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The effects of green finance on the carbon decoupling of marine fishery: analysis based on Tapio method and EKC model

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Marine fishery, with its duality of carbon emission and carbon sink, is an industry that needs full attention during achieving carbon neutrality. In this paper, the decoupling index between net CO2 emissions and gross domestic product of marine fishery in China is calculated using Tapio model, and its evolution characteristics are analyzed by means of nuclear density map and Markov matrix. Some problems are found, such as the decoupling state lacked significant improvement during this period and was unstable. Through theoretical analysis, this paper puts forward the view that solving these problems requires support from green finance. Then, this paper selects panel data from 11 coastal provinces and cities in China from 2010 to 2020 and uses the Logit model and EKC model to investigate the impact of green finance on the carbon decoupling state of marine fishery. The main results of this study are as follows: 1) Green finance can increase the odds ratio of strong or weak decoupling in marine fishery. This effect is more significant in regions with a high degree of digital finance development and the eastern marine economic circle. The effect of green investment is more significant than green insurance. In addition, boosting technological innovation and reducing the proportion of coal consumption can strengthen this effect. 2) The EKC curve between net CO2 emissions and gross domestic product of marine fishery is N-shape, which has a deterioration point. Green finance can delay the arrival of the deterioration point, meaning it can prevent the rapid deterioration of the decoupling state with the development of marine fishery. This paper provides empirical evidence and decision-making reference for resolving the dilemma of carbon decoupling in China's marine fishery.

KEYWORDS

carbon decoupling, marine fishery, green finance, Tapio model, EKC model

1 Introduction

With the advancement of global industrialization, fossil fuel resources have been exploited in large quantities, and greenhouse gas emissions have soared (Francey et al., 2013). This problem has been widely discussed by the international community (Zhang and Da, 2015). In 2016, 175 countries signed the Paris Agreement, committing to achieve a balance between CO2 emitted by humans and absorbed by sinks in the latter half of this century. However, if achieving this goal requires sacrificing economic growth, then the incentive and effort of countries will be far less than they have promised (Wang and Zhang, 2021). Therefore, the international community urgently needs methods and approaches to decouple development from net CO2 emissions. As a responsible country, the Chinese government has also set targets for greenhouse gas emissions, aiming to reach peak carbon emissions by 2030 and achieve carbon neutrality by 2060. However, China is currently in a period of rapid urbanization and industrialization, which needs to consume a lot of energy (Lu et al., 2011; Lin and Ouyang, 2014). In addition, China's coal-dominated energy structure makes China face tremendous pressure to reduce emissions (Zhang et al., 2018). China is facing an arduous mission of balancing the goal of building a socialist modernized country and the international responsibility of tackling global climate change. There is also an urgent need for China to find solutions that can both reduce carbon emissions and boost economic development.

Increasing carbon sinks is a crucial way to achieve "carbon neutrality." The oceans are the largest pool of carbon, storing 93% of the global CO2 and absorbing about a third of the CO2 emitted by human activities each year (IPCC, 2019). As an essential marine industry, marine fishery is a vital carbon sink way, but it is also a typical energy-intensive industry, with fuel costs that can account for 60% of total costs (Tyedmers et al., 2005). In 2016, global marine fishery fuel engines emitted about 207 million tons of CO2, which corresponds to the CO2 emissions of 51 power plants during the same period (Guangliang et al., 2023). What's worse, from 1990 to 2011, the global fishing industry's CO2 emissions increased by 28%, while production barely kept pace (Parker et al., 2018). It can be seen that marine fishery is an obvious source of CO2 emissions, but they are often ignored in global assessments of greenhouse gases. It will lead to a naive optimism about the current state of global greenhouse gas emissions and continue to allow marine fishery to develop in this extensive mode, thereby reducing the effectiveness of marine carbon sinks, putting pressure on climate change, and exacerbating the ecological challenges. Therefore, to make better use of marine carbon pools to assist in the completion of "carbon peak and carbon neutrality", marine fishery's duality needs urgent attention.

Green finance was born to solve the contradiction between environment and development (Kumar et al., 2023). It is an innovative financial tool that provides financial support, risk management, and other financial services for environmental protection projects (Yu et al., 2021). In order to ensure the effective role of green finance, China has gradually established the green finance standard system, financial institution supervision and information disclosure requirements, incentive and restraint mechanism, green finance product and market system, and green finance international cooperation system. At the end of June 2022, the green loan balance of domestic and foreign currency in China reached 19.55 trillion yuan, and the stock size of green bonds reached 1.2 trillion yuan, ranking second in the world. With the development of green finance, the impact of green finance on emission reduction has attracted the attention of the majority of scholars. It has been confirmed to be an effective means to reduce CO2 emissions (Ren et al., 2020; Meo and Karim, 2022). It can inhibit carbon emissions through financial constraints, promoting green technological innovation, adjusting industrial and energy structures, and improving energy intensity (Chen and Chen, 2021; Hu and Zheng, 2022).

There is a broad consensus that green finance can drive emission reduction, but there are few studies on its impact on the state of carbon decoupling. That is to say, it is unclear whether the emission will be reduced at the expense of development. However, the goal of sustainable development should not only focus on "sustainability" but "development." Therefore, it holds significant theoretical and practical importance to examine the influence of green finance on the decoupling state of net CO2 emissions from the gross domestic product (GDP) of marine fishery (hereinafter the decoupling state of net CO2 emissions from the GDP of marine fishery is referred to as carbon decoupling state of marine fishery, which is abbreviated as $CDSMF$).

This paper makes the following contributions: Firstly, this paper focuses on the marine fishery, an important but often overlooked industry, and uses the Tapio model to calculate the decoupling index of net CO2 emissions (NCE) and GDP of marine fishery (GMF) and then uses kernel density, Markov matrix and other methods to comprehensively analyzes the evolution characteristics and distribution characteristics of the decoupling state, and finds out the existing problems, which are helpful to objectively understand the actual situation of carbon decoupling state of marine fishery in China. Secondly, this paper combines Tapio and EKC, two inseparable models that can more directly reflect the conflict between economic growth and environmental pressure. And we creatively investigate the impact of green finance on the decoupling state of marine fishery from two perspectives: "promoting decoupling effect" and "delaying deterioration effect." This enriches the research on the role of green finance in sustainable development. Secondly, this study takes a fresh research perspective from "promoting decoupling effect" and the "delaying deterioration effect." To be more specific, we innovatively investigate the effect of green finance on the carbon decoupling states of marine fishery from the above perspective by combining the Tapio model and the EKC model, two inseparable models that can more directly reflect the conflict between economic growth and environmental pressure. This approach not only reinforces the robustness of our findings but also enriches the research on the role of green finance in sustainable development. Thirdly, this paper uses Logit model to study the impact of green finance on the carbon decoupling state of marine fisheries, instead of using LMDI model to decompose the factors affecting carbon emissions. On this basis, moderating variables are introduced to study the mechanism, so as to enrich the research content. Finally, we establish EKC model and integrate the two methods to study the "delaying deterioration effect" of green finance, so as to improve the robustness and reliability of the conclusion.

2 Research Context and research Hypotheses

2.1 Research context

Given the increasing importance of environmental issues, scholars have come to realize that to achieve green development and carbon neutrality, marine fishery can no longer be ignored. Researchers gradually began to pay attention to the carbon sink function of marine fishery. Yuan et al. (2023), Krabbe et al. (2022), and Wang et al. (2022) identified several factors that influence the carbon sink capacity of the marine fishery, including national policies, fishing output, number of employees, area of shellfish and large-scale seaweed aquaculture farms, total power of fishing vessels, and reform of international fishery law. In addition, Zhang et al. (2023a) and Li et al. (2023c) argued that collaborative efforts among multiple stakeholders and financial support are more advantageous in realizing the ecological value of blue carbon in marine ranches, whereas Alsaleh et al. (2023) discovered that the utilization of fossil fuels serves as a crucial driving force behind the degradation of carbon sinks. Research on carbon emissions in marine fishery is also a hot topic. Some scholars have established a simulation model for the low-carbon development of China's marine fishery by using the system dynamics method to find the factors affecting carbon emissions. Research by Chen et al. (2022a) showed that rapid economic growth has significantly increased carbon emissions of the marine fishery. At the same time, adjustments in energy and industrial structure have contributed to carbon emission reduction. Chen (2023) demonstrated that optimizing the industrial structure of the marine fishing industry can improve carbon emission efficiency. Research on carbon decoupling gradually extended to marine fishery. Li et al. (2022b) argued that industrial structure plays a significant role in contributing to CO2 emissions, and carbon intensity is the main negative driving factor. Wang and Wang (2022) also pointed out that carbon intensity acts as a key driver for carbon reduction and advanced decoupling. Liu et al. (2023a) found that the social and economic system, as well as the scale of marine fishery development, are essential factors driving carbon emissions, and adjusting industry structure will inhibit marine fishery carbon emissions. What's more, Zhang et al. (2023) found that the economic and trade development of marine fishery would increase CO2 emissions, and the technological progress and income growth of fishermen could reduce carbon emissions.

In addition to the aforementioned factors influencing decoupling, green finance is believed to have a positive impact. Zhou et al. (2020) found that green finance promotes economic growth while limiting environmental degradation, shifting the turning point of the Environmental Kuznets Curve (EKC) to the left. This implies that green finance can achieve decoupling at a lower level of economic growth. In addition, scholars generally believe that green finance can curb CO2 emissions (Hu and Zheng, 2022; Meo and Karim, 2022; Li et al., 2023b). Lin et al. (2023) employed spatial measurement methods to investigate the linear and non-linear relationship between green finance and carbon emissions. The study demonstrated that green finance is an effective pathway for reducing carbon emissions. Du (2023) demonstrated the negative impact of green finance on carbon intensity across all quantiles, both in the short and long term. Liang and Song (2022) pointed out that green finance not only has a "local effect" on carbon emission efficiency, but also has a "neighborhood effect." Moreover, Zhang et al. (2022c) constructed indicators to comprehensively measure carbon emission efficiency from the input-output perspective, providing further evidence of the emission reduction effect of green finance. Li et al. (2022a) used CO2 as an undesirable output to measure low-carbon total factor productivity, highlighting the crucial role of green finance in transitioning from a high-carbon to a low-carbon economy. Specifically at the industry level, Ren et al. (2023) proved that green finance can facilitate the low carbonization of industries in pilot zones by using the difference-in-difference method. Xu et al. (2023a) demonstrated that green finance can drive the low-carbon development of industry not only in the region but also in surrounding regions. The research results of Guo et al. (2022) indicate that green finance is expected to play a substantial role in mitigating fertilizer usage and decreasing carbon emissions in the agricultural sector within a decade. Liu et al. (2023b) demonstrated the effectiveness of green finance in promoting emissions reduction in the transportation sector through the construction of a discontinuous regression model.

EKC is a tool that describes the connection between the quality of the environment and income levels (Grossman and Krueger, 1991). According to EKC theory, economic development is eventually expected to lessen the environmental degradation caused by earlier stages of development (Kaika and Zervas, 2013a). Subsequently, the EKC curve theory has been verified in different countries and different industries (Bölük and Mert, 2015; Bento and Moutinho, 2016; Gokmenoglu and Taspinar, 2018; Eyup and Roula, 2020; Qadri et al., 2023). As the research progresses, a series of empirical studies have revealed the existence of non-regular EKC patterns, including U-shaped and N-shaped curves (Kaufmann et al., 1998; Friedl and Getzner, 2003; Jahanger et al., 2023). This also overturns the original EKC theory. Some scholars believe that this may be due to the differences in the economic structure of different economies (Kaika and Zervas, 2013b; Eyup and Roula, 2020). Based on the assumption of EKC, Tapio (2005) proposed the Tapio decoupling model. The same as the EKC model, the Tapio model can also directly reflect the contradiction between economic growth and environmental degradation The difference is that the Tapio decoupling model has a more specific concept and a more concise calculation. This model has been increasingly adopted to analyze the relationship between economic development and environmental pollution (Ren and Hu, 2012; Hao et al., 2019; Luo et al., 2020). After analyzing the decoupling state with the Tapio model, some papers will explore the decoupling state drivers with the LMDI model (Wang and Zhang, 2020; Apeaning, 2021; Chun et al., 2023). In addition, Wang et al. (2021) combined the Tapio model and EKC model, and believed that the combination of these two models can provide mutual testing and support.

Reviewing the literature reveals numerous studies on the impact of green finance on carbon emission reduction, low-carbon transformation, and low-carbon development in industries. However, there are few studies on the marine industry, especially marine fishery. Secondly, previous studies have tried to prove that green finance can reduce carbon emissions, improve carbon emission efficiency, or promote high-quality development, etc., but few literatures have studied whether green finance can alleviate the contradiction between economic development and environmental pressure in a more direct way. Thirdly, previous studies primarily focus on internal characteristics of the economic system when decomposing factors using the LMDI model, with limited examination of the impact of external policies. Simply waiting for economies to adjust spontaneously to maintain strong decoupling state can be time-consuming and laborious. We need tools to help. Therefore, it is imperative to investigate the impact of green finance on the state of marine fishery decoupling.

2.2 Research hypotheses

2.2.1 "Promoting decoupling effect" of green finance

Green finance has three major functions: resource allocation, risk management, and market pricing. First, the resource allocation function guides limited capital resources to environmental protection industries. Specifically for marine fishery, green finance can impose financing constraints and increase financing costs to limit the development of energy-intensive sectors like the marine fishing. Simultaneously, financial support is provided to relatively low-carbon industries such as marine leisure fishing and mariculture. By guiding the allocation of resources to reduce the overall carbon dioxide emissions of the marine fisheries industry. Secondly, green insurance can reduce the risk of green innovation in enterprises, promote green innovation, and thus reduce CO2 emissions (Wang et al., 2017). At the same time, its risk management function can reduce the failure risk of enterprises' low-carbon transformation. Third, the market pricing function of green finance enables the internalization of external pollution costs and facilitates the valuation of ecological environmental products. This helps address market failures by internalizing externalities and promoting environmental protection. For instance, high-emission enterprises in the marine fishing industry may need to purchase carbon emission rights in the carbon trading market, thereby considering the price of carbon emission rights in their costs. And, for leisure fisheries with relatively low carbon emissions and carbon sink fisheries can sell surplus carbon emission rights and obtain additional profits for research and development (Liu et al., 2019).

Besides, green finance has the basic functions of traditional financial instruments and can also promote economic growth in marine fishery through the mobilization of savings, stimulation of capital accumulation, facilitation of risk management, and facilitation of trade. Ngo et al. (2022) found a positive relationship between green finance and economic growth in the Association of Southeast Asian Nations (ASEAN). Xu and Gao (2022) pointed out that green finance is instrumental in facilitating the high-quality development of the marine economy. Su et al. (2021) found financial development is conducive to the growth of marine economy, particularly in the well-established financial system of the eastern marine economic circle, where existing financial resources can be fully utilized. Zheng et al. (2021) argued that the development of fishery economy requires financial instruments, and fishery financial policies are crucial tools to promote its growth.

In a word, green finance can reduce emissions of marine fishery while promoting growth, so this paper posits that green finance can promote carbon decoupling in marine fishery.

Hypothesis 1: Green finance exhibits a "promoting decoupling effect" on marine fishery.

2.2.2 "Delaying deterioration effect" of green finance

According to the EKC hypothesis, in the early stage of economic development, increased income will lead to increased pollution. However, once a certain income threshold is reached, higher income levels can contribute to improved ecological conditions, following an inverted U-shaped EKC curve. This phenomenon stems from scale effect, component effect, and technical effect (Sinha et al., 2017). The scale effect suggests that higher output results in increased pollution. Later, as economies develop, the scale effect is masked by a combination of component effects (services may grow faster than manufacturing, which can change the pollution intensity of output) and technical effects (market-driven technological progress or, as a result of government regulation, less polluting technologies may be adopted by various sectors of the economy), and environmental quality begins to improve with income rose (Torras and Boyce, 1998). However, when the marginal return of industrial structure transformation is exhausted, or when the diminishing return of technological change, the scale effect will once again exceed the combined impact of the component effect and the technical effect, then an N-type EKC curve will appear (Lorente and Alvarez-Herranz, 2016). This process is graphically depicted in Figure 1.

According to studies on carbon decoupling in marine fishery, most of the provinces that achieved strong decoupling did not stabilize at strong decoupling and some experienced deterioration (Guan et al., 2022; Wang and Wang, 2022). However, Wang et al. (2021) analyzed the relationship between the Tapio index and the EKC. If the EKC is inverted U-shaped, the state of carbon decoupling will gradually improve with the development. If the EKC is N-shaped, the deterioration phenomenon will occur, as shown in Figure 1. Therefore, we infer that the EKC of marine fishery is N-shaped, which is also consistent with the related research of Fang and Gao (2023).

Hypothesis 2a: The EKC curve of NCE and GMF is N-shaped.

If the EKC curve is N-shaped, according to the analysis of Wang et al. (2021), there will be an inflection point of decoupling elasticity on the curve, which is called the deterioration point in this paper, as shown by the point GMF^{e^*} in Figure 1. Before the deterioration point, the component and the technical effect gradually exceed the scale effect, making the EKC curve slope downward. After the deterioration point, due to the gradual decline in marginal returns from structural transformation and technological innovation, the decoupling state begins to deteriorate. At this stage, the scale effect surpasses the component and technical effects, leading to a deterioration in decoupling.

Green finance can enhance the component effect and technical effect of marine fishery. Regarding component effect, green finance facilitates the promotion of ecological and advanced structures within the marine fishery industry. For the primary industry, carbon finance can reduce the cost of carbon sink fishery, thereby increasing the proportion of carbon sink fishery. And the marine fishing industry will be subject to financing constraints and reduce its scale. For the secondary industry, the processing industry can extend the industrial chain and increase the added value by obtaining green investment for technological innovation. For the low-energy tertiary industry, it is easier to get the financial support from green finance, so as to attract the inflow of labor, capital, and technology to drive its rapid development. At the same time, through coordinated investment and financing, green finance can foster the development of coordination and management to promote the organization of marine fishery, improve the level of scientific research and innovation to reduce resource consumption and production costs, and solve the obstacles faced during the industrial restructuring of marine fishery (Yang and Su, 2010).

In terms of technical effects, green finance directly invests in green technologies (Kumar et al., 2022). In addition, green finance can effectively address market failures during the green technology innovation process. First of all, green technology innovation has dual externalities, that is, knowledge externality caused by the spillover of innovative technology and adoption externality caused

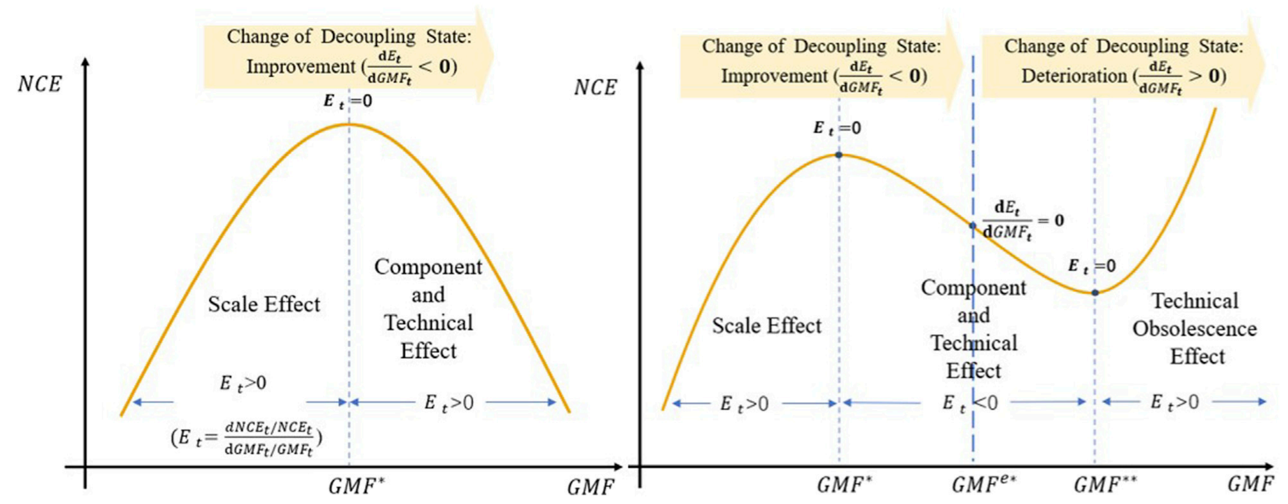

FIGURE 1
Relationship between the decoupling state and EKC (Note: ① $CDSMF = \frac{\Delta NCE_t/NCE_t}{\Delta GMF_t/GMF_t}$ $E_t = \lim_{\Delta \to 0} CDSMF = \frac{dNCE_t/NCE_t}{dGMF_t/GMF_t}$. ②The figure refers to Wang et al., 2021; Torras and Boyce 1998).

by the application of green innovation technology to produce positive social benefits. Double externalities will benefit society and other enterprises, but make green innovators bear the cost of innovation alone, thus discouraging green innovation. Through its market pricing function, green finance can internalize externalities and promote green innovation. Secondly, enterprises are facing incomplete information issues in green technology innovation. Technological innovation is faced with a large number of capital needs and risks. Due to information asymmetry, investors are skeptical about the promised returns. They may demand a premium for investments with such risks, aggravating the difficulty of obtaining investment in green innovation. Green finance, on the other hand, uses its risk management function to transfer risks that may be faced in innovation, while alleviating financial difficulties by strengthening green investment. The risk management function can transfer the risks, while its resource allocation function can alleviate financial difficulties (Jaffe et al., 2005).

In summary, green finance serves as a catalyst for the structural transformation and advancement of green technological innovation in the marine fishery industry, which can better unleash the component and technical effects, delay the rate of marginal decline in component and technical effects, and thus delay the arrival of deterioration points.

Hypothesis 2b: Green finance has a "delaying deterioration effect" on marine fishery.

The "promoting decoupling effect" and "delaying deterioration effect" of green finance are concisely reflected in Figure 2.

3 Data and Models

3.1 Variables selection

3.1.1 Development level of green finance (*GF*)

According to scholars' viewpoints, we undertake a comprehensive evaluation of the green financing system, focusing on green credit, green securities, green insurance, and green investment (Yang et al., 2021; Zhang et al., 2022a). The assessment is quantified using the entropy method, and Table 1 presents the specific indicator system.

3.1.2 Carbon decoupling state of marine fishery (*CDSMF*)

3.1.2.1 Net CO2 emissions from marine fishery (*NCE*, tons)

CO2 emissions from marine fishing motor vessels account for 70% of the industry's CO2 emissions, and many studies have used the CO2 emissions from marine fishing motor vessels as a proxy for the total CO2 emissions from the industry. We refer to the methods of Li et al. (2022b) and Shao et al. (2018) to calculate carbon emissions from marine fisheries. The calculation method is shown in Eq. 1.

$$C = h \times k \times n \times \delta \times \rho \times \sum_{u=1}^{6} (P_u \times \gamma_u) \tag{1}$$

C represents marine fishery CO2 emissions. h represents the fuel oil conversion standard coal coefficient with a value of 1.457. k is effective oxidation fraction, which is 0.982. And n denotes carbon content per ton of standard coal, which is 0.733. δ is the ratio of CO2 emitted from fuel oil to coal combustion under the same heat energy obtained, and it is determined as 0.813. ρ is the conversion constant of carbon to CO2 based on relative atomic mass, approximately equal to 3.670. P_u and γ_u represent the power consumed and the oil consumption coefficient of operating mode u, respectively. For the oil consumption coefficient of different operating modes, refer to the Reference Standard for the Calculation of Oil Allowance for Domestic Motor Fishing Boats issued by the Ministry of Agriculture.

Then, we assessed the carbon sink capacity of marine fishery, particularly through the cultivation of shellfish and algae. Previous studies have identified these as the primary sources of carbon sinks. Due to the relatively small scale of mariculture in Tianjin and Shanghai, this paper assumes a negligible carbon sink contribution from these regions. The specific calculation method is presented in Eq. 2.

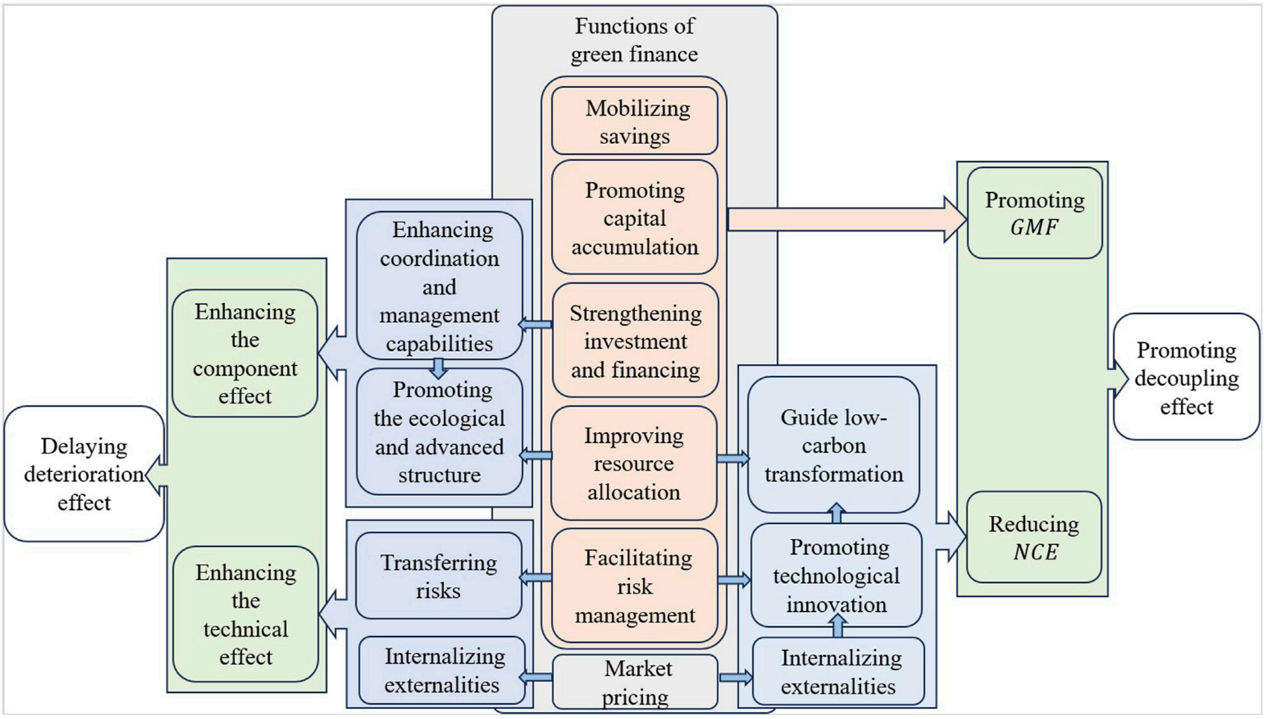

FIGURE 2
The "promoting decoupling effect" and "delaying deterioration effect" of green finance.

TABLE 1 Green finance index system.

First-level indicator	Second-level indicator	Third-level indicator	Definition of indicator	Attribute
Green finance	Green credit	Green credit ratio	Six high energy-consuming industrial interest/industrial interest Huang et al. (2022)	-
	Green securities	Market value ratio of high energy-consuming industries	Market value of high energy consumption industry/total market value Zhang et al. (2022b)	-
	Green insurance	Agricultural insurance scale ratio	Agricultural insurance/total agricultural gross domestic product Huang et al. (2022)	+
	Green investment	Investment ratio in environmental pollution control	Investment in pollution control/GDP Huang et al. (2022)	+

$$S = S_{sh} + S_{al} = \sum_{v=1,2} W_j \times \beta_{jv} \times \eta_{jv} + \sum W_l \times \beta_l \times \eta_l \tag{2}$$

Where S denotes the total number of carbon sinks, with S_{sh} representing the carbon sinks from shellfish and S_{al} representing the carbon sinks from algae. W denotes the yield. β and η represent the coefficient of dry weight and the coefficient of carbon sinks, respectively. j and l represent different species of shellfish and algae, respectively. Additionally, v is used to distinguish between the shell ($v = 1$) and soft tissue ($v = 2$) of shellfish (Li et al., 2022b; Wu and Li, 2022).

Net CO2 emissions from marine fishery can be calculated as Eq. 3.

$$NCE = C - S \tag{3}$$

Where NCE represents net CO2 emissions from marine fishery.

3.1.2.2 GDP of marine fishery (*GMF*, 10 thousand yuan)

Since GMF has not been officially announced, in previous studies, scholars usually use GDP of fishery in coastal provinces to roughly replace GMF, which is not rigorous. Therefore, this paper refers to the method of Wang et al. (2019) to calculate GMF more accurately. The specific calculation method is presented in Eq. 4.

$$GMF = \sum_{q=1}^{10} GMF_q \tag{4}$$

Where GMF denotes the gross domestic product of marine fishery, and GMF_q refers to the gross domestic product of a specific sub-industry within the marine fishery industry. This includes the primary industry of marine fishery, which encompasses the marine fishing industry, mariculture industry, and seawater seedling industry. The secondary industry of marine fishery

TABLE 2 Classification criteria for the decoupling states.

Decoupling state		ΔNCE	ΔGMF	$CDSMF$	Meaning
Decoupling	Strong decoupling	<0	>0	$CDSMF < 0$	Emission declines, economy grows
	Weak decoupling	>0	>0	$0 \leq CDSMF \leq 0.8$	Emission grows slightly slower than economy
	Recessive decoupling	<0	<0	$CDSMF > 1.2$	Emission declines far faster than economy
Negative decoupling	Expansive negative decoupling	>0	>0	$CDSMF > 1.2$	Emission grows far faster than economy
	Strong negative decoupling	>0	<0	$CDSMF < 0$	Emission grows, economy declines
	Weak negative decoupling	<0	<0	$0 \leq CDSMF \leq 0.8$	Emission declines slightly slower than economy
Coupling	Expansive coupling	>0	>0	$0.8 < CDSMF \leq 1.2$	Emission and economy are close
	Recessive coupling	<0	<0	$0.8 < CDSMF \leq 1.2$	Emission and economy are close

includes the seafood processing industry, marine fishing vessels and machinery repair industry, marine fishing net manufacturing industry, and the marine fishing feed, medicine, and construction industry. Lastly, the tertiary industry of marine fishery comprises the marine aquaculture circulation industry, marine aquatic warehousing and transportation industry, and marine leisure fisheries. For a more detailed algorithm, please refer to the work of Wang et al. (2019).

3.1.2.3 Measurement of carbon decoupling state of marine fishery (*CDSMF*)

Based on the definition provided by Tapio (2005), the *CDSMF* in China can be measured as Eq. 5.

$$\boldsymbol{CDSMF} = \frac{(\boldsymbol{NCE_t} - \boldsymbol{NCE_{t-1}})}{\boldsymbol{NCE_{t-1}}} \Bigg/ \frac{(\boldsymbol{GMF_t} - \boldsymbol{GMF_{t-1}})}{\boldsymbol{GMF_{t-1}}} \tag{5}$$

Where *CDSMF* represents the carbon decoupling state of marine fishery, *NCE* represents the net CO2 emissions from marine fishery *GMF* represents the GDP of marine fishery. The subscripts represent year t and year $t-1$, respectively. In accordance with Tapio's classification criteria, *CDSMF* can be classified into three categories and eight subcategories. For further information regarding the decoupling states, please refer to Table 2.

3.1.3 Other variables

3.1.3.1 Moderating variables

(a) Technological innovation (*TI*). *TI* represents the number of patents granted per 10,000 people (b) Energy structure (*ES*). *ES* is expressed by the ratio of coal consumption to total energy consumption.

3.1.3.2 The control variables of the logit model

(a) Marine fishery scale (*MFS*). *MFS* represents the proportion of marine fishery gross domestic product to GDP in the region. (b) The level of urbanization (*LU*). *LU* is measured by the proportion of the urban population to the total population. (c) Environmental regulation (*ER*). Referring to the research of Zhang et al. (2023), this paper selected the ratio of the power of the vessel controlled by the "dual control policy" to the power of the marine motor fishing vessel, which is closely related to marine fishery CO2 emissions, to measure the regulation intensity. (d) Level of financial development (*FD*). *FD* is expressed by the ratio of the total loan balance of financial institutions to GDP.

3.1.3.3 The control variables of the EKC model

The IPAT identity is widely used to analyze the impact of human activities on the environment (York et al., 2003). According to the IPAT identity, besides the degree of affluence (It is represented by *GMF* in this paper), there are also population and technological factors that affect the environment. Therefore, we add population and technological factors related to marine fishery as control variables. (a) The fishing population (*lnPOP*). *lnpop* is expressed in the logarithmic form of the fishing population. (b) Green technological innovation (*lnGT*). This paper uses the logarithm of the sum of green invention patents and green utility patents to measure.

3.2 Data sources

This study utilizes panel datasets from 11 coastal provinces in China, covering the period from 2010 to 2020. The provinces included are Liaoning, Tianjin, Hebei, Shandong in the northern marine economic circle, Jiangsu, Shanghai, Zhejiang in the eastern marine economic circle, and Fujian, Guangdong, Guangxi, Hainan in the southern marine economic circle. The data sources of this study are the China Fishery Statistical Yearbook, the China Energy Statistical Yearbook, the National Bureau of Statistics website, and the Wind database. The sporadic missing data have been filled using linear interpolation. And all economic data has been adjusted to the 2010 price level to account for inflation.

Descriptive statistics for the variables can be found in Table 3. As can be seen, the average value of *GF* is 0.2664, with a maximum value of 0.7937 and a minimum value of 0.1184. This indicates that the development level of green finance is relatively low in most provinces, suggesting significant room for growth. The variance of *LU* is 157.6580, indicating an uneven progress in urbanization. The maximum value of *LnGMF* is 17.4465, the minimum value is 11.6100, and the mean value is 15.2169. This implies that the gross domestic product of marine fishery of a few provinces has not exceeded the average level.

TABLE 3 Descriptive statistics of variables.

Variables			Mean	S.D.	Min	Max
Logit model	Explained variable	*CDSMF*	0.7190	0.2037	0.0000	1.0000
	Explanatory variable	*GF*	0.2664	0.0195	0.1184	0.7937
	Control variables	*MFS*	2.9599	8.1237	0.0660	9.5743
		LU	65.2217	157.6580	40.0000	89.6000
		ER	0.6567	0.0342	0.2674	1.1159
		FD	1.4257	0.1739	0.7530	2.7122
	Moderating variables	*TI*	1.2156	1.1523	0.6952	4.7824
		ES	0.3204	0.0229	0.0902	0.6830
EKC model	Explained variable	*lnNCE*	13.5512	1.3084	10.8944	15.3734
	Explanatory variable	*lnGMF*	15.2169	2.5984	11.6100	17.4465
	Control variables	*lnPOP*	12.3925	2.8609	8.4371	14.1721
		lnGT	8.1311	1.8513	3.8502	10.4864

3.3 Models

3.3.1 The Logit model

This paper aims to examine the influence of green finance on the carbon decoupling state of marine fishery (*CDSMF*). Since the decoupling state is a discrete variable, using the ordinary least square method may result in endogeneity and heteroscedasticity issues. In such cases, the discrete choice model needs to be selected. Therefore, this paper utilizes the Logit model to analyze the impact of green finance on *CDSMF*. According to the Tapio model, the decoupling state can be categorized into eight subcategories, which are presented in Table 2. Because the "decoupling" and "development" are we pursued, so if the decoupling state of a province in a year is strong decoupling or weak decoupling, then $Y_{it} = 1$; otherwise, $Y_{it} = 0$. To account for the potential lag effects of green finance, we select the lagged level of green finance from the previous period as the explanatory variable, which helps address the endogeneity issue. The Logit model constructed is as Eqs 6, 7.

$$Y_{it}^{*} = \beta_1 L.GF_{it} + \sum_{n=2}^{5} \beta_n x_{it} + \alpha_i + \mu_t + \varepsilon_{it} \tag{6}$$

$$Y_{it}^{*} = \log\left(\frac{P}{1-P}\right) \tag{7}$$

Where $L.GF_{it}$ represents the level of green finance lagged by one period, x_{it} represents a set of control variables. α_i and μ_t represent unobservable individual effects and year effects, respectively. ε_{it} denotes a random disturbance, β_1 and β_n represent the coefficients of the explanatory variables. Y_{it}^{*} denotes a latent variable used to connect to explanatory variables and Y_{it}. P is the probability of $Y_{it} = 1$. The subscript i and t, respectively province and year.

It is worth noting that the regression coefficients (β) in the Logit model do not provide direct interpretations as marginal effects of the explanatory variables on the explained variables. Instead, they reflect the percentage change in the odds ratio of the explained variable associated with a unit increase in the explanatory variable. Specifically, in this study, the coefficients indicate the change in the odds ratio of $CDSMF$, $\frac{P(\text{in the state of strong decoupling or weak decoupling})}{P(\text{in other states})}$, caused by each unit change in green finance development is $e^{\beta} - 1$. That is, when $\beta > 0$, the odds ratio increases by $e^{\beta} - 1$, and when $\beta < 0$, the odds ratio decreases.

To further examine the moderating effect, we will construct the following models, as shown in the Eq. 8.

$$Y_{it}^{*} = \beta_1 L.GF_{it} + \sum_{n=2}^{5} \beta_n x_{it} + \beta_6 L.GF_{it} \times M_{it} + \beta_7 M_{it} + \alpha_i + \mu_t + \varepsilon_{it} \tag{8}$$

Where M_{it} represents a set of moderating variables. We focus on the coefficient β_6 of interaction term. A significantly positive β_6, indicates that the moderating variables have a positive role in the process of green finance affecting the decoupling state.

3.3.2 The EKC model

According to the analysis in Section 2.2.2 "Delaying deterioration effect" of green finance, it can be seen that there is a deterioration point on the N-type EKC curve, before which the decoupling state improves with economic development. After that point of deterioration, decoupling progressively deteriorates with economic development. Delaying the arrival of the point of deterioration therefore prevents the rapid deterioration of the decoupling state with economic development and thus enhances the stability of the decoupling state to a certain extent. Next, we will examine the delayed deterioration effect of green finance. Eq. 9 shows the logarithmic transformation of the EKC model.

$$\begin{aligned} \ln NCE_{it} &= a_0 + a_1 \ln GMF_{it} + a_2 \ln GMF_{it}^2 + a_3 \ln GMF_{it}^3 \\ &\quad + \sum_{n=4}^{5} a_n \ln z_{it} + \alpha_i + \mu_t + \varepsilon_{it} \end{aligned} \tag{9}$$

$lnNCE_{it}$ and $\ln GMF_{it}$ are logarithmic forms of net CO2 emission and GDP of marine fishery, respectively, and z_{it} denotes a set of control variables. a_0 represents the constant term. a_1, a_2, a_3 and a_n correspond to the coefficients of the explanatory variables.

It is easy to understand when $a_1 > 0$, $a_2 < 0$, $a_3 > 0$, EKC is N-shape; When $a_1 < 0$, $a_2 > 0$ and $a_3 < 0$, the EKC is inverted N-shaped; If $a_3 = 0$, when $a_1 < 0$, $a_2 > 0$ the EKC is U-shaped. and the EKC is classically inverted U-shaped when $a_1 > 0$, $a_2 < 0$.

If the EKC is N-shape, then there will be an inflection point GMF^{e^*} (as shown in Figure 1). This point, referred to as the deterioration point in this paper, can be calculated using Eqs 10–12.

$$\frac{d^2lnNCE}{dlnGMF^2} = \frac{d\left(a_1 + 2a_2lnGMF + 3a_3lnGMF^2\right)}{dlnGMF} = 2a_2 + 6a_3lnGMF \tag{10}$$

According to the method of calculating the inflection point, let $\frac{d^2lnNCE}{dlnGMF^2} = 0$, it can be deduced that:

$$\ln GMF^{e^*} = -\frac{a_2}{3a_3} \tag{11}$$

That is,

$$GMF^{e^*} = e^{-\frac{a_2}{3a_3}} \tag{12}$$

Then we draw on the methods of Wang et al. (2021) to study the impact of green finance on the shape of the EKC curve. We establish the following model, as shown in the Eq. 13.

$$lnNCE_{it} = a_0 + a_1 \ln GMF_{it} + a_2lnGMF_{it}^2 + a_3lnGMF_{it}^3 + GF_{it} + \sum_{n=4}^{5} a_n ln\, z_{it} + \alpha_i + \mu_t + \varepsilon_{it} \tag{13}$$

If the value of $GMF_2^{e^*}$ of Model (13) is bigger than $GMF_1^{e^*}$ of Model (9), it suggests that green finance has the potential to postpone the occurrence of the deterioration point.

To ensure the robustness of the results, we then build the following model, as shown in the Eq. 14. The derivation of the verification method is shown in Eqs 15–18 (Yin et al., 2015; Gao and Wei, 2022).

$$lnNCE_{it} = a_0 + a_1lnGMF_{it} + a_2 \ln GMF_{it}^2 + a_3lnGMF_{it}^3 + b_0GF + b_1GF \times \ln GMF_{it} + b_2GF \times lnGMF_{it}^2 + b_3GF \times \ln GMF_{it}^3 + \sum_{n=4}^{5} a_n ln\, z_{it} + \alpha_i + \mu_t + \varepsilon_{it} \tag{14}$$

Then,

$$\frac{d^2lnNCE,}{dlnGMF^2} = \frac{a_1 + 2a_2lnGMF + 3a_3 \ln GMF^2 + b_1GF + 2b_2GF \times lnGMF + 3b_3GF \times lnGMF^2}{dlnGMF} = 2a_2 + 6a_3lnGMF + 2b_2GF + 6b_3GF \times lnGMF = 0 \tag{15}$$

It can be deduced that,

$$lnGMF^{e^{*\prime}} = -\frac{a_2 + b_2GF}{3a_3 + 3b_3GF} \tag{16}$$

We can see that $\ln GMF^{e^{*\prime}}$ is a function related to GF. If $GMF^{e^{*\prime}}$ will be delayed with the development of green finance, then $GMF^{e^{*\prime}}$ changes in the same direction as GF, that is:

$$\frac{dlnGMF^{e^{*\prime}}}{dGF} = \frac{a_2b_3 - a_3b_2}{3\left(a_3 + b_3GF\right)^2} > 0 \tag{17}$$

It equals to

$$a_2b_3 - a_3b_2 > 0 \tag{18}$$

In other words, if $a_2b_3 - a_3b_2 > 0$, it indicates that green finance can delay the arrival of the deterioration point; otherwise, it cannot.

4 Results

4.1 Analysis of evolution characteristics of the *CDSMF*

4.1.1 The trend of *CDSMF*

For ease of analysis, we rank the eight decoupling states. Firstly, this paper believes that emission reduction should not come at the expense of development, so the four states with $\Delta\, GMF > 0$ should be better than those with $\Delta\, GMF < 0$. Secondly, we believe that the greater the emission reduction, the better the state, so the eight states can be ranked from bad to good as: strong negative decoupling, weak negative decoupling, recessive coupling, recessive decoupling, expansive negative decoupling, expansive coupling, weak decoupling, and strong decoupling, and are represented by 1–8 respectively. The decoupling states of each province from 2010 to 2020, expressed in numbers, are shown in Figure 3.

From an overall perspective, as shown in Figure 3A, the *CDSMF* is relatively stable, and most years are in the strong or weak decoupling state. Although there was expansive coupling in 2014–2015, this improved immediately in the following year. It should also be noted that in 2019–2020, the state is recessive decoupling, that is, both *GMF* and *NCE* are reduced. But the reduction of *NCE* is more significant than the reduction of *GMF*, which is also a kind of decoupling state. This may be due to normal economic fluctuations. In addition, the outbreak of COVID-19 at the end of 2019, which originated in a seafood market, could potentially have an impact on the volumes of seafood catch and processing.

From a comparative perspective of the three marine economic circles, *CDSMF* is relatively intensive and stable in the south, and relatively rough and fluctuating in the north and east. According to Figures 3B, 4, there are great differences in the state and stability of carbon decoupling in the northern marine economic circle. Shandong Province leads the list, with its *CDSMF* stability second only to that of Guangdong Province and dominated by strong and weak decoupling. However, Liaoning has the worst stability, reflecting the existence of stability differences within the region.

As shown in Figure 4, the stability of the eastern marine economic circle is in the middle and lower reaches. Figure 3C shows that from 2010–2015, the *CDSMF* in the eastern marine economic circle was mainly dominated by strong decoupling and weak decoupling. However, after 2015 the *CDSMF* started to fluctuate wildly. It can be inferred that the stability of the *CDSMF* is insufficient and the improvement effect of *CDSMF* is poor in the eastern marine economic circle.

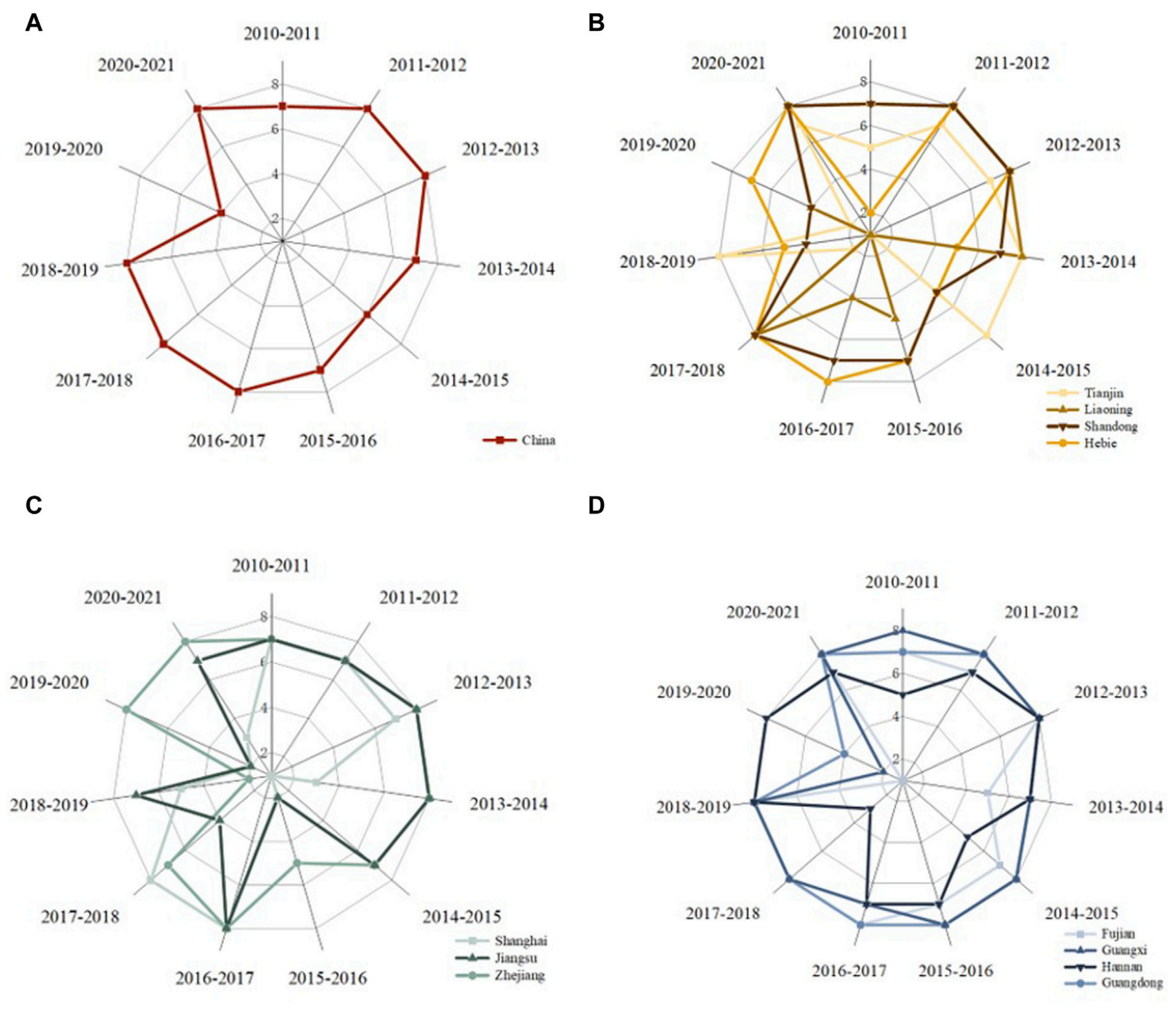

FIGURE 3
Trend of carbon decoupling state of marine fishery **(A)** marine fishery in China **(B)** marine fishery in the northern marine economic circle **(C)** marine fishery in the eastern marine economic circle **(D)** marine fishery in the southern marine economic circle.

As can be seen from Figure 3D, provinces in the southern marine economic circle exhibit a higher number of years in the state of strong decoupling, indicating that the eastern marine economic circle is relatively less dependent on fossil energy and has a relatively intensive development mode. It can be seen from Figure 4 that, except for Fujian, the stability of *CDSMF* in the southern marine economic circle is the most prominent, with Guangdong has the highest stability.

4.1.2 Kernel density analysis

This paper further uses kernel density to describe the overall characteristics and dynamic evolution of *CDSMF* of 11 coastal provinces and cities in China. It can be seen in Figure 5.

In terms of distribution, the main peak is distributed on the right side of the curve, indicating that there are more provinces with good decoupling states. However, the position of the main peak is slightly shifted to the left. In detail, initially, the main peak moves to the right, then to the left, and there is an overall trend to the left, indicating that the improvement effect of the *CDSMF* in China is not obvious, and the state is unstable, which is also confirmed by the previous article.

From a polarization trend perspective, the polarization phenomenon of China's *CDSMF* has eased. There were double peaks in the kernel density map from 2010 to 2019, indicating that the polarity distribution of China's *CDSMF* was significant, and the lateral peak showed a trend of gradually shifting to the right until it merged with the main peak in 2020. It is noteworthy that the width of the main peak increased in 2020, suggesting that although the polarization of the *CDSMF* has been alleviated, the difference remain, which needs to be further strengthened and stabilized.

4.1.3 Markov chain analysis

Limited by the amount of data, we divided the decoupling types into three categories to construct the Markov matrix of *CDSMF* from 2010 to 2020. As shown in Table 4, the data on the diagonal line is the probability that the *CDSMF* has not changed, and the

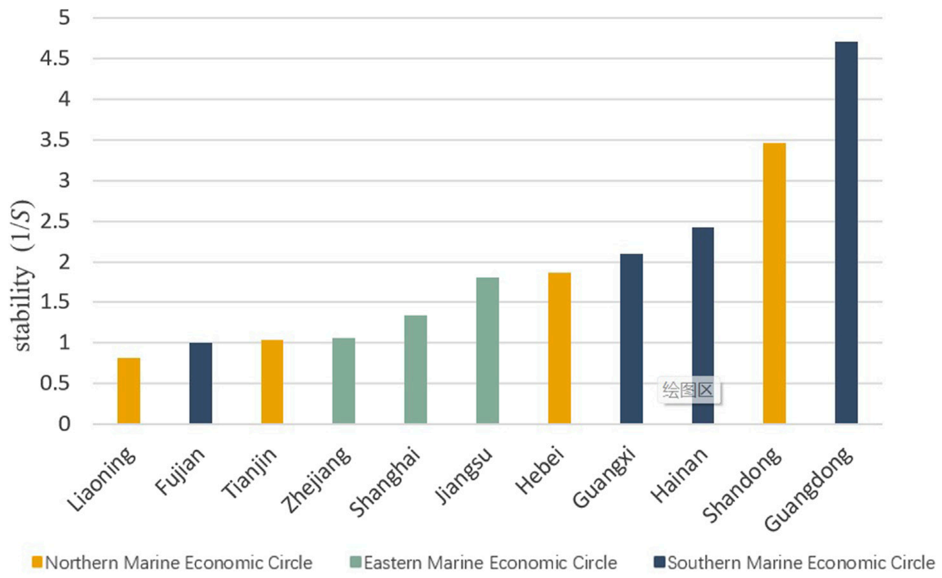

FIGURE 4
Stability of the carbon decoupling state (Note: Based on Liu and Xiao (2022), $s = \frac{1}{N-1}\sum \left|\frac{CDSMF_t + CDSMF_{t-1}}{CDSMF_{t-1}}\right|$. The larger $\frac{1}{s}$ is, the better the stability is).

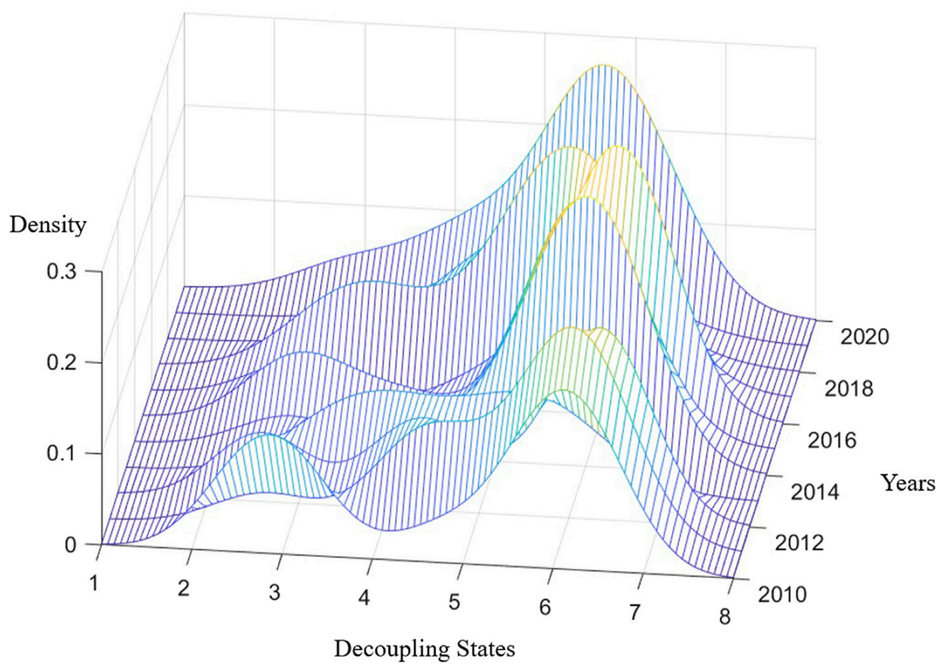

FIGURE 5
Kernel density of the carbon decoupling state of marine fishery.

data on the non-diagonal line is the probability that the *CDSMF* has shifted.

It can be seen that 23.08% of provinces and cities are still in the negative decoupling state after 1 year, and the probability of transferring from "negative decoupling" to "coupling" and "decoupling state" is 3.85% and 73.08%, respectively. The probability of the transition from the coupling state to the "negative decoupling" or "decoupling state" is 50.00%. Of the provinces and cities that were initially in decoupling state, 19.51% were transferred to the "negative decoupling state", 2.44% were transferred to the "coupling state", and 78.05% remained in the "decoupling state."

Based on the thorough analysis presented above, the following conclusions can be drawn: Firstly, the stability of *CDSMF* is poor,

TABLE 4 The Markov matrix.

$CDSMF_{t+1}$ / $CDSMF_t$	Negative decoupling	Coupling	Decoupling
Negative decoupling	0.2308	0.0385	0.7308
Coupling	0.5000	0.0000	0.5000
Decoupling	0.1951	0.0244	0.7805

which is consistent with the above conclusions. The probability of maintenance exceeds the probability of transition only in the case of "decoupling". Second, there is the phenomenon of skip metastasis. The transition between the three states often skips the "coupling state," and transfers between "negative decoupling" and "decoupling." Third, it is mainly to transfer or maintain the "decoupling state". The probability of transition from "negative decoupling state" to "decoupling state" and the probability of "decoupling state" remaining were both greater than 70%.

Based on the above analysis, there are two major problems in China's marine fishery carbon decoupling state: the improvement effect of decoupling state is not obvious and the decoupling state is unstable. Drawing upon the hypothesis presented in Chapter 2, we posit that green finance has the potential to exert a "promoting decoupling effect" and a "delaying deterioration effect" on the problems prevalent in the Chinese *CDSMF*. In order to validate this hypothesis, we will now proceed to the empirical section of our study.

4.2 Analysis of the impact of green finance on the *CDSMF*

4.2.1 Benchmark regression results

This study utilizes STATA 16.0 to estimate the Logit model. The results are shown in Table 5. As depicted in columns (1)–(5), when control variables are gradually added, the coefficient of core explanatory variable *L*1.*GF* consistently exhibits statistical significance, with all coefficients being positive. This means that green finance helps to increase the odds ratio of strong or weak carbon decoupling state of marine fishery in coastal provinces and cities. In other words, the development of green finance improves the *CDSMF*. That is, the "promoting decoupling effect", Hypothesis 1, has been verified.

Regarding the control variables, the scale of marine fishery is significant at the 1% level, and all are less than 0, which means that under current conditions, blindly expanding the scale of marine fishery is not conducive to decoupling. This observation aligns with several studies (Li Z. et al., 2022; Wang and Wang, 2022; Guangliang et al., 2023), which suggests that the current development model of China's marine fishery is still relatively extensive, and it is imperative to find clean development ways and transform to intensive. In addition, both financial development and urbanization levels have a significant positive impact on the carbon decoupling state of marine fishery. However, the effect of environmental regulation is not significant. This may be because environmental regulation will not only control the carbon emissions of fishing vessels but also increase the cost burden on enterprises. The decoupling index is a composite indicator of environmental and economic indicators. The dual impact of environmental regulation may lead to insignificant effects. In addition, this may also be due to poor effectiveness, lagging nature, or inadequate enforcement of environmental regulations.

Technological innovation is widely acknowledged as a driving force and catalyst for achieving sustainability goals (Dwivedi et al., 2023). Technological innovation has the potential to enhance the conversion rate of capital gains, improve the productivity of low-carbon enterprises, lead the orderly flow of capital to low-carbon industries, and strengthen the resource allocation effect of green finance (Xu Y. et al., 2023). Therefore, technological innovation may have a moderating effect in the process of green finance promoting decoupling. To examine this hypothesis, this paper introduces the interaction term of technological innovation and green finance on the basis of the benchmark regression model to analyze the moderating effect, which is listed in columns (6) of Table 5. The results reveal that the interaction term between technological innovation and green finance is positive and is significant at the level of 5%. This implies that technological innovation plays a positive moderating role in the process of green finance promoting carbon decoupling in marine fishery.

In addition, the promoting decoupling effect of green finance may be largely influenced by energy structure. This is because, on the one hand, over-reliance on fossil energy will hinder regional financial development. On the other hand, the large-scale development of clean energy will not only increase the input cost of original fossil energy, but also drive the carbon emission pricing mechanism within the carbon trading market (Yi et al., 2022). Therefore, we further estimated the moderating effect of energy structure. In Table 5 (7), we observe that the coefficient of the interaction term is significantly negative and passes the significance test of 5%. This suggests that the increasing share of coal consumption is hindering the positive impact of green finance on decoupling.

4.2.2 Robustness test

To ensure the robustness of the above conclusions, several robustness tests were conducted. First, we refer to Yang et al. (2021) to reconstruct the measurement system of green finance. Green credit is measured by the ratio of green credit of listed companies to total credit of listed companies. Green securities are represented by the ratio of the market value of listed companies in the environmental protection industry to the total market value. Green investment is set as the ratio of China's fiscal expenditure on energy conservation and environmental protection to China's total fiscal expenditure. Carbon finance is measured by the ratio of carbon dioxide emissions to GDP. And the results are presented in Table 6 (1). Then, to eliminate

TABLE 5 Results of the Logit model.

Explained variable	*CDSMF*						
Explanatory variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)
$L1.GF$	13.9471* (7.4146)	19.9686*** (6.6550)	20.4650*** (6.4910)	20.7861*** (6.433	23.2282*** (7.1498)	29.3287** (13.0054)	40.2541** (18.6356)
MFS		−2.9124*** (1.1098)	−4.9033*** (1.3405)	−5.1279*** (1.4935)	−5.4886*** (1.6342)	−7.5816** (2.4275)	−5.9998*** (1.8087)
FD			5.8981** (2.6725)	6.1913** (2.8450)	7.1009** (2.8062)	11.6833*** (3.6713)	9.7177*** (3.4613)
ER				−3.6422 (6.5337)	−4.8167 (6.8106)	−6.6715 (7.0169)	−13.1964 (9.1695)
LU					0.4410* (0.2596)	1.7728** (0.6427)	1.2467** (0.5361)
TI						1.7905 (1.5232)	
ES							43.9423 (28.5936)
$L1.GF \times TI$						13.7577** (5.6278)	
$L1.GF \times ES$							−77.1118** (33.5399)
Individual FE	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES

Notes: (1) robust standard errors are in parentheses; (2) *, ** and *** denote significance level at 10%, 5% and 1% respectively.

TABLE 6 Results of robust test.

Explained variable	*CDSMF*		
Explanatory variables	(1)	(2)	(3)
$L1.GF$	46.3638*** (12.0508)	23.1953*** (7.1622)	24.87494** (10.0509)
MFS	−5.6640*** (1.4597)	−5.5060*** (1.6336)	−7.2670*** (2.5091)
FD	6.4947** (2.8684)	7.1565** (2.8159)	12.7282 (8.1318)
ER	−7.0714 (7.5029)	−4.9865 (6.7367)	−7.5598 (7.6692)
LU	0.8501*** (0.3015)	0.4557* (0.2667)	0.4753 (0.2826)
Individual FE	YES	YES	YES
Year FE	YES	YES	YES

Notes: (1) robust standard errors are in parentheses; (2) *, ** and *** denote significance level at 10%, 5% and 1% respectively.

the influence of outliers on measurement results, we carry out a 1% bilateral tail reduction for all indicator variables. The results are displayed in Table 6 (2). Finally, considering the unique characteristics of Tianjin and Shanghai as municipalities directly under the central government, which differ significantly from other cities in terms of infrastructure and preferential policies, and notably have a small marine fishery and aquaculture industry, these two municipalities were excluded from the analysis. Subsequently, regression analysis was performed on the remaining samples, and the outcomes are presented in Table 6 (3). Remarkably, the significance and direction of the results obtained from these Robustness tests are largely consistent with the previous findings, indicating the robustness and credibility of the regression results in this study.

4.2.3 Heterogeneity analysis

Various types of green financial instruments may have distinct impacts on the *CDSMF*. In this paper, two green financial instruments, green insurance (*GS*) and green investment (*GI*), which are closely related to the carbon decoupling of marine fishery, were selected to compare their differences, and the data were normalized for comparison. As shown in column (1)–(2) of Table 7, both green insurance and green investment exhibit a significant positive effect on the *CDSMF*. However, green investment is significant at the 1% level, while green insurance only passes the 10% statistical level significance test.

Digital finance, which integrates the Internet and information technology, represents a novel form of financial services that enhances the accessibility and convenience of financial services. It

TABLE 7 Results of heterogeneity analysis.

Explained variable	*CDSMF*						
Explanatory variables	(1) *GS*	(2) *GI*	(3) High	(4) Low	(5) Northern	(6) Eastern	(7) Southern
L1.GF			52.0427*** (16.9082)	42.0769* (23.5776)	16.2529* (8.4769)	36.8753** (15.6682)	−14.6810 (24.6112)
L1.GS	3.4626* (1.8221)						
L1.GI		1.6238*** (0.5584)					
MFS	−3.4252*** (1.2867)	−5.7402*** (1.7465)	−8.2377* (4.7539)	−10.8283** (4.7400)			
FD	4.0659** (2.5254)	8.5717** (2.9275)	18.9396*** (6.8889)	22.5843 (14.1778)			
ER	−4.3793 (7.1507)	−2.9181 (8.8094)	−13.3452 (20.8334)	−23.1529 (16.4969)			
LU	0.8892** (0.4401)	0.4020 (0.2880)	0.5958* (0.3529)	3.8122 (2.4543)			
Individual FE	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES

Notes: (1) robust standard errors are in parentheses; (2) *, ** and *** denote significance level at 10%, 5% and 1% respectively.

overcomes the limitations caused by information asymmetry, thus having the potential to facilitate the expansion of green financial products and improve service efficiency (Ye et al., 2023). By utilizing the median of the digital financial development index, this study categorizes the 11 coastal provinces into two groups based on their levels of digital financial development. Subsequently, we employed the data used in the basic regression to conduct regression analysis on the two groups, aiming to investigate whether digital finance can enable green finance to promote carbon decoupling of marine fishery. The findings, presented in column (3)–(4) of Table 7, demonstrate that the coefficient of green finance in both groups of regions is significantly positive. However, the positive effect of green finance is more evident in regions with high development degree. In addition, in regions with a high level of digital finance development, the impact of green finance is greater, with a coefficient of 52.0427. And the coefficient of the regions with a low level is only 42.0769, indicating the empowering effect of digital finance.

The test of heterogeneity according to the classification of the three marine economic circles is classic and necessary. However, after classification, the amount of data in each group is small, and if too many variables are added, the Logit model cannot be estimated scientifically. Therefore, this paper only adds one core explanatory variable and compares it with column (1) of Table 5. This regression uses the same data as the basic regression. The results are presented in Table 7 (5)–(7). The results indicate that a significant positive relationship between green finance and *CDSMF* in the northern pattern economic circle and the eastern marine economic circle. Specifically, the coefficient of green finance in the eastern marine economic circle is 36.8753, which passes the significance test of 5%. However, in the northern marine economic circle, the coefficient is only 16.2529, and it is only significant at the 10% level. In addition, the effect of green finance is not significant in the southern marine economic circle.

4.3 Analysis of the impact of green finance on the EKC

The regression results for the EKC are reported in Table 8 and column (1) shows the basic EKC model. Column (2) introduced the green finance development index into the model to investigate the influence of green finance on the shape of EKC. Column (3) further introduces the interaction terms between *GF* and *lnGDF*, $lnGDF^2$, and $lnGDF^3$, to verify the "delaying deterioration effect" of the development of green finance again to ensure the robustness of the results.

First of all, according to the coefficients in columns (1)–(3), it is confirmed that the EKC curve between the *NCE* and *GMF* of marine fishery is "N" type (Hypothesis 2a verified). The EKC curves fitted by columns (1) and (2) are shown as M1 and M2 in Figure 6, respectively. In column (1), the $GMF_1^{e^*}$ is the deterioration point mentioned in this paper, and its corresponding *GMF* is 17.0067 billion yuan. In column (2), the regression results reveal a negative coefficient for green finance at a 1% level of significance, and $GMF_2^{e^*}$ becomes 18.5305 billion yuan, indicating that green finance not only has a significant effect on inhibiting net CO2 emissions, but also has a "delaying deterioration effect" (Hypothesis 2b verified). In column (3), $a_2b_3 - a_3b_2 > 0$. According to the analysis of Section 3.1.2, Hypothesis 2b has been verified again. These two empirical results verify each other and confirm the reliability of theoretical Hypothesis 2b. This means that green finance can prevent the *CDSMF* from deteriorating rapidly with the growth of *GMF*, provide space for it to stay in a good decoupling state, and can improve the stability of the *CDSMF*.

In columns (1)–(3), the coefficient of the fishing population is significantly negative, that is, the increase of the fishing population also significantly inhibits the *NCE*, and the phenomenon of negative correlation between population and environmental deterioration is also found in other studies. Patel et al. (1995) and Selden and Daqing

TABLE 8 Results of the EKC model.

Explained variable	*lnNCE*		
Explanatory variables	(1)	(2)	(3)
$lnGMF$	6.2256*** (2.3190)	6.2743*** (2.2802)	6.1688*** (2.2112)
$lnGMF^2$	−0.4347*** (0.1628)	−0.4373*** (0.1601)	−0.4081*** (0.1557)
$lnGMF^3$	0.0101*** (0.0037)	0.0101*** (0.0037)	0.0091** (0.0035)
$lnPOP$	−0.1559** (0.0602)	−0.1613*** (0.0592)	−0.1871*** (0.0584)
$lnGT$	0.1577*** (0.0539)	0.1587*** (0.0530)	0.1211* (0.0521)
GF		−0.3162*** (0.1530)	−0.2552 (0.1841)
$lnGMF \times GF$			−71.1636*** (25.5655)
$lnGMF^2 \times GF$			4.8289*** (1.7624)
$lnGMF^3 \times GF$			−0.1085*** (0.0402)
Individual FE	YES	YES	YES
Year FE	YES	YES	YES
R^2	0.9964	0.9966	0.9970

Notes: (1) standard errors are in parentheses; (2) *, ** and *** denote significance level at 10%, 5% and 1% respectively.

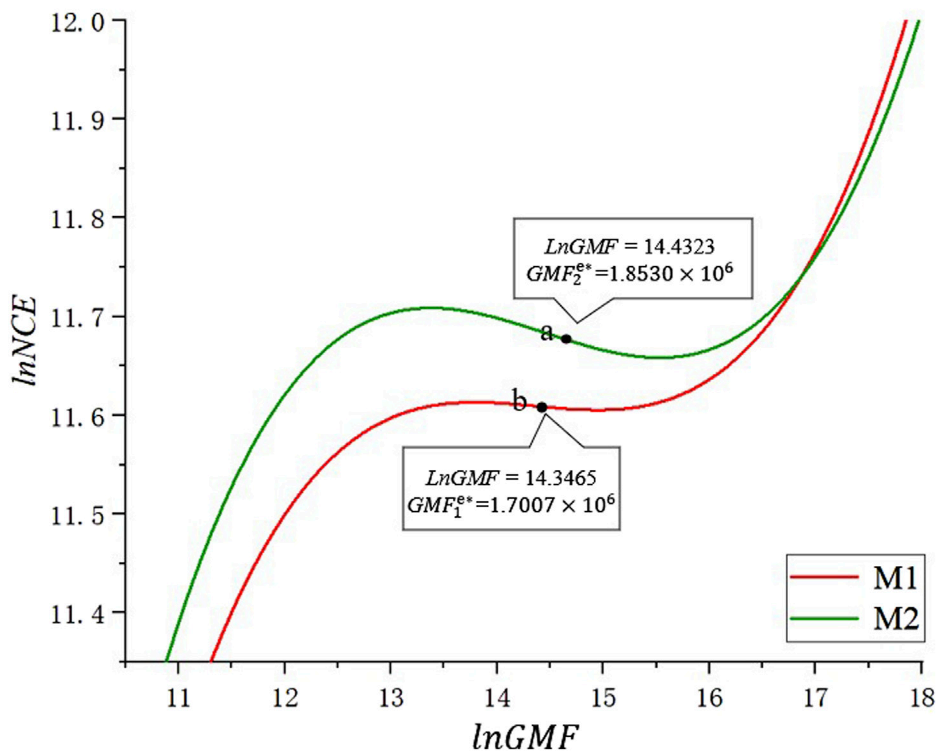

FIGURE 6
The EKC curve between net CO2 emissions and GDP of marine fishery.

(1994) posited that population growth and expansion contribute to a greater awareness of environmental impact, thereby prompting the adoption of more rigorous environmental standards. Furthermore, this study contends that the augmentation of human capital leads to a concomitant enhancement in marine fishery production efficiency, consequently reducing net CO2 emissions at a given level of green finance. This factor also constitutes one of the underlying reasons.

It is important to highlight that the effects of green technologies in this paper seem to contradict common sense, but studies that include technological variables in the EKC analysis have been mixed.

The explanation of Lantz and Feng (2006) for this phenomenon is that time-dependent technological innovation changes regional investment patterns, thereby increasing the demand for fossil fuels. In this paper, we believe that the overall increase in green technology stimulates investment related to marine fishery, thus increasing CO2 emissions. However, at present, the number of green innovations for marine fishery is relatively small. Hence, the effect of green technology on reducing emissions in marine fishery is not apparent, leading to this phenomenon.

5 Discussion

Analysis of the evolution trend of *CDSMF* shows that although the decoupling state of China's coastal provinces from 2010 to 2020 is dominated by strong or weak decoupling states, it is not stable and shows the characteristics of coexistence of multiple types of decoupling. Furthermore, the pattern of *CDSMF* in China's coastal regions displays an imbalance. From the perspective of the marine economic circle, the decoupling of the southern marine economic circle is stable and strong, which aligns with the research findings of Guan et al., 2022. From the provincial level, Guangdong and Shandong are leading the way. This may be because Shandong and Guangdong have rich marine resources, a good marine economic foundation, and strong scientific research strength (Sun et al., 2023). In addition, the kernel density analysis shows that most of the *CDSMF* in China are in a good decoupling state, but the improvement effect is not obvious. What's more, although the polarization phenomenon of the decoupling state has been alleviated, the differences still exist. This may be due to the spatially unbalanced high-quality development level and innovation ability in China's coastal areas (Li et al., 2023a; Sun et al., 2023). According to the Markov chain analysis, although the *CDSMF* is mainly transferred or maintained to the "decoupling" state, they are both still about 70%, and there is still room for improvement. This is supported by the research of Wang and Wang 2022. Moreover, it is found that the instability of the decoupling state is prominent and there is the phenomenon of skip metastasis.

The impact of green finance on the *CDSMF* is significantly positive. Technological innovation can strengthen the positive influence of green finance on *CDSMF*. It may be that technological innovation can improve the financial system by improving the competitiveness of firms to achieve higher profits, thus making green finance more efficient (Khan et al., 2020). What's more, the mitigation of coal consumption can enhance the decoupling impact of green finance. Therefore, in order to maximize the role of green finance in promoting decoupling, it is imperative to prioritize the development of clean energy sources and make necessary adjustments to the current coal-dominated energy structure.

The promoting decoupling effect of green investment is more significant than green insurance. It may be because green insurance mainly allocates capital into assets with green features through risk management means, which may take a considerable amount of time to yield tangible results (Klapkiv and Ülgen, 2023). Secondly, China's green insurance system is not mature, and there are problems such as insufficient incentive measures, few compound talents and lack of innovation, resulting in the function of green insurance cannot be effectively played (Chen et al., 2022b). Besides, the effect is more pronounced in regions with advanced digital finance development. As we all know, digital finance facilitates the efficient sharing of factor resources, and make use of the convenient advantages of digital technology, so that enabling effectiveness of green finance. Moreover, the decoupling effect is stronger in the eastern marine economic circle compared to the northern marine economic circle, while it is not significant in the southern marine economic circle. This disparity may be attributed to the more mature financial system in the eastern marine economic circle, which enables the optimal utilization of financial resources, consistent with the findings of Su et al. (2021). Additionally, as previously analyzed, the southern marine economic circle exhibits a relatively robust *CDSMF* and strong decoupling stability, leaving little room for improvement. Consequently, the role of green finance may be limited in this context, implying that the influence of green finance on carbon decoupling diminishes as the *CDSMF* improves.

The EKC curve between the *NCE* and *GMF* of marine fishery is N-shaped, which is consistent with the related findings of Chen et al. (2017) and Fang and Gao (2023). The "delaying deterioration effect" of green finance explains and supports the "promoting decoupling effect", because with the postponement of the deterioration point, it will undoubtedly provide a greater possibility for the decoupling state to be in strong decoupling and weak decoupling. At the same time, the postponement of the deterioration point can delay the deterioration rate of the decoupling state with the development of the marine fishery, which can enhance its stability.

In a word, green finance is conducive to promoting carbon decoupling in marine fishery and solving the problem that it is difficult to balance economic development and emission reduction. At the same time, attention should be paid to the enabling role of technological innovation, energy structure upgrading, and digital finance on green finance, as well as the differences in instruments and regions of green finance. This will help to formulate targeted policies, to better meet the challenges under the background of low-carbon economy.

6 Conclusion

Based on the analysis of the *CDSMF* and the empirical findings, the following conclusions and discussions can be drawn:

Firstly, the improvement of *CDSMF* is not good enough. In addition, although the carbon decoupling state in China from 2010 to 2020 is mainly strong and weak decoupling, instability is prominent, showing the phenomenon of bouncing back and forth between various states. In addition, the polarization phenomenon of *CDSMF* in coastal provinces and cities has been eased, but there are still differences among and within the three marine economic circles, and there is a phenomenon of multiple decoupling problems and multiple decoupling states coexisting.

Secondly, green finance has a "promoting decoupling effect", which passes the robustness test. In addition, enhancing technological innovation and reducing the reliance on coal can enhance the effect. The heterogeneity test results indicate that this effect is particularly pronounced in regions with a high level of digital finance development, as well as in the eastern marine economic circle. Additionally, the impact of green investment appears to be more significant than that of green insurance.

Thirdly, the EKC curve between carbon emissions from marine fishery and their output value shows an "N" shape, which means that there are deterioration points on this EKC curve. Green finance has a "delaying deterioration effect", which can reduce the possibility of decoupling deterioration and enhance the stability of the decoupling state to a certain extent.

Data availability statement

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

Author contributions

WX: Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision, Validation, Writing–review and editing. YZ: Data curation, Formal Analysis, Investigation, Methodology, Software, Visualization, Writing–original draft.

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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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