.223	0.165	0.064	0.301	0.174	0.266	0.286	27.43	34.59	37.98
2016	0.235	0.170	0.067	0.311	0.201	0.277	0.287	27.31	30.14	42.56
2017	0.247	0.169	0.062	0.338	0.198	0.298	0.306	27.33	28.07	44.60
2018	0.248	0.173	0.061	0.327	0.216	0.295	0.296	27.26	26.65	46.09
2019	0.248	0.173	0.059	0.332	0.209	0.297	0.297	27.68	26.96	45.37
2020	0.256	0.188	0.047	0.330	0.238	0.297	0.306	26.57	32.55	40.88
2021	0.248	0.201	0.040	0.314	0.238	0.287	0.289	26.91	29.74	43.35
2022	0.259	0.221	0.042	0.318	0.259	0.298	0.295	26.72	31.28	41.99
Mean value	0.235	0.189	0.067	0.294	0.211	0.273	0.280	27.55	33.82	38.63

the regional differences and the root causes of the development level of new quality productive forces of China's marine economy. The decomposition results are shown in Table 4.

From the dynamic evolution trend of the overall Gini coefficient (Figure 4), we can see that the coefficient fluctuated from 0.217 to 0.259 during the study period, among which the value was the smallest in 2013, and maintained a relatively stable but sustained growth trend from 2013 to 2020. This trend reveals that the overall pace of the development of China's marine economy's new quality productive forces is relatively slow and accompanied by twists and turns, and highlights the unbalanced characteristics of spatial distribution. In response to this challenge, it is urgent to strengthen the interaction and cooperation between regions, especially in the aspects of talent flow, technical exchange and financial integration, to encourage the developed marine economy provinces to play their leading role, promote the accelerated catch-up in areas with lagging development, so as to optimize and enhance the spatial balance of the marine economy's new quality productive forces.

From the perspective of the mean value of the Gini coefficient within the region, the internal difference of the southern marine economic circle is the most significant, followed by the northern marine economic circle, while the eastern marine economic circle shows a relatively small internal difference. Only the mean value of the Gini coefficient in the southern marine economic circle exceeds the overall average level, reflecting the difference of marine resource endowment and the heterogeneity of marine development strategy among different provinces. These factors jointly act on the interaction degree of marine economic activities, and finally shape the differentiation pattern of marine economy's new quality productive forces level in each marine economic circle.

Combined with Figure 5, it can be seen that the internal differences between the northern and southern marine economic circles showed a trend of expanding at the end of the study period, especially in the southern economic circle, and their internal differences increased year by year. However, after a certain period of fluctuations, the difference in the northern economic circle decreased, but then showed an increasing trend, but it never exceeded the level of the overall Gini coefficient. On the contrary, the internal disparities in the eastern marine economic circle have been decreasing over time, which may be attributed to the continuous efforts of the region in talent introduction and scientific and technological innovation, which have effectively promoted the rapid development of the marine economy, and thus produced a positive effect of narrowing the internal disparities.

From the perspective of the mean value of the Gini coefficient between regions (Figure 6), the differences between the eastern marine economic circle and the southern marine economic circles (hereinafter referred to as the "eastern-southern") and between the northern marine economic circle and the southern marine economic circles (hereinafter referred to as the "northern-southern") were significant, with mean values of 0.280 and 0.273, respectively. Both exceeded the overall mean Gini coefficient of 0.235. This phenomenon shows that the imbalance between the eastern and the southern and the northern and the southern is particularly prominent in the regional distribution of the marine economy's new quality productive forces.

In general, the development trends of regional differences shows obvious fluctuations. Specifically, the inter-regional differences between the northern-southern and the eastern-southern regions are numerically similar, and the peak years of the eastern-southern regional differences are relatively more during the observation period, and there are occasional years when the north-south interregional differences also reach the peak level. In contrast, the inter-regional differences between the northern marine economic circle and the eastern marine economic circle (hereinafter referred to as the "northern-eastern") are the smallest, and their fluctuation range is significantly smaller than that between other regions and the overall differences, which vary from 0.219 to 0.259. From 2013 to 2020, the difference between the northern and eastern regions changed the most drastically, and its change trajectory was close to the level of the overall Gini coefficient at the beginning and end of the observation period, indicating a significant dynamic adjustment process of the distribution of marine economy's new quality productive forces between "northern-eastern" during this period.

Based on the analysis framework of the contribution rate, the dynamic evolution trend of different sources of development level of marine economy's new quality productive forces (Figure 7). The

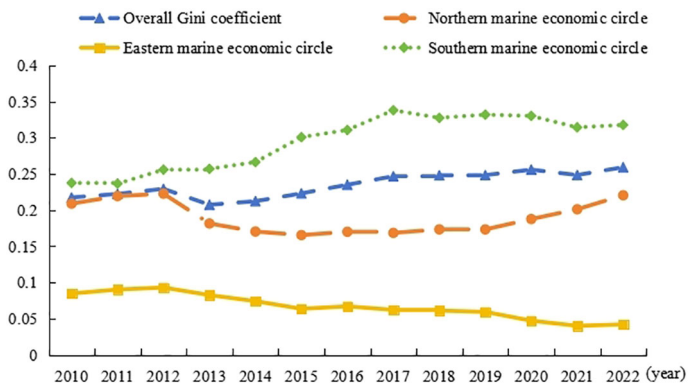

FIGURE 5
Overall and inter-regional differences in marine economy's new quality productive forces from 2010 to 2022.

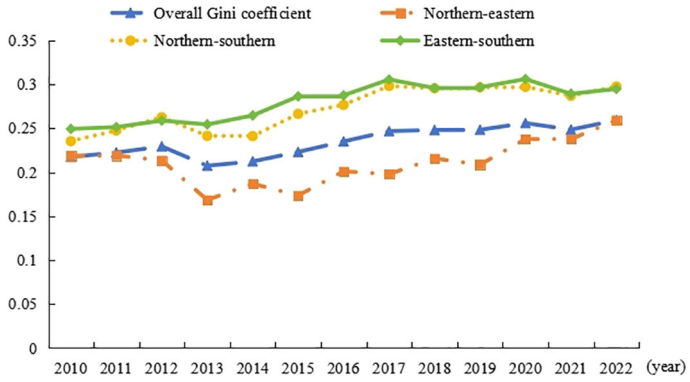

FIGURE 6
Overall and regional differences in marine economy's new quality productive forces from 2010 to 2022.

average contribution rate of the regional differences, the regional differences and the supervariable density were stable at 27.55%, 33.82% and 38.63%, respectively. Through the detailed analysis in Figure 6, it can be observed that the supervariable density occupies a dominant position in promoting the spatial differentiation of China's marine economy's new quality productive forces, and its contribution rate shows a cyclical fluctuation mode of "decrease-increase", and reached the peak of contribution rate in 2017.

In terms of regional differences, it showed a high contribution level in the early stage of the study, with the contribution rate ranging between 35% and 40%. However, with the passage of time, the contribution rate of inter-regional differences gradually showed a downward trend, although there was a slight rebound in some years, but in general, the contribution rate of inter-regional differences in the later stage of the study decreased compared with the early stage of the study, which indicates that the balanced development of marine economy's new quality productive forces between regions has made some progress.

In contrast, the contribution of within-regional differences was relatively smoothly over the study period, with small fluctuation amplitude and the lowest contribution to the overall spatial difference. The reason is that the level of marine economy's new quality productive forces in some provinces has significantly deviated from the average level between regions, resulting in a high degree of overlap and overlap in the economic characteristics and development trajectories between regions. This overlap not only increases the complexity and interdependence of inter-regional economic activities, but also makes supervariable density the main driving force to explain and characterize the spatial differentiation of marine economy's new quality productive forces. Therefore, in the future, in the process of promoting the balanced development of marine economy's new quality productive forces, special attention should be paid to the impact of supervariable density, and the optimal allocation of economic resources should be promoted by strengthening inter-regional cooperation and coordination, so as to achieve the sustainable development of marine economy.

3.3 The spatial and temporal evolution characteristics of the marine economy's new quality productive forces

3.3.1 The dynamic evolution of marine economy's new quality productive forces

The Dagum Gini coefficient revealed the quantitative dimension and its main source of the difference in the China's marine economy's

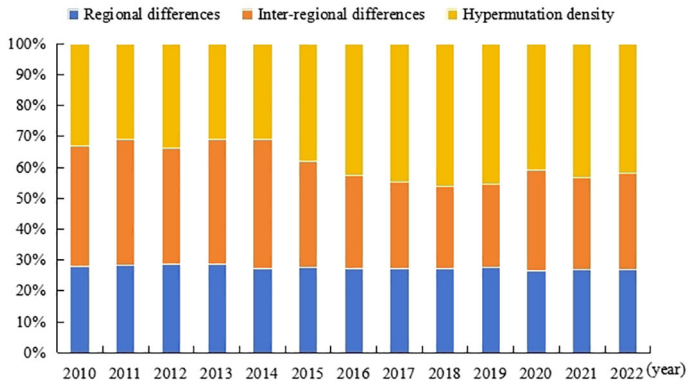

FIGURE 7
Contribution rate of spatial differences in marine economy's new quality productive forces from 2010 to 2022.

new quality productive forces. Through its decomposition mechanism, it can accurately identify the dynamic change trajectory of the relative differences between different regions. However, this method cannot directly show the whole picture of the evolution and complexity of the marine economy's new quality productive forces. To compensate for this shortcoming, a kernel density estimation method was introduced in this study, and a three-dimensional kernel density curve was plotted (Figure 8). Through the interaction of three dimensions (time, the level of marine economy's new quality productive forces, density), the figure comprehensively presents the distribution state and change trend of marine economy's new quality productive forces in the country (Figure 8A) and the three major marine economic circles (northern: Figure 8B, eastern: Figure 8C, southern: Figure 8D) at different time points. Through visualization means, it can not only help researchers to grasp the overall development trend of the marine economy's new quality productive forces from the macro perspective, but also can accurately locate the subtle changes in specific regions and time periods, providing a scientific basis for the formulation of differentiated and accurate marine economic development strategies.

First, from the perspective of the change of spatial distribution pattern, the core areas of the distribution curve of the marine economy's new quality productive forces in the whole country and the northern, eastern and southern marine economic circles show an overall trend of shifting to the right, among which the offset range of the eastern and southern regions is particularly significant, indicating that the level of marine economy's new quality productive forces in the whole country and the marine economic circles is steadily rising, and the growth rate of the eastern and southern marine economic circles is relatively fast. This phenomenon can be attributed to the in-depth implementation of the strategy of maritime power, and each marine economic circle has achieved the vigorous development of the marine economy by virtue of its own unique advantages in marine development strategy. Specifically, the eastern marine economic circle has successfully transformed scientific and technological innovation into a new engine for the development of the marine economy by virtue of its perfect port and shipping system, increasing level of opening up, and continuous convergence of scientific and technological innovation elements (Ni et al., 2024). Relying on a solid marine high-tech industrial foundation and outstanding marine resources, the southern marine economic circle has continuously promoted the deepening of marine economic construction and the transformation and upgrading of marine industries.

Second, from the perspective of the concentration in distribution patterns, the distribution curves of the marine economy's new quality productive forces across the country and within the three major marine economic circles show a high degree of concentration. This indicates that the level of marine economy's new quality productive forces tends to be close in most provinces, municipalities and autonomous regions. However, a few areas significantly deviate from the overall trend, either being notably low or high. The kernel density curve for the entire country, as well as for the northern and southern marine economic circles, extends more on the right side, while the eastern marine economic circle does not exhibit this pattern. This reveals that the development level of the provinces in the eastern marine economic circle is relatively balanced, while individual provinces in the southern and northern regions, such as Shandong and Guangdong provinces, hold significant leading positions. However, due to a similar degree of tailing, these leading provinces did not significantly widen the gap with other provinces, which is consistent with the overall national trend.

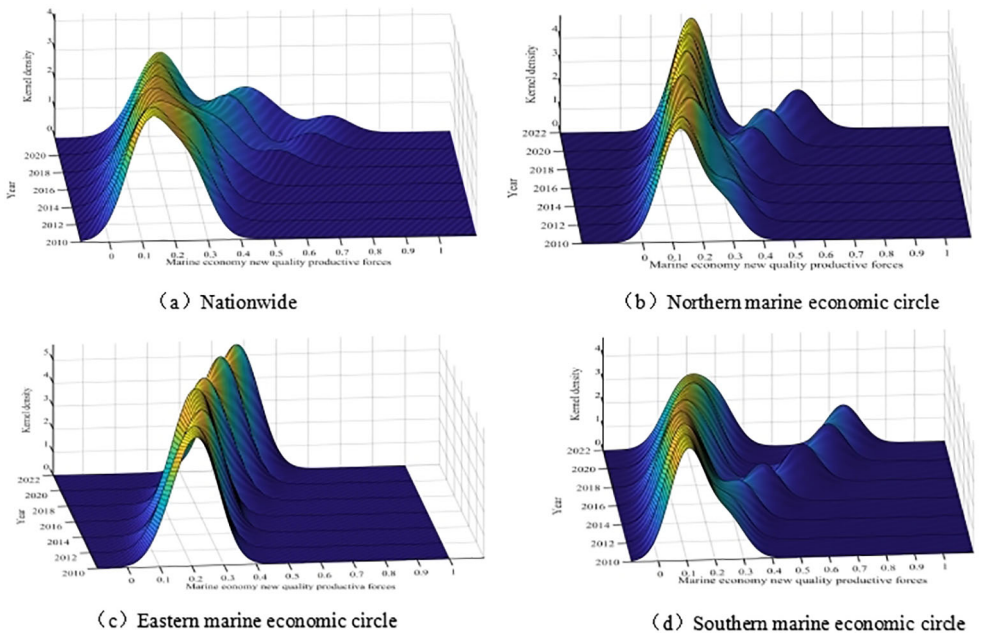

FIGURE 8
(A–D) Estimation of nuclear density of the marine economy's new quality productive forces.

Furthermore, examining the dynamic changes in peak characteristics, the width of the main peak in the distribution curve for the marine economy's new quality productive forces in the southern marine economic circle expanded significantly, while its height decreased year by year. This indicates an increased dispersion of the marine economy's new quality productive forces in this region. At the national level, the height of the main peak also showed a downward trend, while the remaining rest of the regions showed irregular upward and downward changes. This phenomenon reveals the widening development gap between the entire country and the southern marine economic circle, while the other regions showed uncertain gap changes due to the hierarchical development caused by the difference in the structure of the marine industry. Strengthening interregional exchanges and cooperation can help narrow these development gaps and promote an overall level of synergy.

Finally, from the perspective of the evolution of the number of peaks, the national kernel density curve has had a bimodal phenomenon since 2018, and it was a single main peak before. The kernel density curve of the northern marine economic circle showed a pattern of alternating single peak and double peak, with a side peak in 2010, a single main peak from 2012 to 2016, and a side peak and a main peak from 2018 to 2022. The eastern marine economic circle consistently maintained a single-peak state, while the southern marine economic circle exhibited both a main peak and tdistant side peaks. These changes reflect the complex changes in the marine economy's new quality productive forces both nationally and within the major marine economic circles. The trend of multipolarization is increasing nationwide, with the northern marine economic circle first showing a decrease and then an increase in polarization, while the degree of regional differentiation also first decreased and then increased. The development of the eastern region was relatively balanced, while that of the southern region had significant spatial polarization (Zhang et al., 2022). These findings provide an important basis for an in-depth understanding of the regional differences and dynamic evolution of marine economy's new quality productive forces.

3.3.2 Spatial spillover effect of marine economy's new quality productive forces

Based on the quartile standard, the marine economy's new quality productive forces was subdivided into four levels (I, II, III, and IV), corresponding to low, medium-low, medium-high, and high levels, respectively. The calculation results are presented in Table 5. From the traditional Markov transition probability matrix, the following transfer path rules were obtained.

TABLE 5 Probability matrix of traditional markov transition for marine economy's new quality productive forces.

T	T+1				n
	I	II	III	IV	
I	0.833	0.167	0	0	36
II	0	0.853	0.147	0	34
III	0	0	0.750	0.250	32
IV	0	0	0.067	0.933	30

First, there is the phenomenon of consistency and club convergence. The diagonal element of the matrix (i.e., the probability of state self-maintenance) was significantly higher than that of the non-diagonal element. This is evident from the high probabilities of 83.3%, 85.3%, 75%, and 93.3% of the I, II, III, and IV levels, respectively, with a minimum maintenance probability of 75%. This indicates that the marine economy's new quality productive forces in China's coastal provinces, municipalities and autonomous regions exhibit a high degree of stability in their hierarchical distribution. There is a notable "club convergence" phenomenon (Fufa and Kim, 2018), meaning that regions with similar levels tend to maintain their relative positions. Second, the high-level provinces exhibit a convergence advantage. Among the off-diagonal elements, the probability of moving from a high level (IV) to other levels was the lowest, followed by the middle and low levels (II). This suggests that the high probability of the high-level provinces maintaining their leading position and showing an obvious trend of internal convergence. This trend has exacerbated regional imbalances in the development of the marine economy and widened the gap between high- and low-level provinces. Third, there is limited short-term non-cross-stage transferability. The non-diagonal probability was generally low and significantly lower than the diagonal probability, indicating that it is difficult to achieve a leapfrog transformation of the marine economy's new quality productive forces in the short term. This reflects a pattern of gradual and stable development of the marine economy. Fourth, the specificity and possibility of the transfer paths were analyzed. The probabilities of low, medium-low, and medium-high development levels were 16.7%, 14.7%, and 25%, respectively, while the probability of degradation from high to medium-high levels was only 6.7%. In particular, the mid-to-high levels exhibited the highest transfer activity, and each grade mainly followed a single upgrade or downgrade path. Overall, these transfer paths indicate that the possibility of improving the marine economy's new quality productive forces is greater than the possibility of downgrading them, reflecting a positive development trend. Fifth, transitions between adjacent levels were limited. All possible transfer paths were concentrated near the diagonal, and the probability of transfer away from the diagonal was zero. This indicates that the dynamic changes in the marine economy's new quality productive forces are strictly limited to the adjacent levels, excluding the possibility of abrupt changes across multiple levels, and reflecting the continuity and constraints of the change process.

Based on the traditional Markov analysis framework, and considering the influence of spatial factors on the transfer paths, this study constructed an adjacency matrix to form a spatial Markov transition probability matrix for the marine economy's new quality productive forces. This approach aimed to comprehensively analyze the spatial interaction effects of marine economy's new quality productive forces levels among coastal provinces, municipalities and autonomous regions in China (Table 6). Analysis of the diagonal element of the spatial Markov matrix revealed that when a province's marine economy's new quality productive

TABLE 6 Spatial markov transition probability matrix of marine economy's new quality productive forces.

Proximity level		T	T+1				n
			I	II	III	IV	
T	I	I	0.6	0.4	0	0	5
		II	0	1	0	0	11
		III	0	0	0.75	0.25	4
		IV	0	0	0	1	1
	II	I	0.889	0.111	0	0	9
		II	0	0.75	0.25	0	8
		III	0	0	0.846	0.154	13
		IV	0	0	0.167	0.833	6
	III	I	0.833	0.167	0	0	6
		II	0	0.857	0.143	0	7
		III	0	0	0.7	0.3	10
		IV	0	0	0.111	0.889	9
	IV	I	0.875	0.125	0	0	16
		II	0	0.75	0.25	0	8
		III	0	0	0.6	0.4	5
		IV	0	0	0	1	14

forces (level I) is at a similarly low level as its neighboring provinces, the probability of maintaining the original level (60%, 100%, 75%, and 100%) reflects high stability of the marine economy's new quality productive forces in the regional low-level collaborative environment. Compared to the traditional Markov analysis, except for the level I, the provinces at other levels show a higher probability of self-sustainment or upgrading due to spatial association, highlighting the positive impact of regional synergy on the marine economy's new quality productive forces. Additionally, the maintenance probability for level I provinces is the lowest, further confirming that low-level regions are more susceptible to changes from external influences.

With the improvement of the marine economy's new quality productive forces in neighboring provinces, the probability of a province transitioning to a higher level has increased significantly, opening more paths from low level to high levels. This underscores the far-reaching influence of the spatial distribution patterns on the dynamic evolution of the marine economy's new quality productive forces. In particular, when neighboring provinces are at the extreme levels (I or IV), the province shows a strong one-way development trend, that is, there is only an upgrade without the possibility of downgrading. The maintenance probability for the high level (IV) reaches absolute stability (100%), reflecting not only direct manifestation of spatial synergy, but also the strong positive radiation effect of the high-level regions on the surrounding provinces. At the same time, the number of provinces at levels I and IV in the province is opposite to the level IV in the neighboring provinces, that is, when neighboring provinces are at level IV, the focal province tends to have more province at levels I and IV. Conversely, when neighboring provinces are below level I, the number of provinces at levels I and IV in this province decreases. This indicates that the marine economy's new quality productive forces is influenced by spatial factors and has a spatial spillover effect. This not only strengthens the spatial dependence of the marine economy's new quality productive forces, but also provides a basis for policymakers to promote balanced and efficient development of the marine economy's new quality productive forces by optimizing the regional spatial layouts.

4 Conclusion and policy recommendation

4.1 Conclusion

Based on a panel dataset of 11 coastal provinces in China from 2010 to 2022, this study used the entropy method to quantitatively evaluate the overall level of the marine economy's new quality productive forces. It analyzed the internal structure of its uneven spatial distribution using Dagum Gini coefficient and its decomposition technology, explored its dynamic evolution trends with KDE method, and finally revealed its spatiotemporal evolution mechanisms through a spatial Markov chain model. The conclusions of the study are summarized as follows:

(1) Provinces show significant heterogeneity in the marine economy's new quality productive forces, among which Guangdong, Shandong and Shanghai lead the development

of each marine economic circle with their outstanding performance. In the regional dimension, the eastern marine economic circle shows the highest level of new quality productive forces, followed by the southern marine economic circle, while the northern marine economic circle faces challenges due to both a low level and slow growth. Further analysis of the constituent elements reveals that scientific and technological productive forces occupies a dominant position in promoting the marine economy's new quality productive forces. In contrast, green productive forces show less fluctuation but have a much slower growth rate compared to scientific and technological productive forces and digital productive forces. This has become the key factor restricting the improvement of the overall level.

(2) In terms of intra-regional differences, the development of provinces within the eastern marine economic circle is relatively balanced. In contrast, there is a significant "single-core and multi-polar" development pattern between the northern and southern marine economic circles for a long time, especially the internal differences in the northern marine economic circle show a significant expansion trend, which is reflected by the contribution of supervariable density and becomes the leading factor of spatial differentiation. When analyzing regional variations, the differences between "northern-eastern" are relatively small, while the differences between "northern-southern" and " eastern-southern" are close and higher than the overall Gini coefficient, revealing the complex interaction characteristics of the marine economy's new quality productive forces in geographical space.

(3) Nationwide and within marine economic circles, the level of marine economy's new quality productive forces is increasing annually. However, regional inequality is also growing, with signs of polarization emerging. In addition to the differences in regional marine development conditions and strategies, the spatial proximity effect significantly impacts changes in the marine economy's new quality productive forces. Specifically, although the level of the marine economy's new quality productive forces can be relatively stable to a certain extent, this stability helps high-level provinces to maintain the status quo, while for low-level provinces, it may constitute an obstacle to development and inhibit the catch-up process for low-level provinces.

4.2 Policy recommendations

Based on detailed research results and analysis, this study aims to propose a series of forward-looking and targeted policy recommendations for the comprehensive improvement of China's marine economy's new quality productive forces.

(1) Implementing differentiated strategies promotes the regional adaptive development of the marine economy's new quality productive forces. In view of the significant differences in marine resource endowment, industrial structure, and scientific and technological capabilities among China's coastal provinces, it is recommended to adopt a development strategy of "adapting measures to local conditions and implementing policies according to local conditions." Each province should accurately identify its own marine economic development path, leverage regional resources, deepen the development of advantageous areas, and learn from the successful experiences of high-level provinces to explore a development path of marine economy's new quality productive forces in line with its own reality. Specifically, the northern marine economic circle should build on its strong marine manufacturing base, especially Shandong's advantages in marine scientific research, education, and high-tech fields, to promote Liaoning, Hebei, Tianjin and other provinces to strengthen scientific and technological cooperation with Shandong, and accelerate the modernization process of marine industry. The eastern marine economic circle should make full use of the advantages of digital technology to build a digital marine industry chain and enhance its overall competitiveness. The southern marine economic circle should capitalize on its rich marine resources and vast sea area to expand opening up, optimize the marine industrial structure in Hainan and Guangxi, and increase the proportion of the marine tertiary industry.

(2) Internal and external linkage mechanisms should be strengthened to enhance the spillover effects of the marine economy's new quality productive forces. Given the significant developmental differences within and between regions of the marine economic circle, as well as the radiation and driving effect of high-level provinces on the surrounding areas, it is suggested to build a closer regional linkage system. By providing high-level provinces with greater and space for innovation, we can promote the free flow and optimal allocation of marine science and technology, resources, talents, capital and other factors, effectively radiate the development advantages to a wider region, and narrow the development gap between provinces. At the same time, the three major marine economic circles should break the geographical restrictions, establish a cross-regional cooperation mechanism and resource sharing platform, strengthen policy coordination and information sharing, achieve complementary advantages and coordinated development, and jointly promote the overall leap of the marine economy's new quality productive forces.

(3) Science and technology should drive green development and enhance the green content of the marine economy's

new quality productive forces. Given the important impact of green productive forces on the marine economy's new quality productive forces, it is suggested that the concept of green and low-carbon should be deeply integrated into the whole process of marine economic development. Provinces should increase R&D in green and low-carbon technologies, promote the transformation of the marine industry to clean and low-carbon, improve the utilization rate of clean energy, and reduce dependence on traditional energy. The eastern and southern marine economic circles should lead by example, using their own scientific and technological advantages to drive the green transformation of the marine industrial structure, and export green technology and management experience to other provinces. This will form a virtuous circle of "green first and then green", and finally realizing the common green development of the national marine economy. In addition, it is also necessary to fully implement the concept of green development to advance both emerging marine and traditional industries. This includes promoting the green upgrading of infrastructure and production technology, eliminating outdated production capacity, and adopting an innovation-driven green development path, so as to lay a solid foundation for the continuous improvement of the marine economy's new quality productive forces.

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

XJ: Writing – review & editing, Writing – original draft. YW: Writing – original draft, Methodology, Data curation. KY: Conceptualization, 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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