# How do heterogeneous environmental regulations affect the sustainable development of marine green economy? Empirical evidence from China's coastal areas

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# How do heterogeneous environmental regulations affect the sustainable development of marine green economy? Empirical evidence from China's coastal areas

**Abstract**

Under the dual constraints of environment and resources, it is imperative for China to achieve sustainable development of its marine economy through establishing effective mechanism and intensifying environmental regulation to promote green transformation of the marine economy. By incorporating both marine economic development factors and environmental pollution factors into the marine green economy development evaluation system, this study measures the marine green economic efficiency (MGEE) in China. On this basis, the dynamic panel smoothed transition regression model is used to analyze the nonlinear effect and transition mechanisms between environmental regulation and marine green economic efficiency, and the heterogeneous effects of market-based and command-and-control environmental regulation tools are examined by distinguishing the forms of environmental regulation as well as regional development differences. The findings are as follows: ①under the setting of different transition variables, both market-based environmental regulation (MER) and command-and-control environmental regulation (CER) exhibit a non-linear relationship with MGEE during the transition between the high regime and the low regime. ②Both CER and MER contribute positively to the advancement of MGEE after exceeding certain thresholds through changes in the marine industry structure (MIS) and marine technology innovation (MTI). The driving impact of CER is noticeably stronger than that of MER after the threshold of MIS is exceeded, whereas the driving effect of MER is stronger after the threshold of MTI is exceeded. ③When foreign direct investment (FDI) is considered as the transition variable, CER consistently inhibits the growth of MGEE, however, MER's impact progressively changes from negative to positive with FDI surpassing the threshold.

**Keywords: Heterogeneous environmental regulations; Marine green economic efficiency; Sustainable development; PSTR model; Nonlinear effects**

## 1. Introduction

China's coastal areas have pioneered the country's reform and opening up, witnessing the rapid growth over the last two decades in the marine economy thanks to the resource and demographic dividends [1] and the technological spillover effect brought by rising foreign direct investment (FDI) [2]. China's gross ocean product (GOP) increased from US$50 billion in 2000 to US$1,296 billion in 2019, accounting for 17.1% of the GDP of the coastal areas (Fig. 1). However, the speed with which the marine economy has developed and the surge in human activities have inevitably caused severe marine environmental pollution [3] and substantial economic losses [4]. In the meanwhile, high investment, resource consumption, and pollution have significantly limited the potential development of the marine economy. It has become evident that the need for coordinated regional marine economic development and rationalization of the marine industrial structure is very urgent [5]. In this context, it has become crucial to explore a sustainable development mode of the marine economy with an aim to preserve the regional environment and ensure future prosperity.

Previous studies on the sustainable development of marine economy have mainly focused on two perspectives, that is, the "carrying capacity", e.g. marine ecological and economic carrying capacity [6-8], and "efficiency" [12]. The former category of studies has concentrated on measuring the current state of marine economic development in the study areas by incorporating economic development and marine resource utilization into the research framework. In contrast, scholars of the latter emphasized that efficient utilization of high input factors is conducive to mitigating the conflict between protection of environmental resources and rapid economic development [9,10]. However, improvements in economic efficiency have not been matched by dramatic reductions in pollution. It is because when those scholars estimated the performance of economic development, they largely failed to consider environmental factors, which led to overestimated values, thus distorting the evaluation of economic performance [11]. In addition, numerous scholars have explored the changes in marine economic efficiency and total factor productivity under environmental constraints [12,13]. Nonetheless, only adding one or several surrogate variables of environmental pollution into the calculation cannot fully measure the impact. In particular, existing research focuses on traditional economic efficiency and does not pay sufficient attention to "Green Economic Efficiency (GEE)" [14], which combines the cost of resource input and environmental loss with economic growth [15]. In the report of China's 19th National Congress of the Communist Party, the government was explicit in its objective to "promote green development" and "accelerate the construction of a marine power and insist on protecting the marine ecological environment". This acknowledges the unsustainable nature of China's traditional GDP-oriented economic development mode and emphasizes that the development quality will inform the direction of measuring sustainable economic development in the future [16]. As the core of green development, green economic efficiency represents the quality of economic development [15]. Therefore, under the dual constraints of resources and environment, there is an urgent need to re-examine the development of marine economy from the perspective of green economic efficiency.

In addition, due to the externality of environmental problems and the opportunism of microeconomic entities, only relying on market mechanisms cannot achieve environmental protection [17], let alone effectively promote green economic efficiency. As an effective measure to solve market failure and realize environmental protection [18], the importance of environmental regulation is evident. Although the role of environmental regulation in improving the environment has long been recognized in academia, its consequent economic impact has been considerably debated [19,20]. Essentially, there are two viewpoints: "win-win" and "zero-sum". Proponents of the "win-win" perspective argue that environmental regulation can stimulate innovation, offset environmental compliance costs, and improve the competitiveness of businesses [21-23]. Stringent policies will create a win-win situation between industrial development and energy conservation [24]. However, it cannot be verified in all industries and study areas. There are even different conclusions that it can promote innovation in advantageous industries and inhibit innovation in disadvantaged regions (industries) [25]. On the other hand, those who support "zero-sum" believe that it is challenging to balance the interests of enterprises and society, and the increased cost burden on enterprises due to environmental regulations will create new constraints on production performance and ultimately affect regional economic development [26,27]. The economic effects of environmental regulation have been discussed in detail from the perspectives of "compliance costs" and "innovation compensation", but the inconsistency in the direction and intensity of environmental policy implementation and the gradient differences in regional development characteristics have not been considered. Since the tax sharing system reform, local governments have gained a certain degree of economic and financial autonomy and greater flexibility in implementing environmental regulations [28], which has also led to unfavorable competition in environmental regulations to maintain local economic growth [29]. Some scholars have confirmed that local governments may adopt a "race to the bottom " or "race to the top" differentiated strategy for heterogeneous environmental regulations according to different competitive motivations, which will further affect foreign direct investment entry decisions [30] and regional industrial layout [31,32]. In the meantime, the inconsistency of environmental regulations will also lead to the cross-regional transfer of polluting industries [33,34], which will seriously affect the regional economic operation and industrial structure adjustment. As far as the marine field is concerned, there are large differences in marine resource endowments, marine policies and technical levels between regions, resulting in an imbalance in the spatial distribution of marine industries, which in turn leads to significant differences in marine industry structures [35]. More importantly, compared with the development of the land economy, the marine economy is more open and competitive, with more prominent technology spillover effects, and is easily affected by the advanced technologies and experience of other marine countries [2]. Considering differences in marine economic development between regions, the impact of environmental regulation on marine green economic efficiency is complex, and the relationship between them cannot be simply described as a linear positive or negative impact, and moreover there may be even a nonlinear relationship**.** Therefore, it is necessary to conduct an in-depth analysis of the impact of environmental regulation on the marine economy on the basis of fully considering regional differences in marine industrial structure, FDI intensity and marine innovation capacities.

China's "Announcement on the Status of Ecological Environment in 2018" stated that the newly established Ministry of Ecology and Environment would uniformly exercise the responsibilities of ecological pollution discharge supervision and administrative law enforcement, which means enterprises will face stricter environmental supervision in the future. In this context, it is crucial to address the relationship between environmental regulation and marine economic growth. Therefore, this study aims to understand better the impact of heterogeneous environmental regulation on marine green economic efficiency, which has both theoretical and practical significance.

The contributions of this paper are as follows: First, unlike the previous studies, this paper incorporates green factors into the consideration of marine economy to explore the relationship between environmental regulation and marine green economic efficiency. Second, this paper distinguishes the heterogeneous non-linear effects of two environmental regulation tools on marine green economic efficiency, and adopts a dynamic panel smoothed transition regression model, which ensures the reliability of the research results compared with linear studies and other threshold regression methods. Finally, based on the regional differences of marine industrial structure, FDI intensity and marine innovation capacity, this paper conducts an in-depth analysis of the internal mechanism of the nonlinear impact of environmental regulation on marine green economic efficiency under the influence of different threshold variables.

The remaining of the paper is organized as follows: Section 2 analyses the mechanism of environmental regulation affecting the marine green economy; Section 3 explains the setting of the empirical model, indicator selection, and data sources; Section 4 and Section 5 present results and discussion, respectively. Finally, Section 6 draws conclusions with policy implications for China.

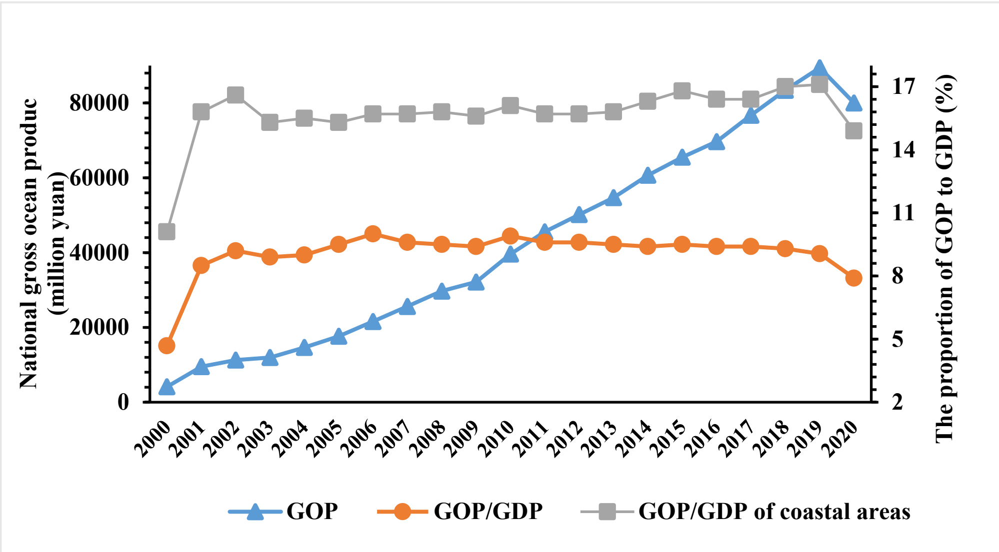


**Fig. 1.** Gross Ocean Product (GOP) of China from 2000 to 2020.

## 2. The mechanism of heterogeneous environmental regulations on marine green economy

The goal of environmental regulation serving marine economic growth and its impact on marine economic performance has recently been widely discussed. Two main environmental regulation instruments, command-and-control environmental regulation and market-based environmental regulation, play an increasingly important role in China. Command-and-control environmental regulation refers to the issuance of regulations or orders by environmental authorities that require emitters to take actions to achieve environmental goals. Management then rewards or penalizes emitters based on whether they meet their targets [36]. The restriction requires enterprises to implement strict environmental regulation measures, and enterprises or organizations can only passively accept them, and violations will be punished. Market-based environmental regulations are an economic tool that reduces social pollution control costs by effectively allocating pollution reductions, pollution control project investments, and financial subsidies among emitters according to the "polluter pays" principle [37]. These approaches allow economic agents to take action based on their own circumstances and can effectively incentivize businesses to adopt appropriate pollution control processes. Combining the previous mainstream views, this study attempts to explain the impact mechanism of heterogeneous environmental regulations on the marine green economy from the perspectives of "cost losses" and "benefits compensation". The impact path is illustrated in Fig. 2.

Environmental costs: One of the direct effects of environmental regulations is to increase the "environmental compliance costs"[1] of marine companies in the short term [38]. These additional costs will not only compress the profit margins of enterprises, but also impose new constraints on the expansion and reproduction of enterprises [39]. In addition, affected by environmental regulations, some raw materials or scarce resources used for production may be further regulated, and the resulting costs also need to be borne by enterprises. For example, implementing a fishing ban forces each fishing unit to bear the additional cost of rising raw material prices or finding alternatives to raw materials during the ban. The increase in the cost burden of enterprises will inevitably affect their production, operation and sales [27], which is not conducive to industrial development and the growth of marine green economy. Another effect of increased environmental costs is the "crowding-out effect". First, the funds originally used by enterprises for technology research and development in the short term will be diverted, which may lead to a decline in the future competitiveness of enterprises [40].

[1] Environmental compliance costs are the extra costs paid for the consumption of resources and the discharge of pollutants.

Secondly, the existence of policy constraints and environmental protection compliance costs have raised the market access threshold, making it difficult for some small and medium-sized enterprises to enter, which is not conducive to competition. Some mandatory environmental policies will also make high-polluting enterprises avoid environmental costs by changing their existing production strategies, such as stopping polluting projects, relocating or even withdrawing from the market [41]. At the same time, the increased regulation of the marine environment may lead to the withdrawal of foreign direct investment (FDI) [42]. There is no doubt that the cross-regional migration of polluting industries and the withdrawal of FDI will adversely affect the output and competitiveness of the regional marine green economy in the short term.

Benefit compensation: In the long run, the implementation of marine environmental regulations positively effects the growth of the marine green economy. Implementing strict environmental regulations can reduce pollution emissions, and at the same time may reduce the demand for fossil energy and increase the supply of new energy, thereby improving environmental quality and positively affecting the development of marine green economy [43]. Furthermore, environmental costs and emissions restrictions are not always bad for business. Governmental pollution control measures combined with R&D subsidy policies can incentive companies to optimize resource allocation, improve energy efficiency and productivity through clean technology innovation, and transform without sacrificing economic growth [44,45]. Meanwhile, the diffusion of advanced production technology and green environmental protection technology among enterprises will significantly enhance the regional marine industry’s competitiveness, and ultimately positively impact marine green economic efficiency. In addition, environmental regulations also play an active role in regulating the upgrading of the marine industry structure and optimizing the direction of FDI [46].

In addition to the above discussion, differences in regional development stages, especially differences in technological basis and industrial structure, may also affect the actual performance of the economic effects of environmental regulations. On the one hand, the secondary sector is the primary source of pollution emissions. When the proportion of the marine tertiary industry is higher than that of the secondary industry, the environmental burden is smaller. Therefore, the cost of environmental compliance will change with the adjustment of the marine industry structure [35]. On the other hand, upgrading pollution control technology and improving enterprise efficiency are inseparable from technological innovation, and the development and promotion of new technologies must be rooted in the regional technology foundation [17]. Therefore, the innovation compensation benefits brought by environmental regulation vary with the actual level of marine technological innovation. At the same time, FDI can also bring certain innovation compensation benefits to the development of regional marine economy through the technological spillover effects. However, capital is profit-seeking, and the scale and industrial preference of FDI is affected by the stage of regional development [2].

In short, the direction and extent of the impact of environmental regulation on marine green economic efficiency largely depends on the relative cost loss and benefit compensation, while the actual impact will be strongly affected by the evolution of factors such as regional technological innovation capabilities, FDI intensity and industrial structure adjustment. Therefore, the impact of environmental regulation on the marine green economy cannot be simply described by linear positive or negative, and there may also be nonlinear effects. Based on the above, the first and second hypotheses are stated as follows.

**H1:** Environmental regulations have a nonlinear impact on marine green economic efficiency.

**H2:** The impact of environmental regulation on the marine green economic efficiency varies with the evolution of the marine technological innovation level, FDI intensity and industrial structure.

In addition, with the deepening of research, many scholars have found that there are significant differences in the economic effects of different types of environmental regulations [27]. Although they can all affect the development of marine green economy from the aspects of "cost losses" and "benefit compensation", the actual effects of different environmental regulations on the marine green economic efficiency may be different due to the influence of regulatory costs, enterprise preferences, enforcement standards, supervision and punishment, and scope of application. As a result, the following third hypothesis is formulated.

**H3:** Different types of environmental regulations have different effects on marine green economic efficiency.

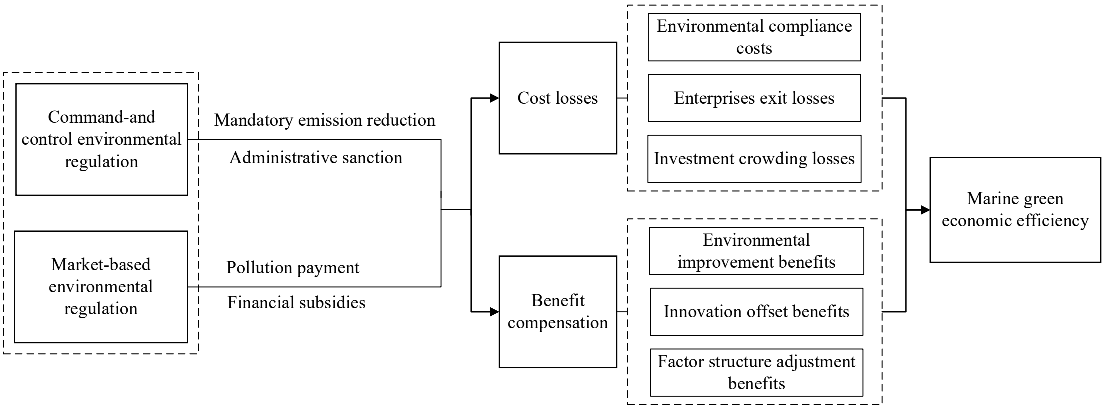


**Fig. 2.** The impact path of environmental regulation on the marine green economic efficiency.

# 3. Research methods and data

## 3.1 Panel smooth transition model

This paper explores the heterogeneous effects of two environmental regulatory tools on the efficiency of the marine green economy under the level of technological innovation, FDI and industrial structure, as well as the threshold effects of these factors. There are two mainstream approaches to testing for threshold effects. The first is the Panel Threshold Regression (PTR) model [47], which has jumps on both sides of the threshold. The second is the Panel Smoothed Transition Regression (PSTR) [48], where the transition is gradual on both sides of the threshold. Considering the nonlinearity and continuity of the mechanistic transition of environmental regulation on the efficiency of the marine green economy, this paper adopts the PSTR model. The specific model settings are as follows:

$$mgee_{it} = \mu_i + \beta_0 cer_{it} + \beta_1 cer_{it} g(q_{it}; \gamma, c) + u_{it} \qquad (1)$$

$$mgee_{it} = \mu_i + \beta_0 mer_{it} + \beta_1 mer_{it} g(q_{it}; \gamma, c) + u_{it} \qquad (2)$$

Where $i = 1,2,3 \ldots \ldots \mathrm{N}$ and $t = 1,2,3 \ldots \ldots T$ are the numbers of cross-section and time dimensions of the panel, respectively. $\mu_i$ denotes fixed effect factors. Explained variable $mgee_{it}$ represents marine green economic efficiency in each of the coastal regions in China. Explanatory variable $cer_{it}$ represents command-and-control environmental regulation, and $mer_{it}$represents market-based environmental regulation. $\mathrm{g}(q_{it}; \gamma, c)$ is the smooth continuous transition function of $q_{it}$, which is the threshold variable corresponding to industrial structure, technological innovation level and FDI intensity in this study. The nexus between environmental regulation and marine green economic efficiency is specified by the parameter $\beta_0$ in the low regime (when $\mathrm{g}(.) = 0$) and the impact of environmental regulation on marine green economic efficiency equal $\beta_0 + \beta_1$ when $\mathrm{g}(.) = 1$ in the high regime. The logistic of the transition function is seen in Eq. (3).

$$\mathrm{g}(q_{it}; \gamma, c) = \left(1 + \exp\left(-\gamma \prod_{k=1}^{m} (q_{it} - c_k)\right)\right)^{-1}, \gamma > 0, c_1 \leqslant c_2 \leqslant \cdots \leqslant c_m \quad (3)$$

$\mathrm{g}(q_{it}; \gamma, c)$ can have a value between 0 and 1, which is associated with the threshold variable ($q_{it}$), the threshold parameter ($c$), and the slope of the transition function ($\gamma$). $\gamma$ is the smoothness parameter portraying the speed of transition from one regime to another and $m$ is the number of thresholds between the two extreme regimes within a given transition function $\mathrm{g}(.)$.

The first step in setting a PSTR model is to test the linearity. Since the transition function in the model contains unknown parameters $\gamma$ and c, this paper replaces the transition equation with the first-order Taylor formula [48]. The model expression is transformed into the following auxiliary regression equation:

$$y_{it} = \mu_i + \beta_0 x_{it} + \beta_1 x_{it} q_{it} + \beta_2 x_{it} q_{it}^2 + \cdots + \beta_m x_{it} q_{it}^m + u_{it} \quad (4)$$

Therefore, testing the linearity of the PSTR model is equivalent to testing $H_0^*: \beta_0 = \beta_1 = \cdots = \beta_m = 0$in Eq. (4). Then the Wald tests, Fisher tests, and Likelihood Ratio tests [49] are employed to test the hypotheses, and their statistics are defined as follows:

$$LM_w = \frac{TN(SSR_0 - SSR_1)}{SSR_0} \quad (5)$$

$$LM_F = \frac{TN(SSR_0 - SSR_1)/k}{SSR_0/(TN - N - k)} \quad (6)$$

$$LR = -2[\log(SSR_1) - \log(SSR_0)] \quad (7)$$

If the linearity test rejects the null hypothesis, a remaining no linearity test is required for the existence of one or at least two transition functions. Similar to the linearity test, the auxiliary regression function is constructed by Taylor expansion. The Wald, Fisher, and Likelihood Ratio tests are used until the null hypothesis $H_0: r = r^*$ cannot be rejected. Then, $r^*$ is the optimal number of the PSTR model transition function.

## 3.2 Variable selection

### *3.2.1 Explained variable*

The explained variable is marine green economic efficiency (MGEE). Referring to Zheng et al. [2], this paper adopts the non-oriented super-efficiency slack-based measure model (super-SBM) to evaluate the marine green economic efficiency of 11 coastal provinces and cities in China using Matlab R2021a software. With reference to the index system constructed by Ren et al. [12], the specific input and output indicators are selected as follows (Table 1):

(1) Input indicators include capital investment, labor and energy input [50]. The marine economic capital stock is used as the capital investment indicator; the number of sea-related employees as the labor input indicator and marine energy consumption as the energy input indicator.

(2) Output indicators include both desirable output and undesirable output. The desirable output is the gross ocean product of each city; the undesirable output is measured by three secondary indicators including marine industrial wastewater discharge, marine industrial sulfur dioxide discharge and marine industrial solid waste [5].

**Table 1**

Evaluation Index System of Marine Green Economic Efficiency.

| Variable | Primary indicator | Secondary indicator | Variable formula | Source |
|---|---|---|---|---|
| input variable | capital input | marine capital stock (100 million yuan) | (GOP /GDP) * capital stock | China Statistical Yearbook |
| | labor input | ocean-related employment (10,000 persons) | （Directly available data） | China Marine Economic Statistical Yearbook |
| | energy input | marine energy consumption (10 kilotons of standard coal) | (GOP /GDP) * energy consumption | China Energy Statistical Yearbook |
| output variable | desirable output | gross ocean product (100 million yuan) | （Directly available data） | China Marine Economic Statistical Yearbook |
| | undesirable output | marine industrial wastewater discharge (10 kilotons) | (GOP /GDP) * industrial wastewater discharge | China Environmental Statistical Yearbook |
| | | marine industrial sulfur dioxide discharge (10 kilotons) | (GOP /GDP) * industrial sulfur dioxide discharge | China Environmental Statistical Yearbook |
| | | marine industrial solid waste (10 kilotons) | (GOP /GDP) *industrial solid waste | China Environmental Statistical Yearbook |

*3.2.2 Explanatory variable*

The explanatory variable is the two types of environmental regulation tools, namely command-and-control environmental regulation (CER) and market-based environmental regulation (MER). CER is an environmental regulation tool by national administrative agencies to achieve environmental governance goals by formulating laws and regulations, environmental standards, or using administrative power to forcibly intervene in various environmental behaviors. To highlight the disciplinary and mandatory features of CER, this study chose to quantify it in terms of the number of regional environmental administrative penalty cases [51,52]. MER is an environmental regulation instrument that gives full play to the role of market incentives. It links the costs and benefits of enterprises with their environmental management behaviors through measures such as environmental taxes, environmental management investments and trading permits. Considering data availability, MER is calculated based on the investment amount of environmental protection acceptance projects [5,53].

#### *3.2.3 Threshold variable*

Marine industrial structure (MIS), marine technology innovation (MTI) and foreign direct investment (FDI) are selected as threshold variables. The ration of the output value of the tertiary industry to the secondary industry is used to measure MIS, which clearly shows the evolution direction of the industrial structure [54]. The number of marine technology patent authorizations is selected to represent the level of marine technological innovation, which directly reflects the level of technological innovation in a region [5]. FDI intensity is expressed as a share of FDI in regional GOP.

### 3.3 Study area and data sources

The study area includes the following 11 coastal provinces and cities in China with advantages in both geography and marine economy: Liaoning, Hebei, Shandong, Tianjin, Shanghai, Jiangsu, Zhejiang, Fujian, Guangdong, Guangxi and Hainan. The data are all collected from the 2008-2018 "China Statistical Yearbook", "China Marine Economy Statistical Yearbook", "China Environmental Statistical Yearbook" and "China Energy Statistical Yearbook".

## 4. Empirical results

### 4.1 Evolution of marine green economic efficiency

Fig. 3 shows the changing trends of the mean values of MGEE, CER and MER in China's 11 coastal provinces and cities from 2008 to 2018. The specific analysis of the three indicators is as follows:

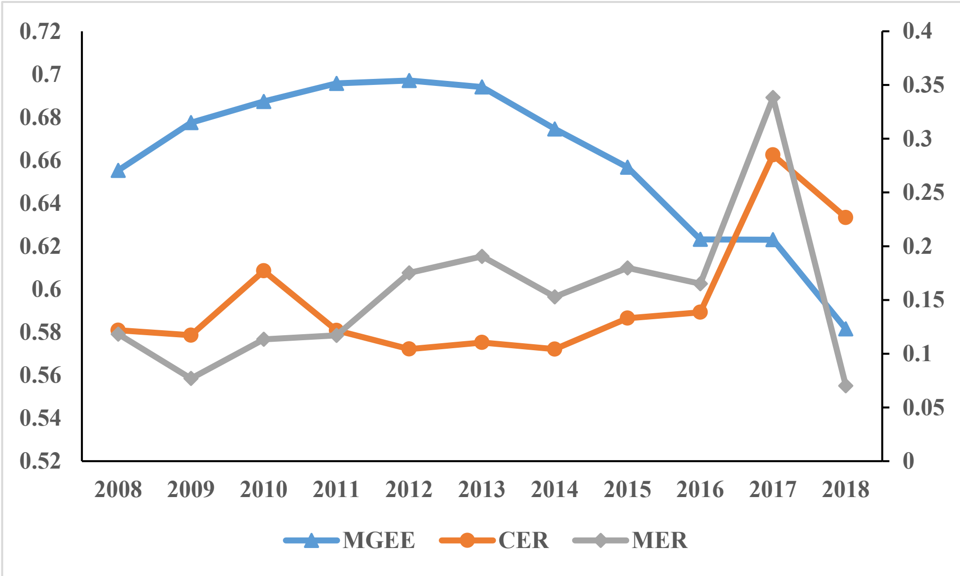


**Fig. 3.** Changes of MGEE, CER and MER of 11 coastal provinces and cities in China.

The average intensities of CER and MER in 11 coastal provinces and cities in China shows a fluctuating upward trend in general, with a significant decrease in 2017. From 2008 to 2017, the average marine green economic efficiency presents a changing trend, as in the figure: it continued to increase from 2008 to 2012, and then gradually decreased.

### 4.2 Linearity tests

This paper uses Matlab R2021a software to test and estimate the PSTR model. Before estimating the PSTR model, a linear test was performed to determine whether there was a nonlinear relationship between different environmental regulation tools and marine green economic efficiency under the influence of different transition variables. As can be seen from the linearity test results in Table 2, all models reject the null hypothesis at the 1% significance level, which means that they are nonlinear and have at least one transition function. Then, the remaining nonlinearity test was carried out, and the results show that none of the models reject the null hypothesis, indicating that all models are suitable for the PSTR model with a single transition function. The current study then determined the number of threshold parameters for each PSTR model. The Akaike criterion (AIC) and Bayesian Criterion (BIC) values for each model were calculated for $m = 1$ and $m = 2$ under the condition that the number of transfer functions is $r = 1$. According to the results (Table 3), $m = 1$ is optimal because the AIC and BIC are the minimum. Therefore, the best setting for the model is $r = 1$ and $m = 1$.

**Table 2**

Tests for linearity and remaining no linearity in the PSTR model.

| Model | transition variable | Linearity test （$H_0$： r = 0； $H_1$： r = 1） | | | Remaining no linearity test （$H_0$： r = 1； $H_1$： r = 2） | | |
|---|---|---|---|---|---|---|---|
| | | $LM_w$ | $LM_F$ | LR | $LM_w$ | $LM_F$ | LR |
| $A_1$ | MIS | 20.059*** | 21.661*** | 21.932*** | 0.104 | 0.092 | 0.104 |
| | | （0.000） | （0.000） | （0.000） | （0.747） | （0.762） | （0.747） |
| $B_1$ | | 28.459*** | 33.520*** | 32.444*** | 0.000 | 0.000 | 0.000 |
| | | （0.000） | （0.000） | （0.000） | （0.993） | （0.994） | （0.993） |
| $A_2$ | MTI | 10.549*** | 10.410*** | 11.037*** | 0.341 | 0.302 | 0.341 |
| | | （0.001） | （0.002） | （0.001） | （0.559） | （0.584） | （0.559） |
| $B_2$ | | 13.370*** | 13.540*** | 14.168*** | 0.011 | 0.010 | 0.011 |
| | | （0.000） | （0.000） | （0.000） | （0.916） | （0.922） | （0.916） |
| $A_3$ | FDI | 29.322*** | 34.862*** | 33.579*** | 2.431 | 2.194 | 2.456 |
| | | （0.000） | （0.000） | （0.000） | （0.119） | （0.142） | （0.117） |
| $B_3$ | | 17.439*** | 18.354*** | 18.831*** | 0.042 | 0.037 | 0.042 |
| | | （0.000） | （0.000） | （0.000） | （0.838） | （0.847） | （0.838） |

*Note*: (1) ***, **, and * denote 1%, 5%, and 10% significance levels, respectively, and the P values corresponding to the statistics are in brackets. (2) $A_i$ and $B_i$ represent models in which the explanatory variables are command-and-control environmental regulation and market-based environmental regulation, respectively.

**Table 3**

Determination of the number of optimal threshold parameters.

| Model | transition variable | r | $m$ | AIC | BIC | Final Results |
|---|---|---|---|---|---|---|

| | | | | | | |
|---|---|---|---|---|---|---|
| $A_1$ | MIS | 1 | 1 | -2.811 | -2.718 | m=1 |
| | | | 2 | -2.783 | -2.667 | |
| $B_1$ | | 1 | 1 | -2.899 | -2.806 | m=1 |
| | | | 2 | -2.874 | -2.758 | |
| $A_2$ | MTI | 1 | 1 | -2.725 | -2.633 | m=1 |
| | | | 2 | -2.700 | -2.584 | |
| $B_2$ | | 1 | 1 | -2.775 | -2.683 | m=1 |
| | | | 2 | -2.751 | -2.635 | |
| $A_3$ | FDI | 1 | 1 | -2.922 | -2.830 | m=1 |
| | | | 2 | -2.874 | -2.758 | |
| $B_3$ | | 1 | 1 | -2.914 | -2.799 | m=1 |
| | | | 2 | -2.811 | -2.718 | |

### 4.3 PSTR estimation results

This paper draws on the method of Gonzalez et al. [48] for estimating the PSTR model. Firstly, fixed effects are eliminated by removing individual-specific means. Then, the grid search method is used to find the threshold parameter c and the threshold slope $\gamma$ of the transition function when the residual sum of squares (RSS) of the correlation model is minimized. Finally, Nonlinear Least Squares (NLS) is used to estimate the parameters. The estimated results are shown in Table 4.

**Table 4**
Results of PSTR models.

| Model | transition variable | $\gamma$ | c | $\beta_0$ | $\beta_1$ | RSS | AIC | BIC |
|---|---|---|---|---|---|---|---|---|
| $A_1$ | MIS | 2.358 | 1.874 | -1.180*** (-5.732) | 11.152*** (6.269) | 6.533 | 2.811 | 2.718 |
| $B_1$ | | 1.345 | 1.371 | -3.240*** (-7.479) | 9.835*** (8.051) | 5.981 | 2.899 | 2.806 |
| $A_2$ | MTI | 4.079 | 3.046 | -1.298*** | 1.434*** | 7.117 | 2.725 | 2.633 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | （-3.976） | （3.763） | | | |
| $B_2$ | | 2.820 | 2.945 | -1.126*** （-3.025） | 1.547*** （4.323） | 6.769 | 2.775 | 2.683 |
| $A_3$ | FDI | 11.618 | 0.172 | -6.029*** （-7.422） | 6.002*** （7.516） | 5.844 | 2.922 | 2.830 |
| $B_3$ | | 10.496 | 0.390 | -1.097*** （-3.462） | 1.622*** （5.194） | 6.533 | 2.811 | 2.718 |

*Note*: ***, **, and * represent significance at confidence levels of 1%, 5%, and 10%, respectively, and the t values corresponding to the statistics are in brackets.

As shown in Table 4, the regression coefficients of all models are significant with a confidence level of 1%, indicating that under the setting of different threshold variables, both CER and MER have dual-regime effects on MGEE. Specifically, except for model $A_3$, the influence coefficients of CER and MER on MGEE changed from negative to positive, and threshold variable transitioned from low state to high state. However, model $A_3$ only shows adverse effects, but there is a clear difference in the magnitude of the influence coefficients. Under the same threshold variable, the threshold parameters and threshold slopes of the two types of environmental regulations are significantly different, indicating that CER and MER have noticeable heterogeneous effects on MGEE.

# 5 Results discussion

## 5.1 Analysis of the impact of CER and MER on MGEE under the evolution of MIS

(1) According to the estimation results of model $A_1$ and model $B_1$, when MIS is lower than the threshold, the model tends to a low regime, both CER and MER have a significant negative effect on MGEE. The low level of marine industry structure means that the secondary industry, which has the most polluting companies, accounts for a relatively high proportion of the marine industry layout. With the increasing environmental regulation intensity, polluting enterprises are the first to be affected.

From the perspective of "compliance costs", levying pollution tax or other mandatory emission reduction measures will bring high environmental costs to enterprises, which may divert the funds away for enterprises to expand production and invest in innovation [55]. Although the intensity of pollution emission has eased, it is far from offsetting the negative impact of production cuts. In addition, it is expected that environmental regulation will be further strengthened in the future, and some polluting enterprises may take measures to increase pollution discharge in order to maximize the current benefits [56], which will harm marine green economic efficiency. With the upgrading of industry structure, both CER and MER have a significant positive impact on MGEE. It may benefit from the "service-oriented" transformation of the industrial structure with some industrial enterprises shifting to the tertiary industry, which is dominated by clean industries with fewer environmental restrictions [57]. In addition, stricter environmental regulation encourages marine production factors to withdraw from the low-efficiency and high-consumption industrial chain links, raises the entry threshold for polluting enterprises, and further enhances the comparative advantage of the marine tertiary industry. At the same time, the higher the level of industrial structure, the more pronounced the benefits of technological innovation, especially green innovation. In short, in order to give full play to the positive role of environmental regulation in improving marine green economic efficiency, enterprises need to continuously move towards the high-end links of the industrial value chain [58].

(2) Combining the estimation results (Table 4) and the transition function diagram (Fig. 4), it can be seen that when MIS is used as the threshold variable, the heterogeneous effects of CER and MER on MGEE is mainly reflected in three aspects, including the influence coefficient, transition speed and threshold. From the impact coefficient, the negative impact of CER on MGEE under low MIS conditions is smaller than that of MER and vice versa under high MIS conditions. In other words, no matter how the regional industrial structure evolves, CER, which regulates corporate behavior through coercive means has a greater impact on MGEE. From the perspective of transition speed and threshold, MER can realize the transition from inhibiting to promoting MGEE earlier, but at a slower speed. In addition, most of the sample

observations are located on the left side of the threshold, indicating that China still has room for improvement in the positive impact of environmental regulation on improving MGEE through industrial structure adjustment.

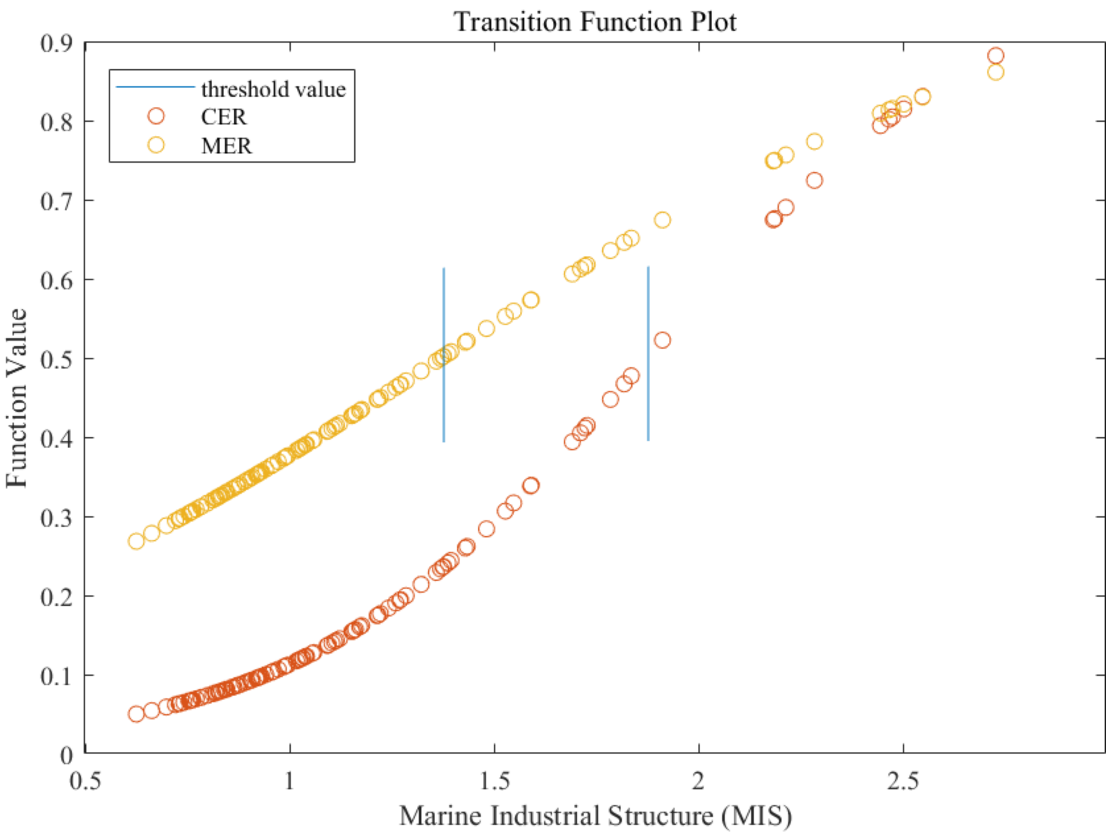


**Fig. 4.** The logistic relation between the MIS and transition functions.

### 5.2 Analysis of the impact of CER and MER on MGEE under the evolution of MTI

(1) According to the estimation results of model $A_2$ and model $B_2$, both CER and MER have a significant negative effect on MGEE in low MTI regime and a positive effect in high MTI regime. Technological innovation can significantly improve the efficiency of factor utilization and is regarded as the primary means for enterprises to maintain a competitive advantage. Under the circumstance that innovation level of marine science and technology is low, most enterprises still use traditional production techniques for production activities. It will inevitably lead to waste of resources and environmental pollution, and it is not conducive to marine green economic efficiency. At the same time, in the face of increasingly stringent environmental protection policies

and pollution discharge restrictions, companies have to readjust their production strategies and find additional funds to deal with environmental costs. In addition, under the dual pressure of fierce market competition and supervision, some low-efficiency and high-polluting enterprises are forced to shut down or withdraw from the market, which is not conducive to regional marine economic output and regional industrial competitiveness, thereby inhibiting the improvement of marine green economic efficiency [59]. With the development of marine technological innovation, the model shifts to a high regime that increases production efficiency and reduces pollution emission. environmental costs can be offset by the economic benefits of increased technological levels and firm productivity. Environmental regulation can stimulate the effect of technology diffusion, enhance the competitiveness of regional industrial, and help strengthen the cumulative effect of ecological benefits brought about by technological innovation [5]. In a word, with the strengthening of environmental regulation, the competitive advantage established by corporate innovation, especially green innovation, has been further expanded [60] and the net benefit brought by it has gradually changed the impact of environmental regulation on marine green economic efficiency from inhibition to promotion.

（2）As shown in Fig. 5, the heterogeneity of the effects of CER and MER on MGEE is not evident with the evolution of MTI. Careful analysis shows that CER has a greater negative impact on MGEE under the low MTI regime and a slightly positive impact under the high MTI regime. It suggests that regardless of the level of MTI, the effect of environmental regulation by collecting pollution discharge tax and investing in environmental protection projects is always better than regulating corporate behavior by coercive means. In terms of transition speed and threshold, with a relatively small slope parameter of 2.820 and a relatively small threshold of 2.945, MER can achieve an earlier, but slower, transition to the promotion of MGEE. In addition, most of the sample observations are located in the high MTI regime, indicating that most of the coastal areas of China have taken measures to improve the level of marine technological innovation in order to achieve the policy objective of environmental regulation tools to promote MGEE.

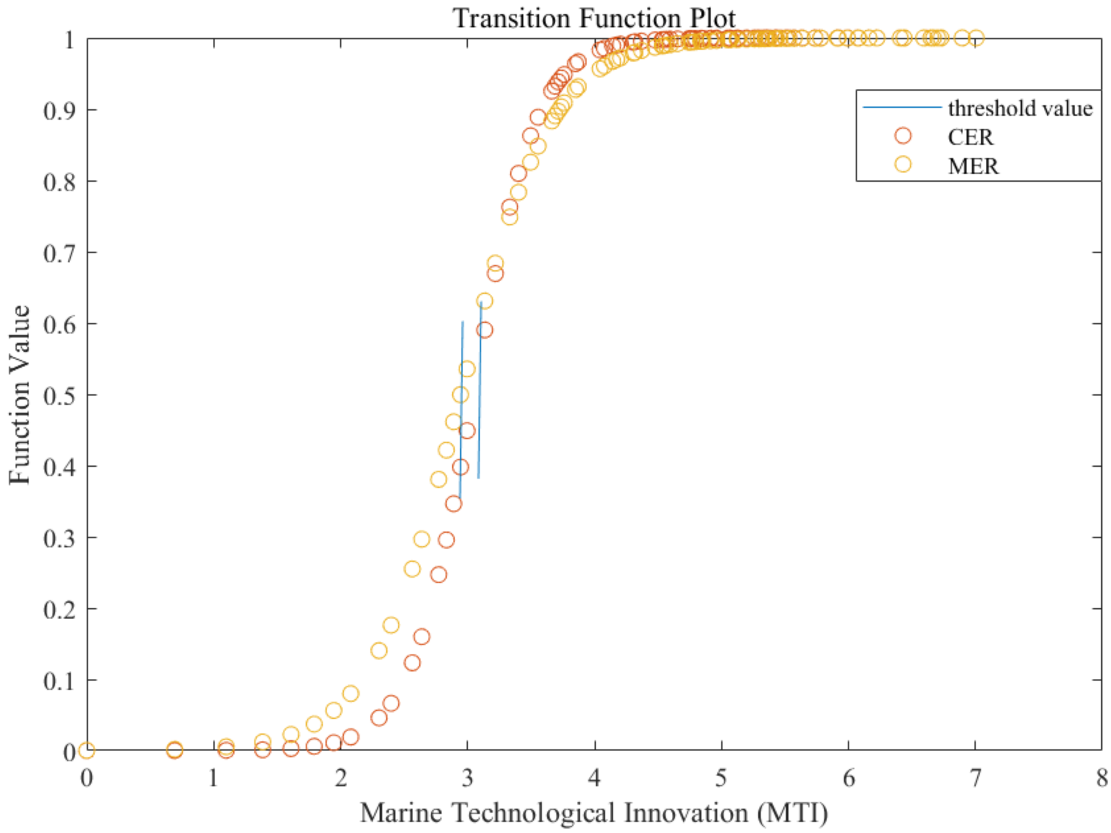


**Fig. 5.** The logistic relation between the MTI and transition functions.

### 5.3 Analysis of the impact of CER and MER on MGEE under the evolution of FDI

(1) The estimation results of model $A_3$ and model $B_3$ show that both CER and MER have a significant inhibitory effect on MGEE when the model is in the low FDI regime. With the increase of FDI intensity, the impact of environmental regulation on MGEE tends to be positive, but there are significant differences in the impact of different environmental regulation tools on MGEE. The marine economy is characterized by high degree of openness and competitiveness. The technology spillover effect is more prominent, and it is easily affected by the advanced technologies and experience of other marine countries. In the initial stage of foreign capital inflow, the main purpose of FDI inflow is to seek cheap resources and labor [61]., The technology blockade and protection cannot bring the "demonstration effect" to local enterprises, resulting in a "pollution heaven" effect. In addition, considering that FDI is

one of the indicators of government performance, in order to attract more foreign investment, the government is likely to compromise in the contest between environmental protection and economic growth [59], resulting in weak enforcement of environmental regulations and negative impact on marine green economic efficiency. With the expansion of foreign investment and the deepening of technical cooperation, the technology spillover effect has become notable [2], which is of great significance to the upgrading of marine technology and the improvement of industrial competitiveness. At the same time, strict environmental policies can filter FDI and increase the proportion of green production enterprises and green technology innovation. Under the combined effect of environmental supervision and market competition, regional green technology progress and industrial green upgrades promote the positive development of the impact of environmental regulation on marine green economic.

(2) With the development of FDI, the effects of CER and MER on MGEE exhibit moderate differences. Firstly, the effect of MER on MGEE shows a gradual transition from the inhibitory effect under the low FDI regime to the promotion effect under the high FDI regime, while the inhibitory effect of CER on MGEE persists, with the elasticity rising from -6.029 to -0.027[2]. This may be due to the fact that the government formulates and implements CER, which imposes mandatory constraints on the polluting production behavior of enterprises, which has a long-term adverse effect on the regional marine economic output, which in turn exerts an inhibitory effect on the improvement of MGEE. The implementation of MER has brought additional cost burdens to enterprises, which to some extent squeezes the funds for expanding production and R&D investment. Therefore, it inhibits MGEE at an early stage. However, with the increase of FDI intensity, the compensation benefits of innovation have become apparent and gradually covered the environmental cost, and eventually play a positive role in promoting MGEE. In addition, the transition speed of model $A_3$ is significantly greater than that of model $B_3$ (Fig. 6), indicating that with the increase of FDI intensity,

[2] This value is calculated by the formula "$\beta_0 + \beta_1$".

the influence of CER on MGEE changes faster than that of MER; meanwhile, the threshold of model $A_3$ is lower than that of model $B_3$, which means the positive impact of CER on MGEE appears earlier.

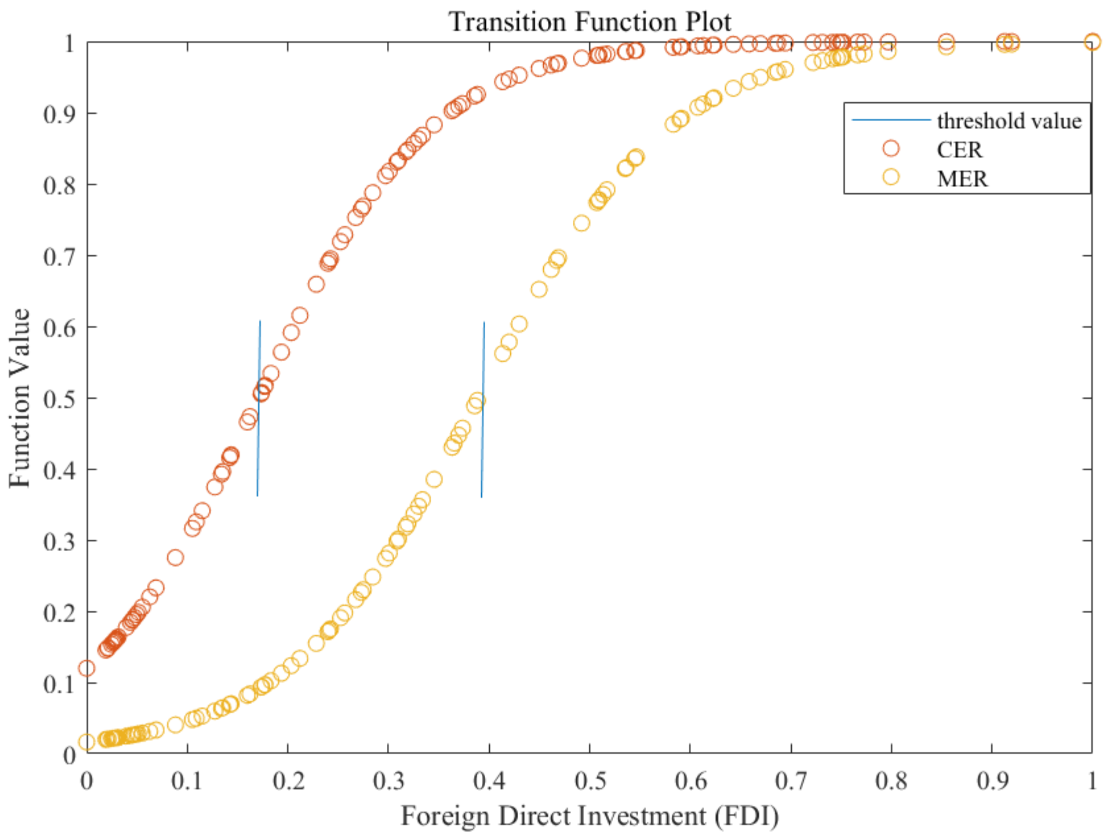


**Fig. 6.** The logistic relation between the FDI and transition functions.

# 6. Conclusions and recommendations

## 6.1 Conclusions and research limitations

Based on the data from 11 coastal provinces and cities in China from 2008 to 2018, this paper adopts the non-oriented SBM model to measure the regional marine green economic efficiency, and empirically tests the nonlinear relationship between heterogeneous environmental regulations and marine green economic efficiency using the PSTR model. The main conclusions are as follows:

(1) Most of the current research on the development of marine economy has been carried out from the perspective of economic efficiency. Based on the current "green development" demands, this study re-examines the development of the marine

economy in China's coastal provinces and cities from the perspective of marine green economic efficiency. The average efficiency of China's marine green economy shows a complex trend of change, presenting a continuous increase from 2008 to 2012, and then a gradual decline. To a certain extent, this indicates that the possibility of improving the efficiency of China's marine green economy is very high.

(2) In contrast to the linear analytical framework of the existing literature, this study adopts the PSTR model to investigate the nonlinear impact of environmental regulation on the marine green economy and the transition mechanism. Under the setting of different transition variables, there is a dual-zone effect of market-based and command-and-control environmental regulations on marine green economic efficiency, that is, there is a nonlinear relationship in the transition between high regime and low regime. On the one hand, as the marine industrial structure (MIS) and marine technology innovation (MTI) exceed certain threshold, both CER and MER have contributed to the improvement of MGEE. When FDI is considered as a transition variable, CER consistently suppresses the growth of MGEE. However, as FDI exceeds the threshold, the effect of MER on it gradually changes from negative to positive as FDI rises over the threshold. On the other hand, there is a big difference in how the two environmental regulations affect MGEE. According to the influence coefficient, when MTI and FDI are below the threshold, the adverse effect of CER on MGEE is greater than that of MER, but when MTI exceeds the threshold, the promoting effect of MER on MGEE is better than that of CER. Furthermore, the promotion of MGEE by CER becomes greater after the MIS threshold is exceeded. In terms of conversion speed and threshold，under different transition variable settings, the transition of the effect of CER on MGEE is faster than that of MER; when MIS and MTI are used as threshold variables, the threshold of the nonlinear relationship between MER and MGEE is smaller than that of CER.

This paper explores the impact of heterogeneous environmental regulation tools on the growth of the marine green economy from the perspective of marine green economic efficiency. However, given the accessibility of data and the diversity of environmental regulation mechanisms, this work has several limitations in that need to be deepened and addressed in future studies. Firstly, in the process of measuring the marine green economic efficiency, the official input-output statistics of the maritime sector have not been made public and can only be estimated based on relevant regional industry-wide data, which may affect the accuracy and reliability of the measurement results. Secondly, each type of environmental policy tool contains multiple sub-tools with different degrees of adaptability and action goals, and correspondingly different environmental consequences. In order to determine the intensity of a specific form of environmental regulation, this paper uses representative indicators exclusively. Additional environmental policy instruments may be identified in subsequent research to provide appropriate remedies for the specific environmental problems we face.

### 6.2 Recommendations

Command-and-control environmental regulation emphasizes the mandatory and punitive nature of regulatory instruments, while market-based environmental regulation emphasizes incentives and flexibility. The adaptability of these two instruments and their impact on marine green economic efficiency vary widely at different stages of regional development. Any combination of regional environmental laws must consider these differences.

(1) The research findings of this paper show that CER and MER have a considerable promoting effect on MGEE after a certain degree of marine industry structure (MIS) and marine technology innovation (MTI). Therefore, improving the industrial structure and stimulating innovation have become the preconditions for the economic promotion of environmental regulation. First and foremost, local governments should formulate reasonable industrial policies and actively guide the development of low-energy consumption, environmental protection, and high-tech industries based on their own resource endowments. At the same time, raise funds for the research and development and utilization of pollution control technologies to promote the technological upgrading of enterprises and improve green economic efficiency. Secondly, the effective combination of environmental regulation means is

the "catalyst" for the transformation of the marine green economy. In regions with high levels of marine innovation MER plays a more significant role in promoting the effectiveness of the marine green economy. To this end, local governments should give priority to the formulation and implementation of market-based policies, and give full play to their external effects through environmental taxes, and emission trading. In contrast, CER plays a stronger role in promoting the marine green economic efficiency in regions with higher industrial structure. In these areas, the government should focus on strengthening the supervision of high-pollution and high-energy consuming enterprises, and at the same time increasing penalties so as to achieve the expected pollution control effect of command-and-control environmental regulation.

(2) The results show that when FDI exceeds the threshold, market-based environmental regulation has a significant promoting effect on improving the marine green economic efficiency, while command-and-control environmental regulation always maintains an inhibitory effect. Therefore, in areas with high foreign investment, excessive government intervention in the economic activities of enterprises should be avoided, and market-based environmental regulation should be gradually strengthened in terms of scope of application and regulation. In addition, in order to attract more "green" foreign investment and actively improve the marine green economic efficiency, tax relief and green credit incentives should be vigorously promoted, green subsidies should be increased and foreign enterprises should be encouraged to develop into low-pollution and high-end R&D areas.

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