J. Resour. Ecol. 2020 11(6): 570–579
DOI: 10.5814/j.issn.1674-764x.2020.06.004
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Evaluation and Driving Force Analysis of Marine Sustainable Development based on the Grey Relational Model and Path Analysis

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Abstract: With the rapid development of the marine economy, the demand for marine resources development and the pressure on marine environmental protection are gradually increasing. It is critical to evaluate and analyze the driving forces of marine sustainable development in order to promote the coordinated development of the marine economy, resources and environment. Taking Jiangsu Province of China as an example, this paper constructs an evaluation index system for marine sustainable development from the three aspects of marine economy, resources and environment, and calculates the weight of the variation coefficient for each indicator. Based on the grey relational model, the average value of the relational degree, calculated by the average value method of correlation coefficients and the weighting method, is then used to evaluate the status of marine sustainable development in this province. The comprehensive index model is used to analyze the dynamic trend of the evolution of marine sustainable development. The driving forces of marine sustainable development are analyzed by the path analysis method combined with the average values of the grey relational degree for each indicator. This analysis found that the marine sustainable development in 2016 and 2012 was good, the situation in 2007 was bad, and the remaining years were intermediate. Compared with the previous years, the optimal conditions of 2008 and 2012 were obvious. The main driving factors of marine sustainable development are cargo throughput of coastal ports, economic losses caused by storm surges in coastal areas, the area of marine nature reserves in coastal areas, coastal wind power generation capacity, and marine biodiversity.

Key words: marine sustainable development; coefficient of variation method; grey relational model; composite index model; path analysis

1 Introduction

With the increasing demand for resources for consumption, coastal countries all over the world consider marine sustainable development as an important development strategy. Marine sustainable development is reflected by several factors, such as the total amount of marine economy that has increased to a certain stage, marine industrial structure is optimized, marine resource development is efficient and reasonable, the marine ecological environment is harmonious, and marine comprehensive strength is improved, which together realize the dynamic balance of the "marine economy-resources-environment" system (Eikeset et al., 2018). Marine resources and the environment are the basis and guarantee for the development of the marine economy, but

Received: 2020-06-02 **Accepted:** 2020-08-20
Foundation: Jiangsu Social Science Fund (19GLC013, 17GLB003); Open Fund of Key Laboratory of Marine Management Technology of State Oceanic Administration (2015105HX90085).
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Citation: GAO Sheng, ZHAO Lin, SUN Huihui, et al. 2020. Evaluation and Driving Force Analysis of Marine Sustainable Development based on the Grey Relational Model and Path Analysis. *Journal of Resources and Ecology*, 11(6): 570–579.

with increasing marine development, the pressures on marine resources and the environment are increasing day by day (Selina, 2018). The contradictions between marine resources, environment and economy are becoming increasingly prominent. As a result, the system is faced with a series of problems and risks, such as low utilization efficiency of marine resources, decline of biodiversity, frequent occurrence of marine disasters, tension between man and land, aggravation of environmental pollution, degradation of the ecological environment, an extensive mode of economic growth, and increasing transformation pressures (Zhang et al., 2019a). Therefore, with the rapid development of the marine economy, marine sustainable development has gradually become the focus of attention and the key for enhancing the comprehensive national strength of coastal countries.

At present, the research on marine sustainable development at home and abroad pays more attention to measuring the development of the marine economy, resources and environment, but ignores the coupling of coordination analysis and driving force analysis (Laura, 2018). Researchers in this field pay more attention to the role of marine resource development in promoting economic development, while ignoring the negative impacts of resource waste and environmental problems on marine development (Wang and Zhang, 2019; Cao et al., 2020). They pay more attention to the impact of marine economic development on the marine environment, but ignore the analysis of the interactions between the marine economy and environment (Zhu et al., 2019); and more attention to the spatial distribution of the marine economy, resources and environment, but ignore the analysis of the spatiotemporal dynamic characteristics of the evolution of coordinated development (Li et al., 2018). Marine sustainable development involves many subsystems, such as economy, resources, and environment. The construction of the index system, selection of the evaluation indicators, standardization of the processing method, calculation of the index weights, determination of the safety threshold and selection of the evaluation models all need to be further discussed (Liang and Li, 2020). In short, the current approach mainly suffers from two limitations. On the one hand, there is a lack of comprehensive analysis of the composite system of the marine economy, resources and environment, and a unified evaluation index system has not yet been formed (Ntona and Morgera, 2018). On the other hand, although the evaluation model method is diversified, it is still not perfect, and the evaluation standard has not been unified (Wang et al., 2019).

In the context of maritime power, the assessment of marine sustainable development is helpful to understand the characteristics of the dynamic evolution of development, and to formulate and adjust effective marine development policies in time. There is a great need to promote the coordinated development of the marine economy, resources and environment (Zhang et al., 2019b). Based on the related research results on the evaluation of marine sustainable development at home and abroad, the marine economy, resources and environment are included in the evaluation index system of marine sustainable development (Liu et al., 2018). In this study, the dynamic trend of change of marine sustainable development from 2006 to 2016 was analyzed by using the grey relational model and the comprehensive index model. The path analysis method is used to analyze the main driving factors of marine sustainable development, combined with the average values of the relational degrees of each evaluation indicator. The corresponding countermeasures and suggestions are put forward to provide the basis for the high-quality development of the marine economy, the rational development and effective utilization of marine resources, and the protection and optimization of the marine environment. The results provide a reference for future marine sustainable development research.

2 Materials and methods

2.1 Research area status and data sources

Jiangsu Province is located on the eastern coast of the Chinese mainland, 30°45'N–35°20'N, 116°18'E–121°57'E, and is bordered to the north by Shandong, to the east by the Yellow Sea, to the southeast by Zhejiang and Shanghai, and to the west by Anhui (Fig. 1). The total area is 10.72×10^4 km^2, accounting for 1.06% of China's total land area, and the coastal zone area is 3.5×10^4 km^2. The total length of coastline is 888.9 km. The total coastline of the island is 84.74 km, with a total area of 59.15 km^2.

Fig. 1 Location of Jiangsu Province, China

Jiangsu Province is located in the Yangtze River economic belt. The Yangtze River Delta urban agglomeration, which is composed of Jiangsu, Shanghai, Zhejiang and Anhui, is one of the six world-class urban agglomerations in the world. Jiangsu Province's per capita GDP, comprehensive economic competitiveness, regional development and people's livelihood index (DLI) are among the highest for China's provinces. By the end of 2019, the permanent pop-

population was 80.7 million, making it the largest province with the largest population density in China. The GDP was 9963.152 billion yuan and the per capita GDP was 123607 yuan. Among the three types of added value within the marine industry, the marine tertiary industry has developed rapidly, from 151.755 billion yuan in 2010 to 352.28 billion yuan in 2017. The added value of marine secondary industry increased from 197.022 billion yuan in 2010 to 340.24 billion yuan in 2017. The primary industry rose slowly, from 17.698 billion yuan in 2010 to 30.185.18 billion yuan in 2016, but dropped to 29.18 billion yuan in 2017, indicating that Jiangsu's marine GDP is gradually accelerating the development of the secondary and tertiary industries (Fig. 2).

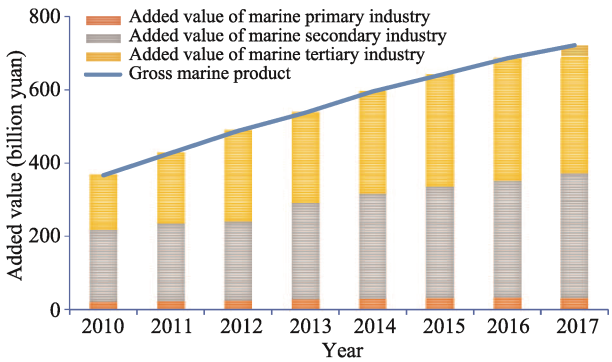

Fig. 2 Added value of the three types of marine industries in Jiangsu Province

The data in this article mainly come from the China Marine Statistics Yearbook, China Fishery Statistics Yearbook, China Port Yearbook, Jiangsu Yearbook, Jiangsu Marine Economic Development Report, Marine Industry Development Report, environmental monitoring data, and other official sources. According to the framework of China's environmental economic accounting system and the framework of China's resource and environmental economic accounting system, the evaluation index system of marine sustainable development in this study is selected and constructed from the three aspects of the marine economy, resources and environment.

2.2 Coefficient of variation method

In the evaluation indicator system, a larger numerical difference indicates greater difficulty in achieving the goal, but this system can better reflect the gaps between the evaluated objects. Due to the different dimensions of each indicator in the evaluation indicator system, direct difference comparisons are not possible. Therefore, the coefficient of variation of each indicator is calculated to measure the degree of difference for each indicator, thereby eliminating the influence of different evaluation indicator units. The coefficient of variation method is an objective weighting method, which directly uses the information contained in each indicator to calculate the index weight (Qian and Jiang, 2019).

The evaluation indicator source data for marine sustainable development is constructed into a matrix $[X_{11\times 21}]$. In order to make the evaluation indicators of different unit values comparable, the norm method is used to normalize the index data by converting it into standardized values in the interval of 0-1 to form a standardized decision matrix $[Z'_{11\times 21}]$, using the following formula:

$$Z'_{ij} = \frac{f_{ij}}{\sqrt{\sum_{i=1}^{n} f_{ij}^2}} \quad (i = 1,2,\cdots,n; j = 1,2,\cdots,m) \tag{1}$$

In formula (1), f_{ij} is the original data in the decision matrix, n is the number of evaluation objects, m is the number of indicators, and Z'_{ij} is the normalized value.

In order to eliminate the influence of different dimensions for each evaluation indicator, it is necessary to measure the difference of each indicator value through the coefficient of variation, and calculate the weights of coefficient of variation method (Zhu and Zhang, 2019). The calculation formula for the coefficient of variation and weight of each indicator is as follows:

$$w_i = \frac{V_i}{\sum_{i=1}^{n} V_i} \quad (i = 1,2,\cdots,n) ; \quad V_i = \frac{\sigma_i}{x_i} \tag{2}$$

In formula (2), V_i is the coefficient of variation of index i, also known as the coefficient of standard deviation, σ_i is the standard deviation of index i, $\bar{x}_i$ is the average of index i, and w_i is the weight of the coefficient of variation method.

2.3 Grey relation analysis model

The grey relational method measures the relational degree of factors according to the similarity or difference of the trends of changes between the factors. If the synchronous degrees of change of two factors are consistent, it indicates that the relational degree is higher; otherwise, it is lower. A greater relational degree indicates a closer relationship between the comparison sequence and the reference sequence (Liu et al., 2019). The correlation coefficient $\xi(X_i)$ of the comparison sequence and the reference sequence at point k is calculated as follows:

$$\xi_i(k) = \frac{\min_i \min_k |x_0(k) - x_i(k)| + \rho \times \max_i \max_k |x_0(k) - x_i(k)|}{|x_0(k) - x_i(k)| + \rho \times \max_i \max_k |x_0(k) - x_i(k)|} \tag{3}$$

In formula (3), $\xi_i(k)$ is the correlation coefficient of the k-th element between the comparison sequence $x_i(k)$ and the reference sequence $x_0(k)$, $0 < \xi_i(k) \leqslant 1$, and ρ is the resolution coefficient. A smaller ρ indicates a larger resolution. The value range is generally $0 < \rho < 1$. When $\rho \leqslant 0.5463$, the resolution is the best, and it is generally 0.5.

Using the average value method of correlation coefficients, the correlation coefficient of each point in the curve is concentrated into one value. The calculated average value is taken as the relational degree between the comparison sequence and the reference sequence, by the following formula:

$$R_i = \frac{1}{n}\sum_{k=1}^{n}\xi_i\left(k\right) \tag{4}$$

In formula (4), R_i is the relational degree, which reflects the relative importance of each indicator. $\xi_i(k)$ is the correlation coefficient between the comparison sequence and the reference sequence of the k-th index.

The grey relational degree is calculated by the weighting method based on the index weights, which can directly reflect the contribution of each evaluation indicator to marine sustainable development. The formula is as follows:

$$R_i = \sum_{j=1}^{n} w_j \xi_i\left(k\right) \tag{5}$$

In formula (5), w_j is the weight of the j-th evaluation indicator and R_i is the relational degree.

According to the research results of the evaluation standard and grade division, this paper divides the evaluation standard of marine sustainable development from [0, 1] into 5 levels (Table 1). Among them, the interval [0, 0.2) belongs to the fifth grade of "very bad". The interval [0.2, 0.4) belongs to the fourth grade of "bad". The interval [0.4, 0.6) belongs to the third level of "neutral". The interval [0.6, 0.8) belongs to the second grade of "good". The interval [0.8, 1.0] belongs to the first level of "very good".

Table 1 Evaluation standard of marine sustainable development

Grade	V	Ⅳ	III	II	I
Evaluation indicator value	[0, 0.2)	[0.2, 0.4)	[0.4, 0.6)	[0.6, 0.8)	[0.8, 1.0]
State	Very bad	Bad	Neutral	Good	Very good

In this paper, the average value method of correlation coefficients and the weighting method are used to calculate the grey relational degree. The average value of the relational degree of the two methods is used as the main basis for the evaluation of marine sustainable development.

2.4 Composite index model

The comprehensive index model is used to compare and verify the dynamic trend of the evolution of marine sustainable development as calculated by the grey relational model. The comprehensive index is the cumulative sum of the standardized values of each indicator multiplied by the weight of the coefficient of variation. The formula is as follows:

$$S_i = \sum_{j=1}^{m} y_{ij} w_j \tag{6}$$

In formula (6), S_i is a comprehensive index, y_{ij} is the standard value of the j-th index in the i-th sample (i=1, 2, ···, n, j=1, 2, ···, m), w_j is the weight of the j-th evaluation indicator, n is the number of samples, and m is the number of evaluation indicators.

2.5 Main driving force analysis

2.5.1 Path analysis

On the basis of multiple regression, path analysis decomposes the interactions (correlation coefficient) of dependent and independent variables into direct influence (direct path coefficient) and indirect influence (indirect path coefficient). These indicate either the direct effect of an independent variable on the dependent variable, or the indirect effect of the other variables on the dependent variable (Hang et al., 2019). For the general multiple linear regression analysis, the independent variables are X_1, X_2, $\cdots$, X_n and the dependent variable is Y. Therefore, the multiple linear regression equations based on standardization are as follows:

$$\begin{cases} r_{1Y} = b_1 + r_{12}b_2 + \cdots + r_{1n}b_n \\ r_{2Y} = r_{21}b_1 + b_2 + \cdots + r_{2n}b_n \\ \vdots \\ r_{nY} = r_{n1}b_1 + r_{n2}b_2 + \cdots + b_n \end{cases} \tag{7}$$

In formula (7), b_i is the partial regression coefficient of X_i as the direct path coefficient of X_i to Y, r_{ij} is the correlation coefficient between X_i and X_j, $r_{ij}b_j$ is the indirect path coefficient of X_i to Y through X_j, and r_{iY} is the correlation coefficient between X_i and Y, for i=1, 2, $\cdots$ n and j=1, 2, $\cdots$ m.

Path analysis can be used to test whether X_1, X_2, $\cdots$, X_n has a significant effect on Y. The most important aspect is to analyze how X_i affects Y directly and indirectly through other independent variables.

$$R_1 = \sum_{i=1}^{n} b_i, \quad R_2 = \sum_{i \neq j}^{n} b_i r_{ij} \tag{8}$$

$$R = \sum_{i=1}^{n}\left(b_i + \sum_{j \neq i}^{n} b_i r_{ij}\right) \tag{9}$$

In formulas (8–9), R_1 is the direct determination coefficient of X_i to Y, and R_2 is the indirect determination coefficient of X_i to Y through X_j.

Because of the complex relationships among the marine economy resources and environmental indicators, it is impossible to account for all the factors driving the dependent variable Y when setting the model. Therefore, we should further calculate the path effect coefficient (b_{Ye}) of the missing variable and error term on the dependent variable Y. This residual effect is calculated as follows:

$$b_{Ye} = \sqrt{1 - R^2} \tag{10}$$

In formula (10), b_{Ye} is the path effect coefficient. If $b_{Ye} <$ 0.05, this indicates that the path analysis has found the main driving factors, otherwise it indicates that some driving factors may be missing. Some driving factors outside of the model should be considered in the analysis.

2.5.2 Grey relational degree of each indicator

The grey relational model is used to calculate the grey relational weight of each evaluation indicator, reflecting the importance of that index in the whole index matrix. The formula $Q_i = w_i \Big/ \sum_{i=1}^{n} w_i$ is used to normalize the relational degrees of the average method and the weighting method for each evaluation indicator, respectively. Taking the average value as the driving force, the main driving factors of marine sustainable development are then analyzed.

3 Results

3.1 Evaluation indicators and weights of marine sustainable development

The evaluation indicator system of marine sustainable development is divided into three layers. The target layer is the status of marine sustainable development. The system layer includes the marine economy, marine resources and marine environment. The indicator layer includes 21 evaluation indicators (Table 2).

Table 2 Evaluation indicator system of marine sustainable development

System layer	Indicator layer	Unit	Coefficient of variation weight
Marine economy	Added value of marine industry (X_1)	$\times10^8$ yuan	0.0460
	Gross marine product of coastal areas (X_2)	$\times10^8$ yuan	0.0488
	The proportion of marine GDP to coastal GDP (X_3)	%	0.0120
	Proportion of marine secondary industry in marine GDP in coastal areas (X_4)	%	0.0074
	Proportion of marine tertiary industry in marine GDP in coastal areas (X_5)	%	0.0083
	Number of employed personnel involved in the sea (X_6)	$\times10^4$ person	0.0138
	Passenger traffic volume in coastal areas (X_7)	$\times10^4$ person	0.0770
Marine resources	Cargo throughput of coastal ports (X_8)	$\times10^4$ t	0.0419
	Per capita water resources in coastal areas (X_9)	m^3 person^{-1}	0.0273
	Mariculture area in coastal area (X_{10})	$\times10^4$ ha	0.0093
	Coastal wind power generation capacity (X_{11})	$\times10^4$ kW	0.0758
	Coastal wetland area (X_{12})	$\times10^4$ ha	0.0288
	Area of marine nature reserves in coastal areas (X_{13})	$\times10^4$ ha	0.1950
	Marine biodiversity (X_{14})		0.0548
Marine environment	Economic losses caused by storm surges in coastal areas (X_{15})	$\times10^8$ yuan	0.2351
	Industrial wastewater discharge in coastal areas (X_{16})	$\times10^4$ t	0.0110
	Standard rate of industrial wastewater discharge in coastal areas (X_{17})	%	0.0011
	Industrial waste gas emissions in coastal areas (X_{18})	$\times10^8$ m^3	0.0242
	Industrial smoke (dust) emission in coastal areas (X_{19})	$\times10^8$ m^3	0.0073
	Disposal capacity of industrial solid waste in coastal areas (X_{20})	$\times10^4$ t	0.0583
	Comprehensive utilization of industrial solid waste in coastal areas (X_{21})	$\times10^4$ t	0.0165

3.2 Evaluation and analysis of marine sustainable development

The average value method of correlation coefficients and the weighting method are used to calculate the relational degree. According to the standard of marine sustainable development (Table 3), the status of marine sustainable development in each year is analyzed. The average value method of correlation coefficients indicates that in 2016, 2014, 2015 and 2013, the values were 0.7146, 0.6345, 0.6273 and 0.6097 respectively, all of which are in the range of 0.6–0.8, so the marine sustainable development status was at a good level. The remaining years were between 0.4 and 0.6, which belong to the neutral level. The coefficient of variation weighting method shows that the value in 2012 was 0.6246, indicating the marine sustainable development was at a good level. In 2009, 2006 and 2007, the values were 0.3834, 0.3634 and 0.3632, which were all between 0.2 and 0.4, indicating the bad level. The remaining years had values between 0.4 and 0.6, belonging to the neutral level.

The average value of grey relational degree is sorted according to the size, which is the basis of the marine sustainable development evaluation. In 2016 and 2012, the values were 0.6513 and 0.6014 respectively, which are in the range of 0.6–0.8, indicating that the marine sustainable development status belongs to a good level. In 2007, it was 0.3850, in the range of 0.2–0.4, belonging to the bad level. Values in the remaining years were in the range of 0.4–0.6, belonging to the neutral level. The dynamic changes of marine sustainable development based on average correlation coefficient method and the weighting method are slightly different, but the overall trends are basically the same (Table 3, Fig. 3).

Table 3 Marine sustainable development based on the grey relational model

Year	Grey relational degree of correlation coefficient average method	Grey relational degree of weighting method	Average value of grey relational degree	Rank
2016	0.7146	0.5881	0.6513	1
2012	0.5782	0.6246	0.6014	2
2014	0.6345	0.5259	0.5802	3
2015	0.6273	0.521	0.5741	4
2013	0.6097	0.5382	0.5739	5
2011	0.5383	0.4455	0.4919	6
2010	0.5487	0.4323	0.4905	7
2008	0.4590	0.4941	0.4766	8
2009	0.4571	0.3834	0.4203	9
2006	0.4474	0.3634	0.4054	10
2007	0.4069	0.3632	0.3850	11

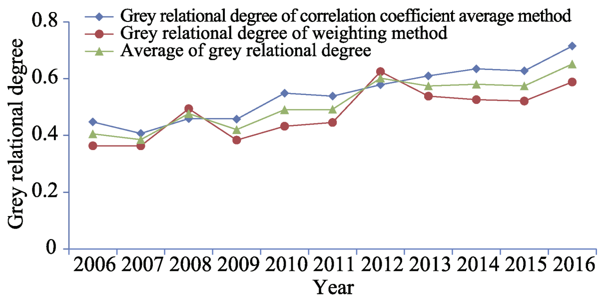

Fig. 3 Comparison of dynamic trends of the evolution of marine sustainable development based on the average correlation coefficient method and the weighting method

3.3 Comparative analysis of dynamic trends of marine sustainable development

The dynamic trends of the evolution of marine sustainable development calculated by the comprehensive index model and the grey relational model are basically consistent (Fig. 4), and the growth fluctuations of 2008 and 2012 are obvious compared with those of the previous year.

3.4 The main driving forces of marine sustainable development

3.4.1 Results of path analysis

According to the principle of path analysis, the average value of the grey relational degree of marine sustainable development from 2006 to 2016 is taken as the dependent variable (Y). The standard values of X_1–X_{21} were used as independent variables to test the normality of the dependent variable Y, and the output results are shown in Table 4.

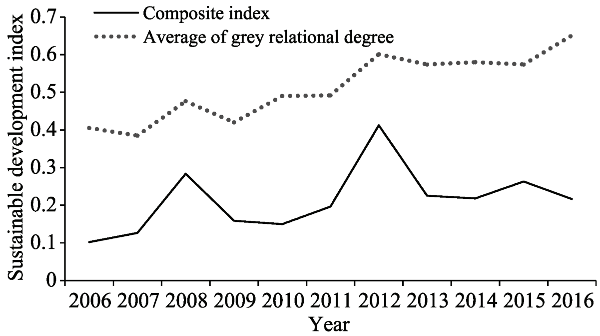

Fig. 4 Comparison of dynamic trend of the evolution of marine sustainable development based on the grey relational model and the comprehensive index model

Table 4 Output results of normality test

Dependent variable (Y)	Kolmogorov-Smirnov(a)			Shapiro-Wilk		
	Statistic	*df*	*Sig.*	Statistic	*df*	*Sig.*
Average value of grey relational degree of marine sustainable development	0.190	3		0.998	3	0.905

The Kolmogorov-Smirnov and Shapiro-Wilk tests were used to test the normality. The former is more suitable for large samples, while the latter is more suitable for small samples. Therefore, after the normality test of dependent variable Y, the output of Shapiro-Wilk test was used. The Shapiro-Wilk statistic was 0.905, $Sig.$ = 0.905>0.05, indicating that the dependent variable Y obeyed a normal distribution, so since Y is a normal variable and can be used for regression analysis. Through stepwise regression analysis, the linear regression equation was established to obtain the path coefficient (Table 5).

Table 5 Model overview output

R	R^2	Adjusted R^2	Std. Error of the estimate
0.951[a]	0.905	0.894	0.0287146

Note: Predictive variable (X_8).

The coefficient of determination (R^2=0.905) and the residual factor ($b_{Ye}=\sqrt{1-R^2}$ =0.3257>0.05) indicated that in addition to the above indicators, there are other factors affecting marine sustainable development. Because there are still some main driving factors not taken into account, the comprehensive analysis of the driving factors needs to be further refined. Based on the results of path analysis (Table 6), cargo throughput of coastal ports (X_8) is found to be the main driving factor, and its direct path coefficient is 0.951, which indicates that it has a great direct impact on marine sustainable development.

Table 6 Decomposition of simple correlation coefficients

Driving factors	The correlation coefficient of Y	Direct path coefficient	Indirect path coefficient total
X_8	0.951	0.951	0

3.4.2 Results of the grey relational analysis of each indicator

Based on the grey relational coefficient table of the marine sustainable development index system, the grey relational weight of each indicator is calculated (Table 7). According to the order of the weights, the main driving factors of marine sustainable development are as follows: Economic losses caused by storm surges in coastal areas (0.1163), Area of marine nature reserves in coastal areas (0.1012), Coastal wind power generation capacity (0.0639), and Marine biodiversity (0.060).

Table 7 Main driving factors of marine sustainable development

Indicator	Grey relational degree of correlation coefficient average method	Grey relational degree of weighting method	Average value of grey relational degree	Driving force ranking
X_{15}	0.0351	0.1975	0.1163	1
X_{13}	0.0357	0.1666	0.1012	2
X_{11}	0.0454	0.0824	0.0639	3
X_{14}	0.0519	0.0681	0.0600	4
X_7	0.0405	0.0746	0.0575	5
X_2	0.0498	0.0583	0.0540	6
X_1	0.0475	0.0524	0.0500	7
X_{20}	0.0410	0.0572	0.0491	8
X_8	0.0473	0.0474	0.0474	9
X_6	0.0659	0.0218	0.0438	10
X_3	0.0673	0.0193	0.0433	11
X_{12}	0.0501	0.0346	0.0423	12
X_{21}	0.0525	0.0207	0.0366	13
X_9	0.0426	0.0279	0.0353	14
X_{10}	0.0564	0.0126	0.0345	15
X_4	0.0536	0.0095	0.0316	16
X_{17}	0.0583	0.0016	0.0299	17
X_{16}	0.0464	0.0123	0.0293	18
X_{18}	0.0352	0.0205	0.0279	19
X_5	0.0415	0.0083	0.0249	20
X_{19}	0.0360	0.0063	0.0212	21

4 Discussion

The evaluation index system for marine sustainable development is a complex system, which is influenced and restricted by many factors. The main driving factors in different coastal areas are also different (Gu and Li, 2018). The selection of indicators is the basis of marine sustainable development evaluation, which directly affects the evaluation results. Therefore, indicator selection must conform to the principles of science, integrity, hierarchy, dynamics and stability, operability and practicability (Ren et al., 2018). At present, the difficulties of marine sustainable development evaluation are mainly reflected in the uncertainties of the evaluation model method, evaluation system framework, evaluation index, evaluation standard and simplification of the evaluation type (Zhang et al., 2019b).

This paper presents a systematic study on the core issues and main links, such as index system construction, marine sustainable development evaluation and driving force analysis. By revealing the characteristics of dynamic changes and the main driving factors of marine sustainable development, this paper provides an important basis for the formulation and adjustment of marine sustainable development policies. Firstly, referring to the results of sustainable development index system research at home and abroad, the evaluation index system of marine sustainable development is constructed from the three aspects of the marine economy, resources and environment. The index data from 2006 to 2016 are constructed into a sample judgment matrix $[X_{11\times21}]$, which represents 11 evaluation schemes, and each scheme has 21 evaluation indicators. A normalized matrix $[Y_{11\times21}]$ is obtained by dimensionless treatment of the judgment matrix by the norm method. The norm method is used to standardize the index data, which will not increase the subjective information, but it also eliminates the adverse impact of extreme values on the evaluation, and improves the accuracy of the weights. Then, the coefficient of variation method was used to calculate the weight of the variation coefficient for each evaluation index. The average value method of correlation coefficients and the weighting method are used to calculate the degree of correlation of marine sustainable development. According to the mean value of the grey correlation degree, the sustainable development of the ocean is analyzed. The comprehensive index model is used to compare and analyze the characteristics of the dynamic trends of marine sustainable development of the grey relational model. Finally, the grey relational degree of each evaluation index in the evaluation index system is calculated, and the driving forces of marine sustainable development are analyzed combined with path analysis. Finally, this paper puts forward the corresponding countermeasures and suggestions to provide a scientific basis for the formulation of marine development strategies, provide decision support for the rational development and utilization of marine resources and their scientific management, and promote the coordination and sustainable development of the marine economy, resources and environment.

At present, the sustainable development index system mainly includes the sustainable development index system of Commission on Sustainable Development (CSD), sustainable development index system of Organization for Economic Co-operation and Development (OECD), sustainable development index system of World Bank, sustainable development strategy research report index system of china, related indicators of global sustainability assessment system (Phondani et al., 2016), and the ecological sustainable development index system of urban coastal zone (Georgia et al., 2013). This paper constructs an index system of marine sustainable development, carries out monitoring evaluation and driving force analysis, provides methods for accurately measuring the status of marine sustainable development in coastal areas, provides a reference for regional development quality assessment objectives, and provides a basis for the timely adjustment of marine development planning and management countermeasures (Hull, 2020). It is of vital importance to reduce the contradictions between marine economic development and the marine resources and environment, and to promote the coordination and sustainable development of marine systems.

In future research, more attention should be paid to the objective selection and simplification of the evaluation indicators of marine sustainable development, so as to reduce the subjectivity in the selection of evaluation indicators. It is necessary to continue to supplement the theoretical research framework of the marine economy, resources and environment, and to sort out the evaluation factors, evaluation systems, evaluation models, evaluation methods, evaluation standards and evaluation types (Di et al., 2018). It is also necessary to explore the interactions among the marine economy, resources and environment and the mechanisms of coupling and coordination. It is necessary to explore the mechanisms of disharmony among the marine economy, resources and environment, and the principle of coordinated governance (Sherman et al., 2019). It is necessary to explore the basic problems of the marine economy-resources-environment composite system, such as the functions, structures, interactive stress relationships and temporal and spatial evolution regulation.

5 Conclusions

In this paper, an evaluation index system of marine sustainable development is constructed, and the average value of the relational degree, as calculated by the average correlation coefficient method and the weighting method, is used as the final basis for evaluating the status of marine sustainable development. The comprehensive index is calculated and compared with the average value of grey relational degree, and the chart is drawn to verify and analyze the evolution of dynamic trends of marine sustainable development. Path analysis is combined with the grey relational degree of each indicator to analyze the driving forces. These analyses led to four main conclusions.

Firstly, the evaluation index system of marine sustainable development in 2006–2016 is developed from the three aspects of the marine economy, resources and environment. The average value method of correlation coefficients revealed that the marine sustainable development in 2016, 2014, 2015 and 2013 was good, and in the remaining years it was neutral. The coefficient of variation weighting method showed that the marine sustainable development in 2012 was good; while in 2009, 2006 and 2007 it was bad and in the remaining years it was neutral. The dynamic changes of marine sustainable development calculated by the average correlation coefficient method and the weighting method are slightly different, but the overall trends are basically the same.

Secondly, according to the average value of the correlation degree, as calculated by the average value method of correlation coefficients and the weighting method, the sustainable development of the marine industry in 2016 and 2012 was good, the situation in 2007 was bad, and in the remaining years it was neutral. By comparing and analyzing the dynamic trends in the evolution of marine sustainable development between the comprehensive index model and the grey correlation model, the overall trends of the dynamic changes obtained by the two models are basically the same. Compared with the previous year, the growth in 2008 and 2012 fluctuated significantly.

Thirdly, the direct path coefficient of X_8 is 0.951. Through path analysis, cargo throughput of coastal ports is found to be the main driving factor of marine sustainable development. The residual factor $b_{Ye} = \sqrt{1-R^2}$ =0.3257> 0.05 indicates that there are other main driving factors that need further analysis. Therefore, combined with the grey relational degree of each indicator, we found that the economic losses caused by storm surges in coastal areas, area of marine nature reserves in coastal areas, coastal wind power generation capacity, and marine biodiversity are the main driving factors of marine sustainable development.

Fourth, there are close interactions between the marine economy, resources and environment. Therefore, the blind pursuit of high economic growth will aggravate the depletion of resources and environmental degradation, and will ultimately be detrimental to further marine development. China's marine development stage is gradually changing from high growth to high quality. At present, China is in the critical period of changing the development mode and the driving force behind the growth. Thus, it is urgent to seek the coordination of the marine economy, resources and environment and to promote the marine sustainable development. On the one hand, we need to pay more attention to the characteristics and adjustment of economic structure, the development and utilization of resources, and environmental protection and optimization in the process of marine development. On the other hand, we need to deal with the coordination and developmental relationships among economy, resources and environment, emphasize the growth of the marine economy, reduce the consumption of resources and protect the environment.

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基于灰色关联模型与通径分析法的海洋可持续发展评价与驱动力分析

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摘　要：随着海洋经济的快速发展，海洋资源开发需求与海洋环境保护压力逐渐增大。进行海洋可持续发展评价与驱动力分析，对促进海洋经济–资源–环境的协调发展具有重要意义。本文以中国江苏省为例，从海洋经济、资源、环境 3 个方面构建了海洋可持续发展评价指标体系，并计算了各指标的变异系数权重。基于灰色关联模型，运用关联系数平均值法与赋权法计算的关联度平均值评价了海洋可持续发展状况。采用综合指数模型对海洋可持续发展的动态演变趋势进行了对比验证分析。采用通径分析法并结合各指标的灰色关联度平均值进行了海洋可持续发展的驱动力分析。研究发现 2012 与 2016 年江苏省的海洋可持续发展状况较好，2007 年较差，其余年份一般，2008 年与 2012 年相对于上年度优化明显。沿海港口货物吞吐量、沿海地区风暴潮造成的经济损失、沿海区域海洋自然保护区面积、沿海地区风能发电能力、海洋生物多样性是海洋可持续发展的主要驱动因子。

关键词：海洋可持续发展；变异系数法；灰色关联模型；综合指数模型；通径分析