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Measuring Chinese Marine Environmental Efficiency: A Spatiotemporal Pattern Analysis

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Abstract: Environmental efficiency standards are often used to evaluate the costs of oceanic economic development. A variety of statistical analyses were applied in this study to quantify the marine environmental efficiency of 11 Chinese coastal provinces and municipalities between 2000 and 2014. Results initially reveal that environmental efficiency measures that incorporate undesirable outputs are more consistent with real production conditions and thus the use of marine economic and environmental efficiencies supplement and complement one another. Second, overall marine environmental efficiency across China tends to be low and can be spatially characterized by a transformation such that the inefficiencies noted in 2000 have subsequently been transformed to comprise a three-tiered structure that encompasses northern, central, and southern cores. Third, variation in absolute and relative marine environmental efficiency differences for the coastal regions of China have been consistent over time; values initially decreased before increasing again in a fluctuating manner over the time period of this analysis. Fourth, data show that the Pearl River Delta area has experienced the highest rate of change in marine environmental efficiency over time when economic zones are used as basic research units, although values have nevertheless fluctuated significantly. Fifth, values for total factor productivity as well as technical efficiency and change across the Chinese marine economy all fluctuated over time but increased. Data show that changes in marine environmental efficiency across China can primarily be attributed to progress in marine science and technology. Finally, levels of capital investment and marine industrial pollution intensity are not significantly correlated with marine environmental efficiency. Indeed, both marine industrial structural levels and environmental protection technologies have had a positive effect on environmental efficiency while levels of investment in marine scientific research as well as the scale of economic development, the marine economy, and the degree of external openness have all exerted negative effects on this key variable.

Keywords: marine environmental efficiency; undesirable output; SBM-Malmquist model; Tobit regression analysis

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1 Introduction

Rapid economic growth exacerbates environmental problems. As this issue is of great concern to society in general, a large volume of research has been carried out with the aim of clarifying the most effective approaches to coordinate environmental and economic development. Although China boasts a wealth of marine resources, effective development imposes a range of stresses on the marine environment that exert different regional impacts. The national 'Thirteenth Five-Year Plan' noted that 'developing an assessment of China's coastal ecosystem and early warning analysis are important measures for preserving marine environments;

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there is an urgent need for immediate protection against the development trends and ecological risks posed to China's coastal environment' (Meng et al., 2015); in this context, the plan also recommended the use of environmental assessments to predict and mitigate future impacts on the national coastal environment.

Derived from physics, our use of the term efficiency refers to situations where no economic resources are wasted and their use has been maximized to achieve greatest level of possible satisfaction (Zhao, 2011) under defined input and technical conditions. Environmental efficiency therefore refers to resources and costs in this context that are consumed during the processes that underlie economic development; this concept therefore incorporates actual, potential, and minimum pollution emissions under specified input-output conditions as well as the economic output of a given entity (Yang et al., 2010). This means that marine environmental efficiency measures are often applied to quantify the costs imposed on these settings by economic development and comprise comprehensive assessment indices that can be utilized to assess the level of coordination between the economy and natural ecosystems (Yang et al., 2012). These measures also provide important references to assess the extent to which marine ecosystems have been exploited as well as how extensively resources and the economy have been developed in these areas; index values will therefore be closely correlated with a range of factors including resource and energy utilization ratios, input and output effects, pollutant emissions, and management capabilities. Research that assesses marine environmental efficiency, trends in development, the factors that influence changes, and the mechanisms that underlie these variables can therefore also elucidate the principles that govern the modifications being made to coastal marine economies and ecosystems, and also provide key statistical reference data for these sectors. Information of this type informs adaptive decision-making, promotes the green development of the marine economy, and thus augments the ecological conditions of Chinese coastal regions.

International research on environmental efficiency has tended to emphasize industrial issues. In one early study, Reinhard et al. (1999) presented an analysis of dairy farms in the Netherlands and argued that units that utilize new technologies are more environmentally efficient than their more traditional counterparts (Reinhard et al., 1999). Similarly, Kerr and Ryan (2001) evaluated the environmental efficiency of Fuji Xerox and determined that recycling production within the copy machine industry does not effectively improve environmental efficiency (Kerr and Ryan, 2001).

Research in this area within China has focused on the issues outlined below.

(1) In terms of research perspective, Fei et al. (2015) performed a material flow analysis utilizing an advanced data envelopment analysis (DEA) model to analyze the economic systems seen in Liaoning Province and undertook a general assessment of their efficiency.

(2) At the regional level, Yang and Ma (2013) carried out a national study that also utilized DEA to analyze the principles governing changes in environmental cost efficiencies and variations in Chinese provincial economic development. In similar work, Liu and Li (2013) applied DEA-slacks-based measure (SBM) and DEA-Chames, Cooper, and Rhodes (CCR) models to assess the environmental and economic efficiencies of 11 western Chinese provinces, while Bai et al. (2013) utilized a SBM- Malmquist-Tobit model to evaluate differences in these variables and the factors that underlie them within nine Yellow River provinces and regions. At the provincial level, Gai et al. (2014) utilized Random FrontierAnalysis and SBM models to analyze environmental efficiencies within Liaoning Province.

(3) In terms of research content, Yang et al. (2012) assessed the resource efficiency of the economic-environmental coordination that characterizes northeastern Chinese cities, while Zhao et al. (2016) analyzed the evolutionary stages and mechanisms that underlie this variable within the coastal region of the country. In similar research, Liu et al. (2015) applied a DEA-Malmquist model to tourism in Chinese coastal regions in order to analyze industrial spatiotemporal evolution, underlying factors, and mechanisms of formation. Hu et al. (2017) also performed a systematic analysis of the spatiotemporal evolutionary changes that characterize the efficiency of the three major tourism sectors within China, scenic areas, hotels, and travel agencies.

It is noteworthy that earlier studies to address environmental efficiency have tended to emphasize specific perspectives such as tourism, industry, or municipalities. Previous work in this area has not assessed the marine environment and the fundamental research units utilized to date have often comprised entire western regions of the country or the whole of China; eastern and coastal areas as well as the three key national coastal economic zones have not been assessed so far in this context. These latter regions are made up of zones established on the basis of the Chinese national 'One Belt, One Road' initiative; it is therefore critical to assess the marine environmental efficiencies of these regions if this major development initiative is to be effective, while research is also key to the coordinated development of the national marine economy and ecological maintenance. Investigations that assess the extent and efficiency of the Chinese marine environment are critical in light of the strategic frameworks established by the 'One Belt One Road' and 'Ocean Power' initiatives, and knowledge is urgently required to inform the future development of the national marine economy and environment. A comprehensive assessment of the Chinese coastal marine economy and environment between 2000 and 2014 is therefore presented in this paper alongside an analysis of their coupled relationship. The ability of these environments to mitigate the harmful effects of undesirable outputs is also assessed, including removal of the 'three wastes' (i.e., waste gas, water, and industrial residue), alongside effectiveness. A number of deficiencies in environmental preservation technologies and scale efficiencies are identified by this analysis, and a series of recommendations for the improvement of coastal regions are proposed that could be implemented within the context of the 'Thirteenth Five-Year Plan'. The development status of marine environmental efficiency in coastal regions is also assessed in this study alongside an evaluation of the spatial patterns and factors that characterize and influence these changes. Research on marine environmental efficiency is necessary to inform ecological protection, achieve viable resource utilization, and promote sustainable development within the coastal regions of China.

2 Methodology

2.1 The SBM model including undesirable outputs

Research to date in this area has shown that DEA comprises a very effective tool for measuring the efficiency of decision-making units; this approach therefore provides a suitable systematic analytical method for assessing the input-output ratios of variables (Charnes et al., 1978). However, although both CCR and Baker, Chames, and Cooper (BCC) models are traditional DEA approaches and have desirable outputs, undesirable components are ignored, and issues related to input-output slack can not be resolved. In order to mitigate these issues, Tone (2003) proposed use of the SBM model which includes a slack variable within the objective function and therefore resolves the problems inherent to traditional models. As this approach is considered broadly reliable for assessing environmental and ecological efficiencies (Li and Shi, 2014), the SBM model was applied in this analysis to assess marine environmental efficiency, as follows:

$$\rho^* = \frac{1 - \frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{io}}}{1 + \frac{1}{s_1 + s_2}\left(\sum_{r=1}^{s_1}\frac{s_r^g}{y_{ro}^g} + \sum_{r=1}^{s_2}\frac{s_r^b}{y_{ro}^b}\right)} \tag{1}$$

$$st = \begin{cases} x_0 = X\lambda + \overline{s} \\ y_0^g = Y^g\lambda - s^g \\ z_0^b = Z^b\lambda - s^b \\ s^- \geq 0, s^g \geq 0, s^b \geq 0, \lambda \geq 0 \end{cases} \tag{2}$$

In these expressions, ρ^* denotes marine environmental efficiency, while m, s_1, and s_2 refer to the value of investment as well as desirable and undesirable output factors, respectively. Similarly, $s = (s^-, s^g, s^b)$ denotes slack variables for input as well as desirable and undesirable outputs, respectively, while x, y^g, and z^b , i is the input; r is the output, denote values for inputs as well as desirable and undesirable outputs, respectively, and λ is the weight factor. In this model, '0' denotes the unit being evaluated, while x, y^g, and z^b denote matrices comprised of inputs as well as desirable and undesirable outputs, respectively. The objective function, ρ^*, is therefore dependent on s^-, s^g, and s^b and decreases strictly monotonically when $0 < \rho^* \leq 1$. This means that when $\rho^* = 1$ (i.e., when $s^- = 0$, $s^g = 0$, and $s^b = 0$) production units are completely valid but can be viewed as having lost efficiency when $\rho^* < 1$; in other words, optimizing input volume and desirable outputs means that the volume of undesirable outputs can also be enhanced and marine environmental efficiency increases.

2.2 Malmquist-Luenberger (ML) productivity index model

We applied the ML productivity index in concert with the directional distance functions proposed by Fare and Shepard and consulted the total-factor productivity index proposed by Zhao et al. (2016) in order to further analyze dynamic change characteristics and the decomposition of marine environmental efficiency. Incorporating undesirable outputs, the ML productivity index was established as follows:

$$ML_t^{t+1}=\left[\frac{1+\vec{D}_0^{t}\left(x^t,y^t,z^t;y^t,-z^t\right)}{1+\vec{D}_0^{t}\left(x^{t+1},y^{t+1},z^{t+1};y^{t+1},-z^{t+1}\right)}\times\frac{1+\vec{D}_0^{t+1}\left(x^t,y^t,z^t;y^t,-z^t\right)}{1+\vec{D}_0^{t+1}\left(x^{t+1},y^{t+1},z^{t+1};y^{t+1},-z^{t+1}\right)}\right] \tag{3}$$

In this context, the *ML* index can be decomposed into an efficiency change index, *EFFCH*, and a technical change index, *TECH*, that are correlated via a decomposition function, as follows:

$$ML_t^{t+1}=EFFCH_t^{t+1}\times TECH_t^{t+1} \tag{4}$$

$$EFFCH_t^{t+1}=\frac{1+\vec{D}_0^{t}\left(x^t,y^t,z^t;y^t,-z^t\right)}{1+\vec{D}_0^{t}\left(x^{t+1},y^{t+1},z^{t+1};y^{t+1},-z^{t+1}\right)} \tag{5}$$

$$TECH_t^{t+1}=\left[\frac{1+\vec{D}_0^{t+1}\left(x^t,y^t,z^t;y^t,-z^t\right)}{1+\vec{D}_0^{t}\left(x^{t+1},y^{t+1},z^{t+1};y^{t+1},-z^{t+1}\right)}\times\frac{1+\vec{D}_0^{t+1}\left(x^t,y^t,z^t;y^t,-z^t\right)}{1+\vec{D}_0^{t}\left(x^{t+1},y^{t+1},z^{t+1};y^{t+1},-z^{t+1}\right)}\right] \tag{6}$$

In these expressions, ML_t^{t+1} denotes the total-factor productivity change index for the decision-making unit and therefore the conditions of inter-temporal dynamic change in marine environmental efficiency, while $\vec{D}_0^{t}\left(x^t,y^t,z^t;y^t,-z^t\right)$ and $\vec{D}_0^{t}\left(x^{t+1},y^{t+1},z^{t+1};y^{t+1},-z^{t+1}\right)$ denote decision-making unit distance functions that apply to the technical state at reference time *t* as well as at times *t* and *t*+1. Similarly, $\vec{D}_0^{t+1}\left(x^t,y^t,z^t;y^t,-z^t\right)$ and $\vec{D}_0^{t+1}\left(x^{t+1},y^{t+1},z^{t+1};y^{t+1},-z^{t+1}\right)$ denote the decision-making unit distance functions that apply to the technical state at reference time *t+1* as well as at times *t* and *t*+1, while $EFFCH_t^{t+1}$ denotes the efficiency change index for the decision-making unit between times *t* and *t*+1, and $TECH_t^{t+1}$ denotes the technical change index for the decision-making unit between times *t* and *t*+1. Thus, there has been an improvement in overall productivity when $ML_t^{t+1}>1$, while technical efficiency has increased if $EFFCH_t^{t+1}>1$, and there have been improvements in production technology if $TECH_t^{t+1}>1$. The corresponding efficiencies will be low in all opposite cases.

2.3 Index selection and data sources

The basic production input factors that influence economic activity are capital, labor, and land (Mankiw, 1977). It is noteworthy that production capacity bearing on economic activity in the marine realm is actually more conducive to modern systems research than terrestrial inputs because these environments are the hosts of such activity, and thus their efficiencies are closely related to the value generated by the internal links between inputs and outputs.

We selected the value of fixed investments from coastal areas to represent capital input to assess the marine environmental efficiency input index, we reduced the fixed asset investment amount using an appropriate investment reduction index to eliminate the inflation price factor, and applied the perpetual inventory method to estimate the fixed capital stock (Zhang and Zhang, 2003) using 2000 as the base year, as follows:

$$K_t=I_t+(1-\alpha_t)K_{t-1} \tag{7}$$

In this expression, K_t denotes capital stock in year *t*, while K_{t-1} refers to this variable in year *t*+1, I_t e is fixed asset investment and α_t is the depreciation rate, both in in year *t*. We consulted previous research to derive a 6% depreciation rate (α_t ; Gai et al., 2014; Zhao et al., 2016) and utilized the ratio of marine technical personnel as the labor input variable alongside per-capita marine area, marine farming area for each coastal region, sea salt production capacity, and the port throughput volume index for large-scale coastal ports. We then used weighted results to generate a comprehensive index variable for production capacity that is the result of marine environmental efficiency inputs.

We utilized marine production volume in the output index as in our original data, and used real gross domestic product as our desirable output subsequent to price deflation correction. Previous studies in this area have generally used carbon emission intensity and per capita values as undesirable outputs (Zhan and Feng, 2010); however, as marine industries exhibit unique characteristics that depend on particular environments, we utilized a comprehensive weighting of two indices as our undesirable output variable, direct wastewater emission volume and direct solid waste emission from marine industries.

We then standardized all our data in order to mitigate dimensional influences on results; a linear transformation was applied to achieve this and a new series was generated by mapping the original data between 0.1 and 1 (Liu et al., 2010), as follows:

$$X' = \frac{X - \min_A}{\max_A - \min_A}(new\max_A - new\min_A) + new\min_A \quad (8)$$

In this equation, X' denotes the newly mapped data, while X refers to the original data, $\max_A$ and $\min_A$ denote the maximum and minimum values of the old series, respectively, and newmax_A and newmin_A denote the maximum and minimum values of the new data, respectively.

This paper takes 11 provinces and municipalities in China (excluding Taiwan, Hong Kong and Macao), namely Liaoning, Hebei, Tianjin, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, Guangdong, Guangxi and Hainan. The data used in this study encompass the period between 2001 and 2015 and were sourced from the *China Marine Statistical Yearbook* (State Oceanic Administration, 2001-2015), *Statistics on Investment in Fixed Assets of China*, and the *China Economic and Social Development Statistical Database*. Some data were calculated based on values extracted from the *Statistical Yearbook* (National Bureau of Statistics Fixed Assets Investment Statistics Division, 2000).

3 Results

3.1 Marine economic and environmental efficiency measurements and analysis

We calculated a series of economic efficiency values for Chinese coastal regions between 2000 and 2014 using the software MaxDEA applying both CCR and SBM models but without taking undesirable outputs into account. We then re-calculated these values incorporating undesirable outputs (Qin, 2016) (Fig. 1) and followed this procedure for the remainder of the analysis. Our use of real 'economic efficiency' incorporates the concept of 'environmental efficiency'.

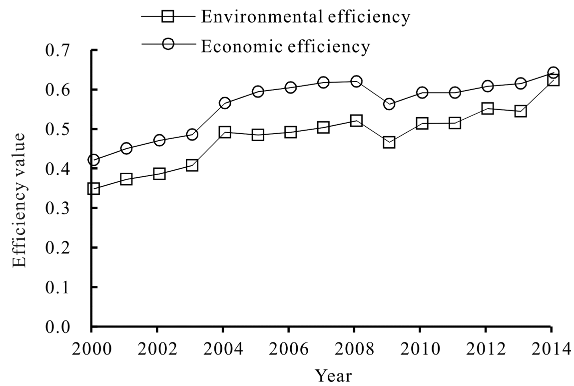

Fig. 1 Temporal variation in marine economic and environmental efficiency values for Chinese coastal areas

The results of this study reveal that both economic and marine environmental efficiency values remained temporally consistent with one another within the coastal areas of China between 2000 and 2014, although the latter always remained lower than the former (Fig. 1). Indeed, values for the two variables were increasingly in pace with each other between 2000 and 2008, rising to their highest rates in 2004, 20.8% and 16.4%, respectively. The rate of change in both variables decreased in 2009 before gradually and moderately increasing again each year between 2010 and 2014; results show that the discrepancy between the two rates gradually decreased to just 0.019 in 2014. It is also the case that values for environmental efficiency incorporating undesirable outputs tend to be lower than those for economic efficiency that do not consider these variables; this suggests that economic efficiency rates that incorporate undesirable outputs tend to be more realistic. In addition, as marine economic development is dependent on resource environments, these two variables tend to supplement and complement one another, changing consistently in step.

Throughout the implementation period of the 'Tenth Five-Year Plan', robust development of the marine economy was extensively promoted within China in order to more effectively garner marine resources. Coastal regions therefore relied on their original environments for the robust development of industries and to increase marine economic and environmental efficiency rates. Similarly, throughout the period of the 'Eleventh Five-Year Plan', energy savings and emissions reduction plans were implemented across China in response to the rapid consumption of resources and environmental pollution. These changes enhanced the country's ability to mitigate environmental issues; at the same time, the environmental efficiency rate declined throughout this period while differences versus the economic efficiency rate increased. As a result of impacts from the global financial crisis on economic trade in coastal regions, both marine economic and environmental efficiency rates declined in 2008, while China has enforced macroeconomic regulations and reassessed the structural optimization of marine industries subsequent to implementation of the 'Twelfth Five-Year Plan'. These changes have enabled a reassessment of transformative developments within the marine economy (Di et al., 2013). The intensity of new energy source utilization has also increased over the time period of this study, and clean energy technological development has been enhanced leading to sustained increases in marine economic and environmental efficiency rates.

In order to directly analyze variation in marine economic and environmental efficiency levels within the coastal areas of China, we calculated average values for these parameters for the period between 2000 and 2014 (Fig. 2).

We then combined the results of this study with those from the earlier works of Tu (2008) and Liu and Li (2013) who also addressed Chinese industrial economic and environmental efficiency levels and divided the closeness of marine economic-environmental efficiency into three area categories, convergence, near-convergence, and divergence. We then used the software SPSS19.0 to perform a cluster analysis using the 'within-groups linkage' setting and selecting the 'square Euclidian distance' option to measure standard-intervals.

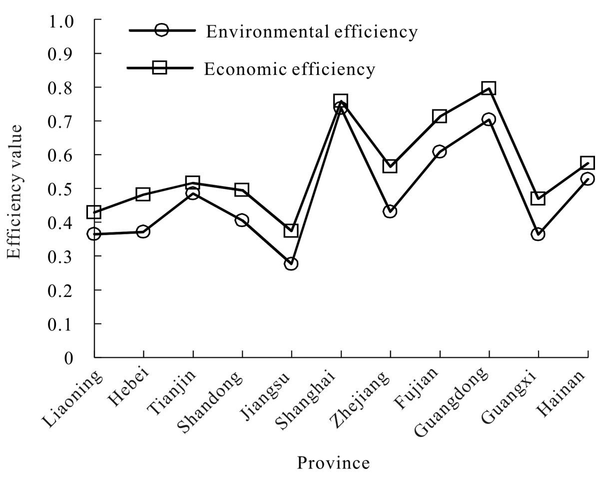

Fig. 2 Trends in marine economic and environmental efficiency values for 11 coastal Chinese provinces

This analysis resulted in the generation of a cluster tree; this diagram reveals that the 11 coastal provinces and regions of China cluster into three groups when $6 \leq \lambda \leq 8$ (Fig. 3). Results also show that the provinces of Tianjin, Shanghai, Guangdong, and Fujian all comprise areas of economic-environmental efficiency convergence, while Shandong, Zhejiang, and Hainan are areas of near-convergence, and Liaoning, Hebei, Jiangsu, and Guangxi are areas of divergence. As the marine economies of Tianjin, Shanghai, Guangdong, and Fujian all developed relatively early within the time period of this analysis they all exhibit good rates of economic and environmental efficiency. These areas have all achieved a high degree of economic-environmental efficiency convergence due to the impetus provided by marine resources, national policies and regulations, as well as technical market controls. The provinces of Shandong, Zhejiang, and Hainan, in contrast, are dependent on the advantages furnished by their natural resources; service industries comprise high proportions of the marine economy in these areas, while high-polluting and energy-consuming activities comprise a relatively small proportion. Results show that marine economic-environmental efficiency rates are at near-convergence within these areas, while economic development is dependent on high levels of resource consumption in Liaoning, Hebei, Jiangsu, and Guangxi provinces. These regions are all characterized by high proportions of heavy industry that leads to a more marked disparity between economic-environmental efficiency rates. The primary cause of this disparity is that the economies of these regions are dependent on marine investment to drive economic growth during development and so the level of environmental pollution is high. This means that improvements in marine technology will be advantageous if optimized coordination is to be achieved between the economy and the environment in these Chinese provinces.

3.2 The evolution of marine environmental efficiency spatiotemporal patterns

Earlier workers have demonstrated that environmental efficiency values provide a useful proxy for real production conditions when undesirable outputs are taken into account (Zhao et al., 2016). We therefore incorporated undesirable outputs when assessing and analyzing Chinese marine efficiency of China in this research.

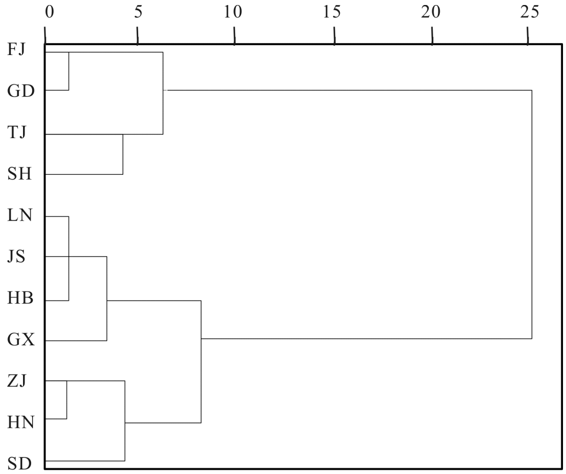

Fig. 3 Cluster diagram of marine economic-environmental efficiency levels in Chinese coastal regions, LN, Liaoning; HB, Hebei; TJ, Tianjin; SD, Shandong; JS, Jiangsu; SH, Shanghai; ZJ, Zhejiang; FJ, Fujian; GD, Guangdong; GX, Guangxi; HN, Hannan

We separated the environmental efficiency rates used in this analysis by building on the earlier DEA model-based work of Ma (2010). The $\rho = 1$ condition in this case denotes perfect efficiency, while the relationship $0.8 \leq \rho < 1$ denotes good efficiency, $0.6 \leq \rho < 0.8$ indicates moderate efficiency, and $\rho \leq 0.6$ denotes inefficiency. We chose cross-sectional data for analysis from the tenth, eleventh, and twelfth national Five-year plans in addition to recent data from 2014; records were combined with marine environmental efficiency values spanning the period between 2000 and 2014. These data enabled us to reconstruct spatial patterns of marine environmental efficiency across China (Fig. 4) and lead to a number of general conclusions.

Data show that the marine environmental efficiencies of each Chinese coastal region were inefficient at the start of the 'Tenth Five-Year Plan' in 2001, with the highest values seen in Guangdong (0.495) and Hainan (0.486) provinces. In contrast, in 2006, the year that the 'Eleventh Five-Year Plan' was initiated, Shanghai had the highest environmental efficiency (1.000), a perfect score, while other regions remained at more inefficient levels. Growth between 2001 and 2006 was seen in Fujian (0.560), Hainan (0.547), and Guangdong (0.516) provinces as these regions approached moderate efficiency; indeed, the spatial efficiency pattern over this period was such that values were high in central coastal China and generally low in the north and south. In comparison, by 2011, the efficiency level of Shanghai (0.918) had declined to just a good score, while values for Guangdong (0.768), Fujian (0.650), and Tianjin (0.615) had further increased, bringing the environmental efficiency levels of these provinces up to moderate while all other regions remained comparatively inefficient. A three-tier spatial pattern began to form at this time centered around Tianjin in the north, Shanghai in central coastal China, and around Fujian and Guangdong in the south (Fig. 4). This three-tiered spatial pattern had become more pronounced by the end of our research period (2014) as Tianjin, Fujian, and Guangdong had all attained perfect efficiency, Shanghai (0.859) remained at a good level, and Shandong (0.672) increased to a moderate level. It is generally the case that marine environmental efficiency levels remain low across the coastal regions of China and improvements have been slow; coordination of economic and environmental conditions must therefore be further enhanced if these regions are to achieve comprehensive efficiency improvements and eventually attain perfect scores.

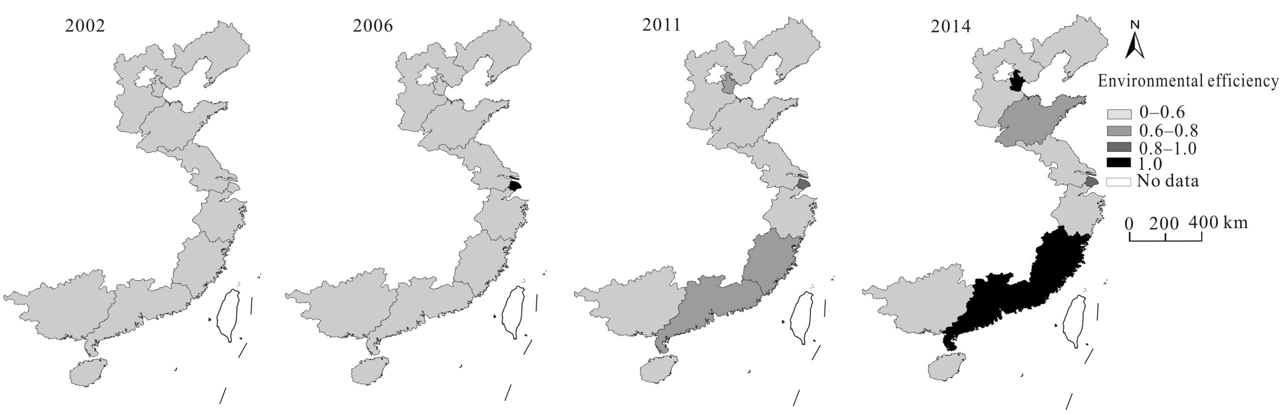

Fig. 4 Spatiotemporal patterns in Chinese marine environmental efficiency

3.3 Evolutionary characteristics of regional variation in marine environmental efficiency

We utilized the efficiency values generated in this study and combined standard deviation and variation coefficient formulae to calculate marine environmental efficiencies for Chinese coastal regions between 2000 and 2014 as well as to assess absolute and relative differences across regions. We then also created a run chart to illustrate changes in these variables across China over the study period (Fig. 5), a process which generated a number of clear conclusions. In the first place, data show that changes in both absolute and relative differences in the marine environmental efficiency of coastal areas are consistent with each other while fluctuating and increasing over time (Fig. 5). Values for the standard deviation (0.078) and variation coefficient (0.194) were smallest in 2003; these values then increased rapidly between 2003 and 2005, subsequently decreased slightly, and then increased at a relatively stable rate. As China has vigorously developed its marine economy since the initiation of the 'Tenth Five- Year Plan', coastal areas have undergone rapid economic development; at the same time, however, regional variations have remained relatively low due to the overall abundance of marine resources. In contrast, pressures on natural resources and the environment have remained relatively severe since the start of the 'Eleventh Five-Year Plan', and so resource conservation in the context of a more environmentally friendly society has been promoted nationally. Throughout this period of constant upgrades to marine industries and the rapid development of new ones, regions that boast better developmental foundations across the area have been the first to see the creation of high-technology, low-polluting alternatives while more traditional high-energy consuming, polluting, and emission-heavy industries have tended to shift into regions where economies are less well-developed, such as Hebei in the Bohai Sea and Guangxi in the Beibu Gulf. These phenomena have led to gradual rate divergence increases in environmental efficiency within coastal areas.

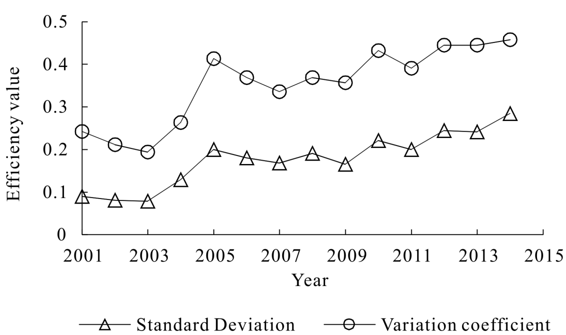

Fig. 5 Temporal trends in Chinese marine environmental efficiency 'deviation' and 'variation'

3.4 The marine environmental efficiency of economic zones

The environment of any given area does not exist in isolation but is influenced by that of neighboring regions. Thus, the use of economic zones as research units provides a practical basis for investigating Chinese marine environmental efficiency. One additional aim of this research was therefore to also provide a comprehensive assessment of the marine environmental efficiencies of the Bohai, Yangtze River Delta, Western Taiwan Straits, and Pearl River Delta economic zones, as well as the Beibu Gulf Economic Rim (Fig. 6). Results reveal that the Pearl River Delta (Guangdong in this study) is characterized by a higher environmental efficiency rate than is the case for the other economic zones and that this value has tended to both fluctuate and increase over time; indeed, this rate was 1 between 2005 and 2014 which suggests that this delta zone attained the maximum level of efficient production over this period. Data show that the environmental efficiency rate of the Taiwan Straits Economic Zone is ranked second to the Pearl River Delta; this region reached the maximum value of 1 in 2014 and has since remained in a state of perfect efficiency. In contrast, the marine environmental efficiency of the Yangtze River Delta has exhibited a stable and increasing trend over time with a 45.9% growth rate, while efficiency values for both the Bohai and Beibu Gulf rim areas have remained relatively low, both with efficiency rates of less than 0.5; of these, the environmental efficiency of the Beibu Gulf Rim area has exhibited a negative growth trend over time, decreasing by 24.5% in 15 years. The marine economy of the Pearl River Delta area developed relatively early and has had a clear developmental basis; the capacity of this region for marine technological innovation has consistently improved in concert with marine environmental efficiency. In contrast, the primary explanations for why the Bohai and Beibu Gulf rim areas have been characterized by low environmental efficiencies are that their development began relatively late, their marine economies developed slowly, and the ratio between high-energy

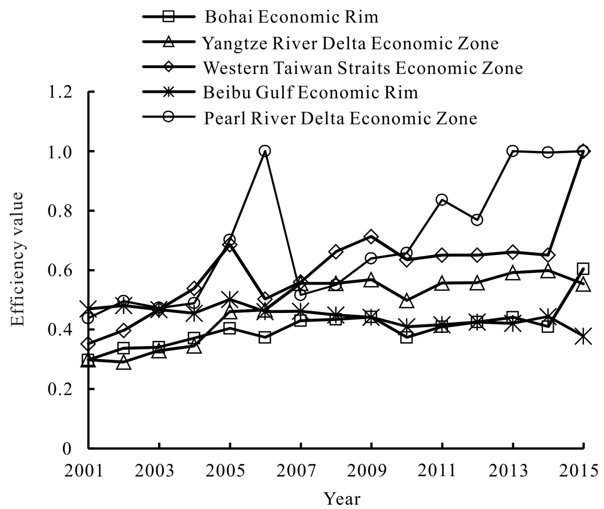

Fig. 6 Trends in marine environmental efficiency within Chinese coastal economic zones

consumption and high pollution industries in these regions is high. These regions should emphasize the development of new energy sources, strengthen their intensive industrial development, and focus on innovation in environmentally friendly technologies in the future.

3.5 Marine environmental efficiency total factor productivity and decomposition

We combined the Malmquist productivity index model with its decomposition equation to calculate marine environmental total factor productivity and decomposition indices across China for the period between 2000 and 2014. We also generated a run chart to show variation in total factor productivity, efficiency change, and technical change indices for the Chinese marine environment (Fig. 7). Results reveal an average value of 1.072 for the total factor productivity change index when this variable is calculated for the period between 2000 and 2014, corresponding to a growth rate of 8.0%; this shows that the overall operating efficiency of the Chinese marine environment has tended to slowly increase, albeit with fluctuations from year-to-year. Indeed, the trend between 2000 and 2014 was characterized by fluctuations leading to an overall increase, although the sudden decline seen in 2005 to 0.927 suggests that the overall production efficiency of the marine environment was at a low level at this time. The fluctuating increase seen between 2006 and 2014 illustrates an overall improvement in production efficiency; the efficiency change index had an average value of 0.998 between 2000 and 2014, corresponding to an overall increase of 3.5%. This index fell to its minimum (0.849) in 2005 before continuing to fluctuate and increase from 2006 onwards; this general trend in fluctuations is consistent with total factor productivity as well as the fact that overall changes in technical efficiency have remained at a low level. The technical change index, in contrast, had an average value of 1.042 between 2000 and 2014, corresponding to 10.7% growth; this value is higher than both total factor productivity and technical efficiency indices and illustrates that marine economic technology levels have consistently increased since 2000 in concert with improvements in environmental issues. It is therefore clear that all three indices exhibit fluctuating and increasing tendencies; marine environmental efficiency improvements have come from advances in science and technology, even though technical efficiency and changes each year have played contrasting roles.

4 Factors Influencing Marine Environmental Efficiency

We used a Tobit regression model to determine the influence of possible factors on marine environmental efficiency. We also consulted the existing literature in this area as we utilized annual marine environmental efficiency values for each region as variables (Ding et al., 2015), specifically total fixed asset investment (X_1), the ratio of marine technical personnel (X_2), the increased value of the marine industry (X_3), wastewater output per 10,000 yuan within the marine industry (X_4), the total marine output value in coastal areas (X_5), international standard container throughput in coastal ports (X_6), the ratio of tertiary marine industry (X_7), and the comprehensive utilization rate of industrial solid waste (X_8) as explanatory variables. These variables

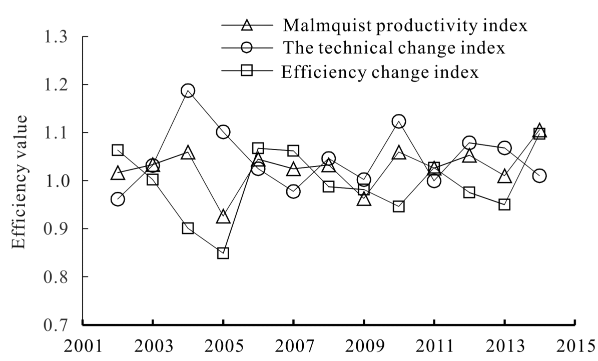

Fig. 7 Temporal changes in total factor productivity and the decomposition index for Chinese coastal area marine economies

denote the level of capital investment, the level of investment in marine scientific research, the level of marine economic development, the intensity of marine industrial pollutant emissions, the scale of the marine economy, the level of openness to the outside world, the structural level of the marine industry, and the technological level of marine environmental protection, respectively. All data for the period between 2000 and 2015 was sourced from the *China Marine Statistical Yearbook*.(State Oceanic Administration, 2001-2015),

The regression equation used for this analysis is as follows:

$$Y_{it} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 + \beta_7 X_7 + \beta_8 X_8 + c \tag{9}$$

In this expression, Y_{it} denotes the marine environmental efficiency level of province i at time t, while β_0, β_1, and β_2... β_8 refer to the regression coefficient for each variable, and C represents the error term. We used the software EVIEWS to conduct unit root tests in concert with the software STATA for Tobit regression analyses (Table 1).

The regression results reported here lead to a number of clear conclusions.

(1) Capital investment levels and the intensity of marine industrial pollutant emissions were not significantly correlated with marine environmental efficiencies over the time period of this research. Although capital investment can expand the scale of the marine economy to a certain extent, the environmental costs of the economic value generated by this input remains unclear, and so this process alone is insufficient to enhance marine environmental efficiency. At the same time, the intensity of marine industrial pollutants has not significantly affected marine environmental efficiency even though the emission of these chemicals does have a marked influence on the environment. As environmental efficiency is the overall result of the relationship between inputs and outputs, no significant correlation is seen when just pollutant emission intensity is considered.

Table 1 Chinese marine environmental efficiency factor regression results

y	Co ef.	SE	*z*	*P*
x_1	–0.07646	0.08268	–0.92	0.355
x_2	–0.25997	0.13993	–1.86	0.063*
x_3	–0.16973	0.09301	–1.82	0.068*
x_4	0.05728	0.10269	0.56	0.577
x_5	–0.31547	0.12463	–2.53	0.011**
x_6	–0.28326	0.12630	–2.24	0.025**
x_7	0.18497	0.07914	2.34	0.019**
x_8	0.14106	0.09174	–1.54	0.024**
c	1.36683	0.18922	7.22	0

Note: ** denotes statistical significance at the 5% level; * denotes statistical significance at the 10% level

(2) Data show that both the structural level of marine industries and the technological extent of marine environmental protection have both exerted positive effects on marine environmental efficiency over the time period of this research. Results show that optimizing marine industrial structure is also helpful in enhancing marine environmental efficiency; when the ratio of tertiary marine industries is increased by just one unit, marine environmental efficiency improves by 0.185 units. Improving marine environmental efficiency necessitates an emphasis on developing high value-added, low energy consuming tertiary industries, new energy sources, and an increased ratio of such businesses. Thus, data show that when the comprehensive utilization rate of solid industrial waste increases by one unit, marine environmental efficiency increases by 0.014 units; advances in environmentally friendly technologies are therefore helpful in promoting the comprehensive utilization of industrial waste and consequently improving marine environmental efficiency.

(3) The results of this analysis show that the level of investment in marine technical research manpower, development and scale of the marine economy, as well as the degree of openness to the outside world all exerted a negative effect on marine environmental efficiency over this research period. Regression results reveal that when the marine technical research personnel level is increased by one unit, marine environmental efficiency decreases by 0.260; this result is consistent with the previous studies of Su *et al*. (2013) and Zhao et al. (2016). Increases in the number of marine technical personnel are not easily converted into technological results, however, and so advances in the economy of this sector are not necessarily the result of internal technological innovations but rather the limitations of external technologies; this result can not therefore be considered useful for improving marine environmental efficiency. Developments in both the level of the marine economy

and expansions in its scale are unhelpful for improving environmental efficiency. Similarly, expanding the scale of the economy results in increasing pollution levels, an increased variety of pollutants, and a higher environmental cost for each unit of value within the marine realm. The level of openness to the outside world is also negatively correlated with marine environmental efficiency; foreign exports from China are weak, and so it is difficult to effectively utilize external trade as a proxy to promote technical revolutions and therefore openness exerts a negative impact on marine environmental efficiency.

5 Discussion and Conclusions

5.1 Discussion

(1) We suggest that coastal areas possess a range of industrial advantages, increase the pace of industrial transformation and enhancements, and enable the optimized coordination of marine economic-environmental development. In this context, Fujian Province can be characterized by increases in the pace of industrial transformation and upgrades by nurturing new industries, models, and creating demonstration areas for marine developments. Hainan Province, for example, has constructed a diversified marine tourism product system, supported the development of new marine industries including transportation, equipment manufacturing, biomedicines, and water desalinization, and has therefore promoted the accelerated development of port industries. In contrast, Shandong Province has vigorously implemented a range of innovative development strategies and has promoted marine technologies by constructing an innovation center, increasing the pace of transformation and upgrades to traditional industries, and nurturing the development of emerging industries including marine equipment manufacturing and cutting-edge machinery. This province has also promoted the rapid development of other knowledge-intensive industries.

(2) We suggest the strengthening of marine technological innovation systems as a means to improve efficiency. In one example, Qingdao Province has constructed a National Laboratory for Marine Science and Technology including a series of high-tech resources and a national deep-sea base, and has established the Qingdao National Ocean Science Research Center to promote the efficient allocation of marine science research resources, collaborative innovation, and cooperation in order to take advantage of clustering effects, improve basic innovation abilities, and drive marine technical innovation across this coastal region.

(3) We suggest that each coastal region within China should develop and promote marine ecological restoration programs and environmental protection projects in accordance with local conditions in order to enhance marine environmental efficiency. Liaoning Province, for example, has strengthened the extent of its marine ecological environmental monitoring and protection, and has enhanced wetland ecology monitoring and management. In similar moves, the city of Tianjin has implemented a coastal water pollution control program including the establishment of a strict redline and has improved its ecological compensation mechanisms, while the provinces of Shandong, Jiangsu, and Zhejiang have expanded areas designated as marine protection zones, strengthened the protection of key waterways, and enhanced the ecological and environmental protection of coastal areas and lakes. Fujian Province, in contrast, has strengthened its use of coastal restoration projects, expanded prevention and control mechanisms for industrial pollution, appropriately developed coastal resources, and has established a new model for coastal ecological agriculture, while Guangdong Province has strengthened its management system for marine utilization and has developed a comprehensive restoration program for its coastal belt and islands. These innovations have occurred alongside the promotion of a marine ecology cultural demonstration zone and the construction of a 'Beautiful Bay' area. Similarly, Hainan, Hebei, and Guangxi provinces have all adhered strictly to green development principles and have therefore strengthened their use of control mechanisms and the dynamic monitoring of coastal pollution volumes in addition to establishing ecological and environmental resource redlines, putting in place scientifically-based strict upper limits on resource consumption. These provinces have also defined lower-limits on acceptable environmental quality and redlines for ecological protection.

5.2 Conclusions

This study applied DEA and Malmquist productivity index models across 11 coastal provinces and regions of China to quantify and analyze marine environmental efficiency rates between 2000 and 2014. The results of this analysis lead to a number of clear conclusions.

(1) Measures of environmental efficiency tend to be more consistent with real production conditions when undesirable outputs are also incorporated into models; as the marine economy is dependent on the surrounding environment, the efficiency rates of both variables supplement and complement one another and exhibit consistent developmental trends. Data show that both marine economic and environmental efficiency levels remain relatively low across China and both should therefore be enhanced in the future.

(2) The levels of marine environmental efficiency across the coastal regions of China remain relatively low; although a fluctuating increasing trend is apparent throughout the time period of this research, the enhancement level remains low. Data show that while each region remained spatially inefficient in 2000, a three-tiered pattern had evolved by 2014 centered on Tianjin in the north, Shanghai in central coastal China, and Fujian and Guangdong in the south. We can therefore learn from the development models and governance measures applied within these three regions to augment the national level of marine environmental efficiency.

(3) Data show that absolute and comparative variations in coastal region environmental efficiencies can be characterized by initially decreasing and then increasing trends that are marked by consistently fluctuating changes and an overall increase with time. As these results imply unbalanced environmental efficiencies and development levels in coastal areas, future developments should emphasize the minimization of regional differences and promote stable all-round enhancements.

(4) The results of this study reveal that the marine environmental efficiency of the Pearl River Delta Zone is higher than any other economic zone within China, albeit subject to significant fluctuations over time. The Taiwan Straits and Yangtze River Delta economic zones exhibited the next highest efficiency levels, while the Bohai area and Beibu Gulf Rim Economic Zone are characterized by relatively low efficiencies that have nevertheless changed over time in a relatively stable manner. The Pearl River Delta continues to be the most efficient of these zones within China, while the Bohai Bay and Beibu Gulf economic zones have emphasized adjustments and optimizations to their industrial structures.

(5) The data presented in this study reveal that values for total factor productivity as well as technical efficiency and change across the Chinese marine economy have all fluctuated and increased over time. Benefits to marine environmental efficiency have been derived in particular from advances in science and technology, although technical efficiency and changes have also played alternating annual roles. Measures that could be implemented to enhance marine environmental efficiency might include improvements to industrial science and technology, the promotion of progress in these areas, the realization that high added value can be produced, and the stimulation of innovations.

(6) Data show that both the capital investment level and pollutant emission intensity are not significantly correlated with marine environmental efficiency. At the same time, however, optimal marine industry structural levels and environmentally friendly technologies both have positive effects on efficiency in this area. The level of investment in marine technical research manpower, the extent of economic development and scale, and the degree of openness to the outside world are also all negatively correlated with marine environmental efficiency. Optimizing marine industrial structures and promoting the development of environmentally friendly technologies are therefore likely to enhance the overall efficiency of Chinese coastal areas.

References

Meng Wei, Shu Yimin, Zhang Linbo,2015.China Engineering Science, 2015, 17 (8): 39–45. (in Chinese)

Bai Yongping, Zhang Xiaozhou, Hao Yongpei et al., 2013. Research on regional environmental performance and its influential factors based on SBM-Malmquist-Tobit model. *Areal Research and Development*, 32(2): 90–95. (in Chinese)

Charnes A, Cooper W W, Rhodes E, 1978. Measuring the efficiency of decision making units. *European Journal of Operational Research*, 2(6): 429–444. doi: 10.1016/0377-2217(78)90138-8

Di Qianbin, Liu Xinxin, Cao Ke, 2013. Spatial and temporal disparities of marine economic development and dynamic changes in China. *Scientia Geographica Sinica*, 33(12): 1413–1420. (in Chinese)

Ding Lili, Zhu Lin, He Guangshun, 2015. Measurement and influencing factors of green total factor productivity of marine economy in China. *Forum on Science and Technology in China*, 2(2): 72–78. (in Chinese)

State Oceanic Administration, 2001–2015. *China Ocean Statistical Yearbook. Beijing: Ocean Publishing House*. (in Chinese)

Fei Wei, Liu Xin, Yang Chen, 2015. Economic and environmental efficiencies based on material flow analysis and data envelopment analysis: a case study of Liaoning Province. *Acta Ecologica Sinica*, 35(11): 3797–3807. (in Chinese)

Gai Mei, Lian Dong, Tian Chengshi et al., 2014. The research for Liaoning environmental efficiency and spatialtemporal differentiation. *Geographical Research*, 33(12): 2345–2357. (in Chinese)

Hu Yuna, Mei Lin, Chen Yan, 2017. Spatial and temporal differentiation analysis on the efficiency of the three mainstays of tourism industry in China. *Scientia Geographica Sinica*, 37(3): 386–393. (in Chinese)

Kerr W, Ryan C, 2001. Eco-efficiency gains from remanufacturing: a case study of photocopier remanufacturing at Fuji Xerox Australia. *Journal of Cleaner Production*, 9(1): 75–81. doi: 10.1016/S0959-6526(00)00032-9

Li H, Shi J, 2014. Energy efficiency analysis on Chinese industrial sectors: an improved Super-SBM model with undesirable outputs. *Journal of Cleaner Production*, 65: 97–107. doi: 10. 1016/j.jclepro.2013.09.035

Liu Hui, Li Zhicui, 2013. Research on the difference between industrial environment efficiency and economic efficiency in the West Part of China-comparative analysis based on DEA-SBM model and DEA-CCR model. *Western Forum*, 23(6): 90–96. (in Chinese)

Liu Jia, Lu Ju, Liu Ning, 2015. Space-time evolution, influencing factors and forming mechanisms of tourism industry's efficiency in China's coastal area of based on DEA-Malmquist model. *Resources Science*, 37(12): 2381–2393. (in Chinese)

Liu Yi, Huang Jianyi, Ma Li, 2010. The assessment of regional vulnerability to natural disasters in China based on DEA model. *Geographical Research*, 29(7): 1153–1162. (in Chinese)

Ma Zhanxin, 2010. *The Models and Methods on Data Envelopment Analysis*. Beijing: Science Press. (in Chinese)

Mankiw N G, 1977. *Principle of Economics*. London: Oxford University Press.

Qin Quande, Li Xin, Chen Xiude et al., 2016. Energy efficiency analysis of China's twelve eastern coastal provinces considering undesirable outputs. *Science and Technology Management Research*, (4): 54–58. (in Chinese)

Reinhard S, Lovell C A K, Thijssen G, 1999. Econometric estimation of technical and environmental efficiency: an application to Dutch dairy farms. *American Journal of Agricultural Economics*, 81(1): 44–60. doi: 10.2307/1244449

State Oceanic Administration, 2001–2015. *China Marine Statistical Yearbook*. Beijing: China Ocean Press. (in Chinese)

National Bureau of Statistics Fixed Assets Investment Statistics Division,1950–2000.*Statistics on Investment in Fixed Assets of China*. Beijing: China Statistics Press. (in Chinese)

Su W, Gu C L, Yang G S et al., 2010. Measuring the impact of urban sprawl on natural landscape pattern of the Western Taihu Lake watershed, China. *Landscape and Urban Planning*, 95(1–2): 61–67. doi: 10.1016/j.landurbplan.2009.12.003.

Su Weihua, Wing Long, Li Wei, 2013. The factor research of total factor productivity of marine economy in China: based on spatial panel data model. *Collected Essays on Finance and Economics*, (3): 9–13. (in Chinese)

Tone K, 2003. Dealing with undesirable outputs in DEA: a slacks-based measure (SBM) approach. GRIPS Research Report Series I-2003-0005.

Yang Jun, Shao Hanhua, Hu Jun, 2010. Empirical study on evaluation and determinants of environmental efficiency of China. *China Population Resources and Environment*, 20(2): 49–55. (in Chinese)

Yang Qingshan, Zhang Yu, Li Yajun, 2012. Research on environmental efficiency evaluation of urban agglomerations in northeast China based on DEA model. *Economic Geography*, 32(9): 51–55, 60. (in Chinese)

Yang Ying, Ma Feng, 2010. Environmental cost efficiency evaluation and comparison of Chinese Provincial Economy. *Ecological Economy*, 3 (3): 43–46. (in Chinese)

Zhan Haoyong, Feng Jinli, 2010. Environmental-economic efficiencies of main industrial provinces in China based on SBM. *Ecological Economy*, (9): 42–46. (in Chinese)

Zhang Jun, Zhang Yuan, 2003. Revaluation of China's capital stock. *Journal of Economic Research*, (7): 35–90. (in Chinese)

Zhao Lin, Zhang Yushuo, Jiao Xinying et al., 2016a. An evaluation of Chinese marine economy efficiency based on SBM and Malmquist productivity indexes. *Resources Science*, 38(3): 461–475. (in Chinese)

Zhao Lin, Zhang Yushuo, Wu Di et al., 2016b. Marine economic efficiency and spatiotemporal characteristics of inter-province based on undesirable outputs in China. *Scientia Geographica Sinica*, 36(5): 671–680. (in Chinese)

Zhao Wensi, 2011. *Research on Technology Innovation Efficiency of High-tech Industry in the Yangtze River Delta*. Nanjing: Nanjing Normal University. (in Chinese)