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Sustainable development in marine economy: Assessing carrying capacity of Shandong province in China

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Abstract

The sustainable development of the marine economy has drawn increasing attention from all the countries of the world. This paper proposes a marine ecological carrying capacity framework that uses the AHP-entropy based TOPSIS method to carry out a multi-angle evaluation of marine ecological carrying capacity. Using the data from Shandong province in China between 2008 and 2017, the dynamic analysis is undertaken. The results showed that the carrying capacity in Shandong province presented a varying trend between 2008 and 2017. Specifically, it declined from 2008 to 2012, with the index value falling from 0.52 to 0.34. From 2013, the carrying capacity gradually increased; nonetheless, the overall value was still at a low level before 2015. The marine ecological carrying capacity increased rapidly in the last two years and reached its optimum (0.53) in 2017. Further investigation found that population growth, increased number of tourists, and industrial pollution were the leading causes of declining carrying capacity. These findings provide valuable insights into the study of carrying capacity and policy implications for achieving sustainable development in the marine sector.

***Keywords*:**

Marine ecological carrying capacity; Sustainability; AHP-entropy-based TOPSIS; Marine economy

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1. Introduction

Currently, the world faces a rapid growth of population, which has consequently created an unprecedented demand for natural resources (Zhao et al., 2014). Therefore, many countries have developed interest on the oceans (Stebbings et al., 2020; Gilliland and Laffoley, 2008), which have the vast potential to help meet several significant challenges, such as growing demand for food, energy, raw materials, employment, and economic growth (Zhao et al., 2014; Morrissey et al., 2011; Sun et al., 2018). In recent years, a substantial expansion of marine economic activities around the globe has added enormous value to the world economy. Since the 21st century, it is estimated that the marine economy contributed approximately US$1.5 trillion annually, accounting for roughly 3% of the global value-added trade, and this is projected to more than double by 2030 (OECD, 2016). However, the fast development of the marine economy and the surge in human activities have inevitably caused severe problems such as over-exploitation, pollution, rising ocean temperature and levels, loss of biodiversity and water quality degradation (Tan et al., 2021; Rayner et al., 2019; Yu et al., 2019; Lotze et al., 2006). Sustainability has become more critical than ever to preserve the ocean's health and ensure the world's future prosperity. Some coastal developed countries such as the United States (US), the United Kingdom (UK), Russia and Japan have successfully formulated and adjusted their marine strategies to focus more on sustainable utilization of marine resources and improvement of the marine environment (Song et al., 2019).

As a country with an extensive area of coastline, China has also attached great importance to developing the marine economy (Luo et al., 2020). Since 2000, the marine economy has maintained a double-digit growth rate although this rate has been decreasing since 2011 (Sun et al., 2018; Liu et al., 2017). In the meantime, like other countries, those severe environmental problems caused by increased economic activities have made it an urgent task for China to realize sustainable development in its marine economy.

In this context, evaluating marine carrying capacity plays a fundamental role in underpinning the scientific basis for informed policy decisions. Marine carrying capacity refers to the capacity of the marine ecological environment to support human economic activities and social development on the premise of not exceeding the elastic limit of the marine ecosystem within a certain period (Stojanovic and Farmer, 2013; Han et al., 2018). Evaluating the ecological carrying capacity can provide an objective understanding of the current status of the marine environment and potential utilization of the regional resources, which is of great significance for the regions to protect the marine ecological environment and promote sustainable development (Graymore et al., 2010; Halpern et al., 2008).

There has been intensive research on marine carrying capacity; nevertheless, no consensus has been reached on the evaluation method and framework. Earlier studies of marine carrying capacity are mostly limited to a single resource and environmental element, such as beach carrying capacity (Silva, 2002), aquaculture environmental carrying capacity (Byronor et al., 2014), and carrying capacity for coastal tourism (McCool and Lime, 2001). Recently, some studies have attempted to construct a general conceptual model to systematically evaluate the carrying capacity of marine ecosystems to address the influence of human activity factors on the carrying capacity (Ma et al., 2017; Chen et al., 2021). Nonetheless, there is still a lack of satisfactory methods to evaluate marine carrying capacity. So far, there have been several methods adopted to evaluate marine carrying capacity, such as the ecological footprint analysis (Galli et al., 2012; Gu et al., 2015; Peng et al., 2018), state space method (Tang, 2015) and comprehensive index evaluation method (Wang et al., 2018; Song and Du, 2019). With the advancement in computer technology, some mathematical models, such as system dynamics models (Wang et al., 2014) and TOPSIS method (Sun et al., 2017), have been gradually applied to the field of ecology. The ecological footprint method is simple and easy to implement, but it is more inclined to natural conditions and cannot reflect the impact of social and economic factors on ecological carrying capacity. The state space method can describe complex systems and express the relationship between variables; however, this method, like the ecological footprint method, does not use a specific value to describe the carrying capacity of the study area but only assesses whether it is overloaded (Shi et al., 2019). The comprehensive index evaluation method incorporates various resource, environmental, social and economic factors that affect the ecological carrying capacity into the index system, which is more in line with the actual situation (Xiao et al., 2019). However, the index's weight and the accuracy and sensitivity of the index need to be further studied. For instance, Han et al. (2018) explored the ratio of pressure index to support index to reflect changes in marine carrying capacity. This calculation method can better reflect the relative relationship between pressure and support changes, but there is still a lack of scientificity in explaining the marine carrying capacity. In comparison, mathematical models have advantages that other evaluation methods cannot match in complex process analysis and accuracy. However, their modeling process requires more parameter indicators and more accurate ecological carrying capacity concepts to support model construction.

This paper combines the comprehensive index evaluation method and TOPSIS method to evaluate marine carrying capacity to overcome the limitations of the methods adopted in previous studies. TOPSIS is an effective method for solving problems existing in multi-attribute decision-making with finite alternatives and has been widely used in the performance evaluation or benefit evaluation of relevant policies in ecological civilization construction (Sun et al., 2017; Lin et al., 2020). To construct a comprehensive evaluation index system for marine ecological carrying capacity, several factors must be considered. We adopt the "pressure-state-response (PSR)" indicator framework, which is widely recognized by academia, to better reflect the interdependence of nature, economy, environment, and resources (Li et al., 2019). Based on the PSR framework, a marine ecological carrying capacity framework containing two subsystems (Support & Pressure) was established. The method considered a total of 17 indicators with 59 variables. Based on empirical data from 2008 to 2017 and the AHP-entropy-based TOPSIS method, Shandong province's marine ecological carrying capacity was analyzed.

2. Materials and methods

2.1. Study Area

Shandong province is located in the eastern coast of China and has a land area of 155,800 square kilometres and coastal area of 47,300 square kilometres (Fig. 1). In 2011, the Chinese State Council officially approved the

"Blue Economic Zone" (BEZ) development plan on the Shandong Peninsula, which is the nation's first regional development strategy centred on the marine economy. Hence, Shandong province was authorised to develop the marine economy and resulted in marine economy growth from $2.91 in 1991 to $225.4 billion in 2018. Since 2001, Shandong's GDP (gross domestic product) and GOP (gross ocean production) have been both on the rise (Fig. 2). The GOP has accounted for approximately 20% of the GDP of the province in 2017, which indicates the importance of the marine sector to the economy of Shandong province. Therefore, the sustainability of the marine economy is crucial for the province to achieve further economic development.

Fig. 1. The location of Shandong province

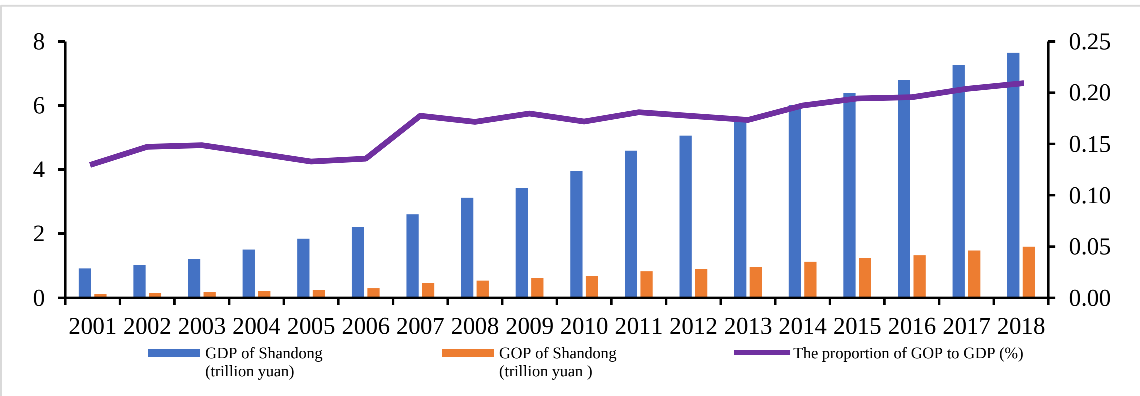

Fig. 2. Gross Domestic Product (GDP) and Gross Ocean Product (GOP) of Shandong from 2001 to 2018[1]

2.2. Marine ecological carrying capacity framework and index system

In order to establish a comprehensive indicator system to evaluate the carrying capacity, OECD developed a Pressure and Support (PS) framework in 1994 (Woodward, 2009). On the basis of this, we designed the ecological carrying capacity framework, including two subsystems of support and pressure. The logic relationship can be illustrated in Fig. 3. On one hand, the Pressure index includes three second-level indicators, i.e., marine natural disasters, human-caused disasters, and social pressure. Marine natural disasters and human-caused disasters are linked to the marine ecosystem, while the other is linked to the social-ecological system.

Moreover, the support system also includes three second-level indicators: industry and governance support, environmental support, and resource support. These indicators consider both natural and human factors. In the ecological carrying capacity evaluation system, the pressure indicators are perceived as unfavourable as they create a burden on the marine carrying capacity. By contrast, the support indicators are regarded as positive as they can improve the carrying capacity.

In this paper, some specific indicators are chosen to reflect the main characteristics of the six second-level factors of the Pressure and the Support subsystem. Following the major principles of selecting the indicators, namely objective, measurable, usable, and representative, we select 17 indicators with ten on the Pressure side and seven on the Support side[2]. Moreover, in order to measure those indicators, the quantifying variables (32 pressure variables and 27 support variables) are adopted, selected from authoritative data published by local government or administration. They are all reliable annual statistics and closely related to the marine environment, development activities and social economy (Table 1).

[1]Data are collected from China Marine Statistical Yearbook and Shandong Marine Statistical Yearbook (2001-2018).

[2]Although the numbers of the sub indicators on the two sides are not equivalent due to the availability of the data, it does not affect the results.

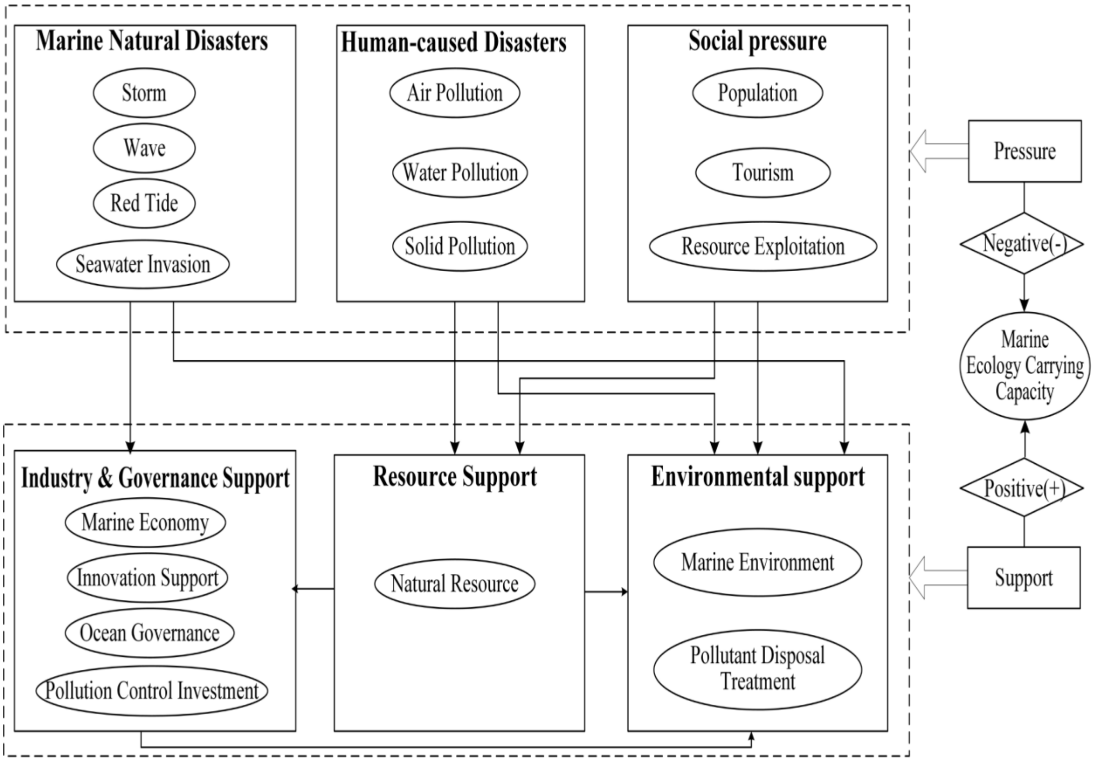

Fig. 3. Marine ecological carrying capacity framework

Table 1
Indicators, quantifying variables of the PS index system of Shandong province

Subsystem	Second-Level indicator	Indicator	Quantifying variables	Unit (Annual)
Pressure	Marine natural disasters	P1 Storm	Annual financial loss	10^6 yuan
			Facility Damage of Coastal Works	km
			Annual affected population	10^4 persons
		P2 Red tide	Number of red tide	/
			Affected Area	km^2
		P3 Wave	Disaster area affected by aquaculture	hectare
			Damage length of Coastal works	km
			Damage to the vessel	/
			Economic loss	10^4 yuan
		P4 Seawater invasion	Section length	km
			Severe invasion distance from shore	km
			Minor invasion distance from shore	km
	Human-caused disasters	P5 Air pollution	SO_2 emission	10^4 tons
			CO_2 emission	10^4 tons
			Total smoke and dust emissions	10^4 tons
			Concentration of inhalable particulate matter to pollution load	g/m^3
		P6 Water pollution	Waste-water disposal	10^4 tons
			Chemical Oxygen Demand	10^4 tons
			Ammonia nitrogen content	10^4 tons
			Comprehensive pollution index of water quality	%
			Eutrophication index of sea water	/
		P7 Solid pollution	Common Industrial Solid Wastes Produced	10^4 tons
			Common Industrial Solid Wastes discarded into the sea	10^4ton
	Social pressure	P8 Population	Density of population	person/km^2
			Population growth rate	‰
		P9 Resource exploitation	Marine cultivable area	10^4 hectares
			Aquaculture area	10^4 hectares
			Total marine catching	10^4 tons
			Number of fishing boat	/
		P10 Tourism	Number of travel agency	/
			Number of five-star hotel	/
			Tourist arrivals	10^4 persons
Support	Industry and governance support	S1 Marine economy	Proportion of GDP	%
			Fishery economic value added	10^8 yuan
			Fisherman income	10^4 yuan
			GDP per capita	yuan/person
			Total of import and export	10^4 dollars
			Fishery total investment	10^7 yuan
		S2 Innovation support	Number of marine R&D institutions	/
			Number of marine human resource	10^4 persons
			Number of marine students	person
			Fund total of marine scientific research	10^8 yuan
		S3 Pollution control investment	Pollution control investment	10^8 yuan
			Proportion of pollution control investment of GDP	%
		S4 Ocean governance	Number of ocean institutions	/
			Marine conservation area construction	10^4 km^2
			Number of fisheries Enforcement Agencies	/
	Resource support	S5 Natural resource	Used area per capita	10^4 km^2
			Cultivated sea land per capita	10^4 km^2
			Purified water per capita	ton
			Natural gas production	10^8 m^3
			Crude oil production	10^4 tons

		Salt production	10^4 tons
Environmental support	S6 Marine environment	Annual average precipitation PH	/
		Water qualified rate of marine functional area	%
		Proportion of first standards water	%
	S7 Pollutant disposal treatment	Sewage treatment rate	%
		Number of waste-water treatments	/
		Conversion rate of industrial solid waste	%

2.3. Data sources and data standardization

The data covering the study period between 2008 and 2017 were collected from: 1) various official statistical yearbooks from 2009 to 2018, including China Marine Statistical Yearbook, China Statistical Yearbook, Shandong Statistical Yearbook, China Statistical Yearbook on Environment, China Fishery Statistical Yearbook; 2) statistical bulletins from 2009 to 2018, including China Marine Environmental Quality Bulletin, China Marine Disaster Bulletin, Bulletin of Marine Environment Status of Shandong, China Sea Level Bulletin, Shandong Water Resources Bulletin, Environmental Quality Bulletin of China Offshore; 3) academic papers published by Elsevier, Taylor & Francis, etc.

The raw data collected to be used in the pressure and support subsystem cannot be directly compared and calculated due to its different dimensions and distribution intervals. Therefore, all data are normalized by using the min-max normalization method (Nagelkerken et al., 2000; Wei et al., 2014). All variables are standardized within the range between 0 and 1. The specific methods are given as follows:

$$Y_{ij} = \left(X_{ij} - X_{i\min}\right) / \left(X_{i\max} - X_{i\min}\right) \quad \text{(positive)} \tag{1}$$

$$Y_{ij} = \left(X_{i\max} - X_{i}\right) / \left(X_{i\max} - X_{i\min}\right) \quad \text{(negative)} \tag{2}$$

Where X_{ij} is the original value of indicator i; Y_{ij} is the standardized value of X_{ij}; $X_{i\max}$ and $X_{i\min}$ are the maximum and minimum values of the indicator X_{ij}, respectively.

2.4. Weight determination

According to the steps of TOPSIS method, it is necessary to determine the attribute weight. Different indicators have different contributions to the whole index system. Therefore, the determination of reasonable weights plays an essential role in guaranteeing the accuracy of evaluation results (Mikulic et al., 2015). This study adopts the analytic hierarchy process-entropy method (AHP-EM), which considers both the qualitative and quantitative criteria (Al-Aomar, 2010; Graham et al., 2015).

The AHP method (Saaty, 1994) aims at quantifying relative priorities for a given set of alternatives on a ratio scale based on the judgment of the decision-maker. The AHP method firstly compares the indicators, then, the 1~9 ratio scale method is used to construct the comparison matrix. Moreover, the maximum eigenvalue and its eigenvectors of the comparison matrix are determined (Clark and Tilman, 2017). The relative weight w_{1i} of each indicator is thus obtained.

The entropy weight method (EM) (Hwang and Yoon, 1981) is used to calculate the information entropy of the evaluation index according to how a relative change in the evaluation index influences the whole system and then determine the index weight. The main steps are as follows:

$$F_{ij} = y_{ij} \Big/ \sum_{i=1}^{m} y_{ij} \tag{3}$$

Where F_{ij} was the proportion of the i-th index.

$$E_i = -K\sum_{i=1}^{m} F_{ij} \ln F_{ij} \tag{4}$$

where E_i is the entropy of the i-th attribute; m is the number of alternatives; $K = 1/\ln m$. In particular, when $F_{ij} = 0$, let $\ln F_{ij} = 0$ (Huang et al., 2015).

$$W_{2i} = \left(1-E_i\right) \Big/ \sum_{j=1}^{n}\left(1-E_i\right) \tag{5}$$

where W_{2i} is the weight of the i-th indicator; n is the number of attributes.

Finally, Z_i represents the integrated weight of the evaluation indicator i, which can be calculated according to the following formula:

$$Z_i = \beta w_{1i} + \left(1-\beta\right) w_{2i} \tag{6}$$

In this article, it is assumed that the two weighting methods have the same importance, and $\beta = 0.5$. W_{1i} and W_{2i} are the weight of indicator i derived from the AHP and the EM, respectively.

2.5. TOPSIS comprehensive model evaluation

TOPSIS is an effective method for solving problems existing in multi-attribute decision-making with finite alternatives. The principle of this method is to rank the alternatives by calculating the distance of each alternative from the ideal solution and the negative ideal solution for problems in decision-making, thus determining the optimum alternative (Zyoud et al., 2016; Chen, 2019). According to the principle of TOPSIS method, the best rank of the alternative is obtained when it has the shortest distance from the ideal solution and the longest distance from the negative ideal solution (Jahanshahloo et al., 2011, 2009). This method has been widely used in the performance evaluation or benefit evaluation of relevant policies in the field of ecological civilization construction, such as ecological compensation system performance evaluation (Sun et al., 2017; Du and Gao, 2020), lake eutrophication evaluation (Lin et al., 2020), and Eco-Security evaluation (Zhang et al., 2021). The specific steps are as follows:

1. Construction of standardized evaluation matrix $R_{m\times n}$;

$$r_{ij} = a_{ij} \Big/ \sqrt{(\sum_{j=1}^{n} a_{ij}{}^{2}} \tag{7}$$

According to the different properties of the selected indicators, different formulas are used to standardize the respective forward, reverse, and moderate indicators. The calculation formula refers to formula (1) and formula (2). $A_{m\times n}$ is the original sample data matrix.

2. Calculate the standard decision matrix $U_{m\times n}$;

$$U = \begin{bmatrix} u_{11} & u_{12} & \dots & u_{1j} \\ u_{21} & u_{22} & \dots & u_{2j} \\ \vdots & \vdots & \vdots & \vdots \\ u_{i1} & u_{i2} & \dots & u_{ij} \end{bmatrix} = \begin{bmatrix} z_1 r_{11} & z_1 r_{12} & \cdots & z_1 r_{1j} \\ z_2 r_{21} & z_2 r_{22} & \cdots & z_2 r_{2j} \\ \vdots & \vdots & \vdots & \vdots \\ z_i r_{i1} & z_i r_{i2} & \cdots & z_i r_{ij} \end{bmatrix} \tag{8}$$

3. Determine the positive ideal solution and negative ideal solution, D^{+} is the optimal solution, D^{-} is the worst solution;

$$\begin{cases} D^{+} = \{\max u_{ij} | i = 1,2,\ldots,m\} = \{d_1^{+}, d_2^{+}, \ldots, d_m^{+}\} \\ D^{-} = \{\min u_{ij} | i = 1,2,\ldots,m\} = \{d_1^{+}, d_2^{+}, \ldots, d_m^{+}\} \end{cases} \tag{9}$$

4. Calculate the Euclidean distance between each alternative and the ideal solution;

$$\begin{cases} c_j^{+} = \sqrt{\sum_{i=1}^{m} \left[Z_i(r_{ij} - d_i^{+})\right]^2} \\ c_j^{-} = \sqrt{\sum_{i=1}^{m} \left[Z_i(r_{ij} - d_i^{-})\right]^2} \end{cases} \tag{10}$$

5. Calculate the relative closeness g_j between the evaluation value and the ideal solution, and use it to express the change of each index.

$$g_j = c_j^{-} \big/ (c_j^{+} + c_j^{-}) \tag{11}$$

In this paper, all indicators are incorporated into the carrying capacity evaluation matrix, and TOPSIS method is used to calculate the relative closeness between the annual observed data of each year between 2008 and 2017 and the ideal solution, so as to show the dynamic changes of the marine ecological carrying capacity. Among them, the ideal solution defined in this paper is the optimal level of various economic, social and environmental indicators during the study period. In the TOPSIS method, the value g_j in formula (11) is between 0 and 1. When the value tends to 1, it indicates that the marine ecological carrying capacity is closer to the optimal state, and vice versa.

Moreover, in order to further analyze the influencing factors that cause the changes of carrying capacity, according to the classification of indicators in Table 1, we construct the corresponding evaluation matrices of two subsystems and indicators respectively, and calculate the values to show their changing trends.

3. Results

3.1. Weight of the index system

The AHP weight, entropy weight and the integrated weight of the indicators are shown in Table 2. It can be noted that in the pressure system, water pollution (P6) and resource exploitation (P9) are the most influential factors, with a weight of 0.235 and 0.182, followed by tourism (P10, 0.143) and population (P8, 0.110). In the support system, the marine industry (S1, 0.376) has the highest weight, followed by innovation support (S2, 0.211) and pollution control investment (S3, 0.141).

Table 2

Weight of the indicators (Support index and Pressure index).

Subsystem	Indicator	Quantifying variables	W_1 (AHP)	W_2 (EM)	Z	Total weight
Pressure	P1	Annual financial loss	0.010	0.013	0.011	0.034
	Storm	Facility Damage of Coastal Works	0.017	0.013	0.015	
		Annual affected population	0.003	0.013	0.008	
	P2	Number of ride tide	0.011	0.040	0.025	0.051
	Red tide	Affected Area	0.032	0.020	0.026	
	P3	Disaster area affected by aquaculture	0.005	0.013	0.009	0.036
	Wave	Damage length of Coastal works	0.003	0.014	0.008	
		Damage to the vessel	0.002	0.013	0.007	
		Economic loss	0.011	0.013	0.012	
	P4	Section length	0.003	0.016	0.009	0.034
	Seawater invasion	Severe invasion distance from shore	0.013	0.016	0.015	
		Minor invasion distance from shore	0.005	0.016	0.010	
	P5	SO2 emission	0.020	0.049	0.035	0.111
	Air pollution	CO2 emission	0.014	0.037	0.026	
		Total smoke and dust emissions	0.007	0.024	0.016	
		Concentration of inhalable particulate matter to pollution load	0.038	0.030	0.034	
	P6	Waste-water disposal	0.064	0.032	0.048	0.235
	Water pollution	Chemical Oxygen Demand	0.029	0.053	0.041	
		Ammonia nitrogen content	0.029	0.050	0.039	
		Comprehensive pollution index of water quality	0.117	0.060	0.089	
		Eutrophication index of sea water	0.014	0.023	0.018	
	P7	Common Industrial Solid Wastes Produced	0.053	0.027	0.040	0.062
	Solid pollution	Common Industrial Solid Wastes disposed into the sea	0.026	0.018	0.022	
	P8	Density of population	0.113	0.028	0.071	0.110
	Population	Population growth rate	0.056	0.022	0.039	
	P9	Marine cultivable area	0.037	0.035	0.036	0.182
	Resource exploitation	Aquaculture area	0.012	0.067	0.039	
		Total marine catching	0.063	0.113	0.088	
		Number of fishing boat	0.024	0.014	0.019	
	P10	Number of travel agency	0.024	0.026	0.025	0.143
	Tourism	Number of five-star hotel	0.024	0.062	0.043	
		Tourist arrivals	0.121	0.030	0.075	
Support	S1	Proportion of GDP	0.152	0.003	0.078	0.377
	Marine economy	Fishery economic value added	0.027	0.053	0.040	
		Fisherman income	0.013	0.037	0.025	
		GDP per capita	0.059	0.076	0.068	
		Total of import and export	0.030	0.013	0.021	
		Fishery total investment	0.106	0.183	0.145	
	S2	Number of marine R&D institution	0.079	0.001	0.040	0.211
	Innovation support	Number of marine human resource	0.028	0.002	0.015	
		Number of marine students	0.028	0.047	0.037	
		Fund total of marine scientific research	0.145	0.093	0.119	
	S3	Pollution control investment	0.028	0.108	0.067	0.141
	Pollution control investment	Proportion of pollution control investment of GDP	0.078	0.069	0.074	
	S4	Number of ocean institution	0.004	0.074	0.039	0.106
	Ocean governance	Marine conservation area construction	0.019	0.095	0.057	
		Number of fisheries Enforcement Agency	0.007	0.014	0.010	
	S5	Using area per capita	0.004	0.000	0.002	0.055
	Natural resource support	Cultivated sea land per capita	0.006	0.000	0.003	
		Purified water per capita	0.010	0.052	0.031	
		Natural gas production	0.003	0.017	0.010	
		Crude oil production	0.001	0.010	0.006	
		Salt production	0.001	0.006	0.003	
	S6	Annual average precipitation PH	0.003	0.000	0.003	0.032
	Marine Environment	Water qualified rate of marine functional area	0.025	0.014	0.022	
		Proportion of first standards water	0.014	0.000	0.007	
	S7	Sewage treatment rate	0.074	0.005	0.039	0.079
	Pollutant disposal treatment	Number of waste-water treatment	0.014	0.025	0.019	
		Conversion rate of industrial solid waste	0.039	0.003	0.021	

3.2. Results of carrying capacity evaluation

Through TOPSIS, we respectively measure the dynamic changes of marine ecological carrying capacity (E index), support index (S index) and pressure index (P index). The evaluation results of Shandong province from 2008 to 2017 are shown in Fig. 4.

The results showed that the marine carrying capacity in Shandong province presented a varying trend, with the lowest level appearing between 2012 and 2015. Specifically, it was declining from 2008 to 2012, with the index value falling from 0.52 to 0.34. From 2013, the carrying capacity showed a modest rebound, wherein the E index value gradually increased from 0.35 in 2013 to 0.37 in 2015. Nonetheless, the overall value was still at a low level. The marine ecological carrying capacity increased rapidly in the last two years and reached its optimum (0.53) in 2017.

For the subsystems, we found that the P index and the E index have the same trend, and both showed a varying trend. The P index value dropped from 0.55 in 2008 to 0.30 in 2014. After 2014, the P index value presented an opposite trend, gradually rising from 0.30 to 0.50 in 2017, indicating that the environmental pressure has been alleviated to a certain extent. In the meantime, the value of the support subsystem index showed a steady upward trend from 2009 to 2016, reaching the highest value (0.75) in 2016. However, the S index showed a downward trend in 2016-2017, with the index value falling from 0.73 to 0.71.

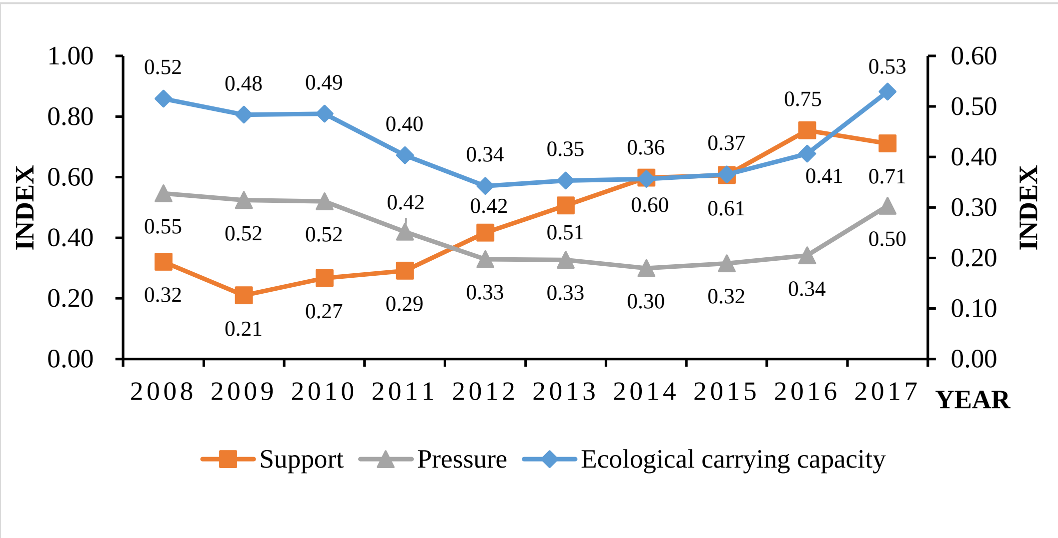

Fig. 4. Evaluated results of Ecological carrying capacity index, Pressure index and Support index

3.3. Variations of second-level indicators

On the pressure index determination, all sub-indices showed a varied trend across the study period with an exception of the social pressure sub-index which revealed a decline trend between 2008 and 2016. Among them, the indicator of marine natural disasters fluctuated most. There were three obvious turning points in 2009, 2012 and 2014 respectively. The rapid decline of social pressure brought a huge burden to the marine environment, with the value dropping from 0.53 in 2009 to 0.16 in 2016. The human-caused disasters sub-index value decreased slightly from 0.43 in 2008 to 0.39 in 2009 and rose to its optimum (0.74) in 2015, but fell again in the last two years (Fig. 5).

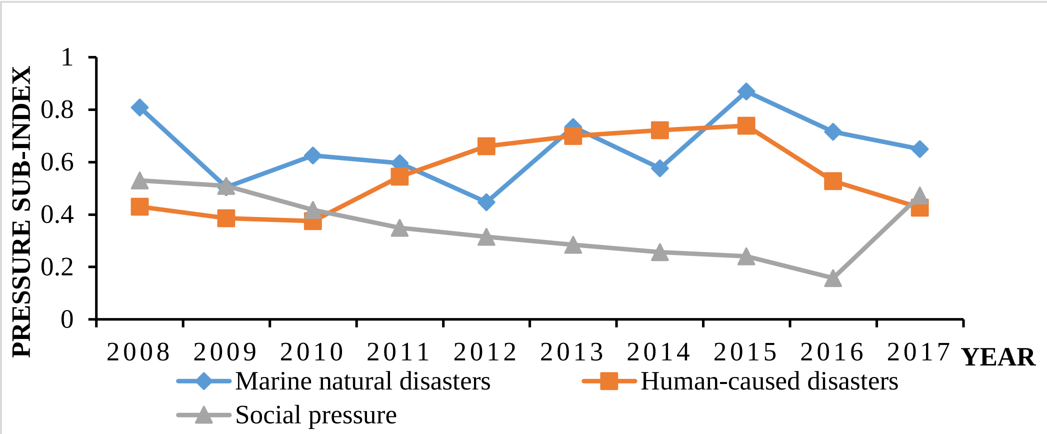

Fig. 5. Evaluated results of second-level indicators of Pressure index

In the support subsystem, the industry and governance support as well as environmental support sub-indices indicated a gradual increase with time during the study period. However, the resource support sub-index revealed a relative decreasing trend. Specifically, the industry and governance support sub-index value rose from 0.30 in 2008 to 0.72 in 2017, with an annual growth rate of 10%[3], and the environmental support sub-index value increased from 0.30 in 2008 to 0.78 in 2017. At the same time, the resource support sub-index value dropped sharply from 0.84 in 2008 to 0.20, and gradually recovered after 2014, but it did not yet achieved better improvement (Fig. 6).

[3] The annual growth rate $\bar{R}$ is calculated by the formula ($\bar{R} = \left(\sqrt[9]{\frac{X_{2017}}{X_{2008}}} - 1\right) \times 100\%$).

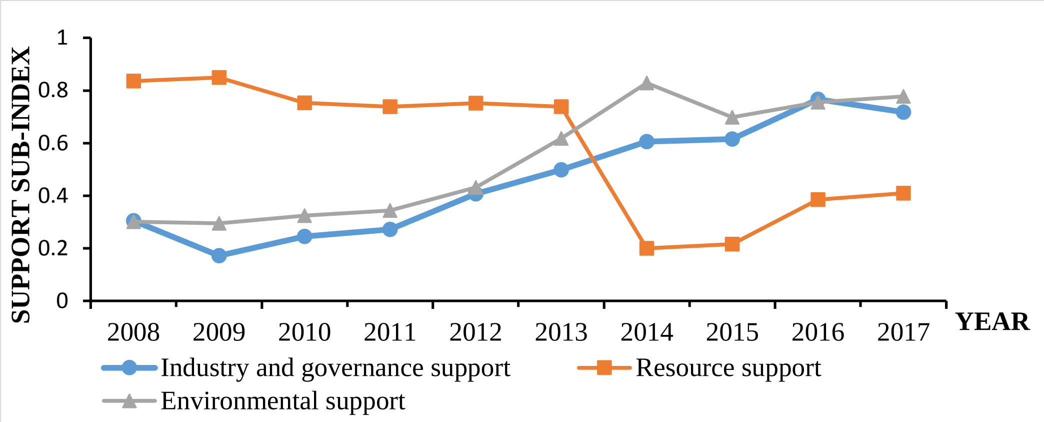

Fig. 6. Evaluated results of second-level indicators of Support index

3.4. Variations of specific indicators

In order to accurately display the dynamic trend of the specific indicators of the Pressure and Support subsystems, we also calculate the relative approximate degree of each specific indicator and their ideal solution, and the results are shown in Fig. 7 and Fig. 8.

There are 10 specific indicators of the P index, categorized into three groups. The first category is related to the natural disasters, which includes the indicators of storm (P1), red tide (P2), wave (P3) and seawater invasion (P4). The changes of these four indicators are random and uncontrollable. However, it is not difficult to find that in 2012 and 2016, the values of P1-P4 indicators were relatively low, which means that Shandong province has suffered more pressure from natural disasters. The second category has three indicators, i.e., air pollution (P5), water pollution (P6), and solid pollution (P7). During the period 2010-2013 and 2015-2016, they all showed a rapidly declining trend. The third category includes population (P8), resource exploitation (P9) and tourism (P10). The P9 and P10 values significantly reduced from 2010 to 2015. The value of P8 indicator fluctuated significantly from 2013 to 2017 and reached a minimum in 2013 (Fig. 7).

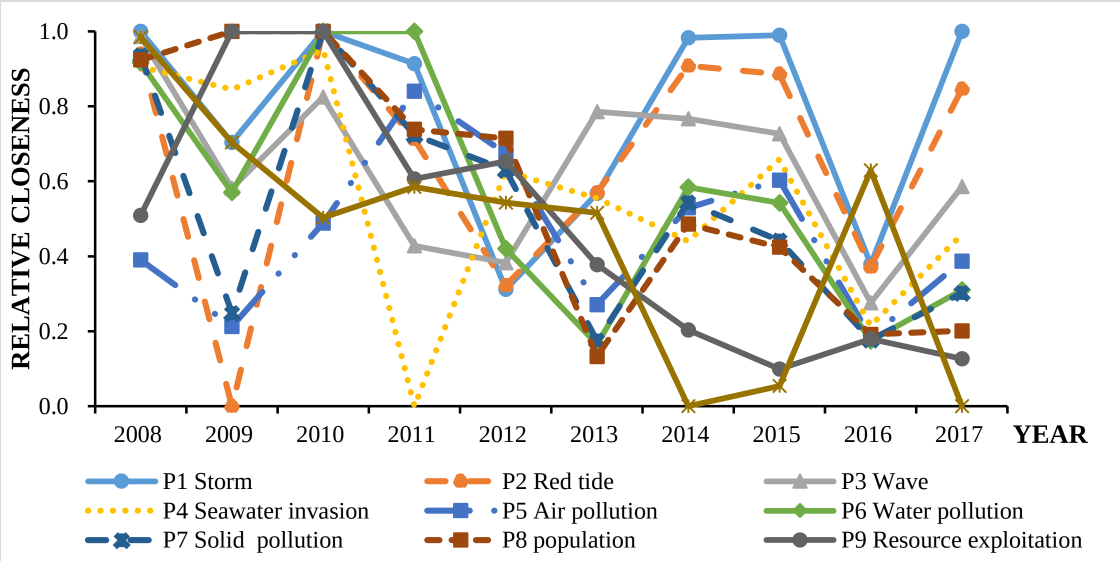

Fig. 7. Dynamic evolution of specific indicators of Pressure index (2008-2017)

There are seven specific indicators of the S index, which can also be classified into three categories. The first category includes four indicators, marine industry (S1), social support (S2), pollution control investment (S3) and ocean governance (S4). The two indicators of S1 and S2 both presented an upward trend. At the same time, the S3 indicator showed a varying trend, wherein the value declined from 0.62 in 2008 to 0 in 2010 and then gradually improved to 0.87 in 2014. The S4 indicator increased sharply from 2008 to 2012, and then began to slowly decline. The resource support (S5) indicator continuously declined from 2008 to 2014, particularly from 2013 to 2014. The other two indicators refer to marine environment support (S6) and pollutant disposal treatment (S7). The S7 indicator showed an upward trend with some fluctuations around 2014. Meanwhile, the S6 indicator value significantly reduced from 2008 to 2011 and then gradually rebounded.

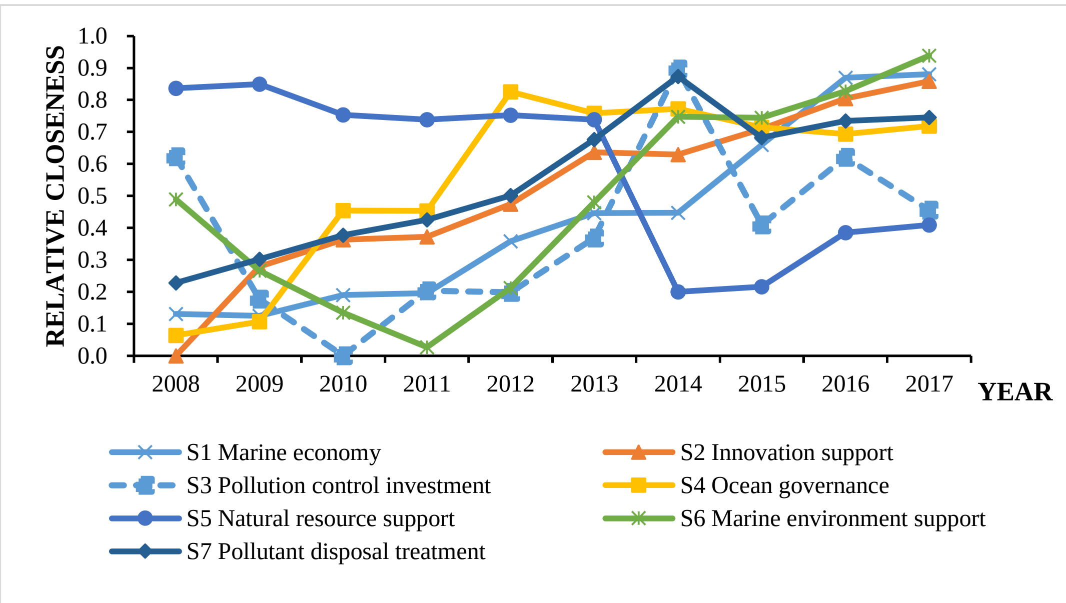

Fig. 8. Dynamic evolution of specific indicators of Support index (2008-2017)

4. Discussion

The assessment of marine ecological carrying capacity is essential for guiding local planning and development in a sustainable way (Han et al., 2018). The marine ecological carrying capacity of Shandong province presented a varying trend. It fell from 2008 to 2012 and then remained at a low level until 2015. This finding is consistent with that of other studies, which observed the same downward trend in other regions in China during the same period (Ma et al., 2017, Han et al., 2018, Liu et al., 2020). The carrying capacity of Shandong province gradually improved from 2015 and reached its optimum in 2017. This finding contributes to the existing literature as there have been very few studies that have investigated dynamic changes of marine ecological carrying capacity since 2015 due to difficulties in data collection and limitations of the research field.

Furthermore, the results show that, between 2008 and 2012, population growth, increased number of tourists, and industrial pollution were the main reasons for the decline of the marine ecological carrying capacity in Shandong province. The population density in Shandong coastal areas increased from 599 person per km^2 in 2008 to 634 person per km^2 in 2017, which is more than four times China's average population density (i.e. 148 people per km^2). In the meantime, the expansion and diversification of tourism had an increasing environmental impact on ecosystems (Canteiro et al., 2018). During this period, tourist arrivals doubled (from 240.46 million in 2008 to 487.39 million in 2012). The greater the population pressure in coastal areas, the more resource consumption and thus the more serious environmental pollution (Liang and Hui, 2016), adversely affecting the carrying capacity. A similar finding has also been reported by a case study of the ecological carrying capacity conducted in Dongtou Islands (Ma et al., 2017) and a case study of the resource-environmental carrying capacity in Jiangsu coastal zone (Liu et al., 2020).

In the 21st century, Shandong's marine economy has developed rapidly (Sun et al., 2018) with the GOP reaching more than 20% of its GDP in 2017. Alongside the fast growth, it has become evident that the uncontrolled discharge of pollutants from industries and increased economic activities have caused severe environmental damage to the marine ecosystem (Arrow et al., 1995; Kildow and Mcllgorm, 2010). For instance, the oil spill in Bohai Bay in 2011 caused pollution of 5,500 square kilometers of sea area, and as a result the water quality of 840 square kilometers area dropped from Grade 1 to 4, severely damaging the ecosystem in Bohai Bay (Zhou et al., 2014; Wang et al., 2018). In the meantime, due to increased shipping activities, there has been a surge in the consumption of fossil resources and the emissions of harmful and greenhouse gases (Xu et al., 2021; Wan et al., 2021). Alongside this, the proportion of pollution control investment in GDP declined from 0.78% to 0.38% during 2008-2012, which implies the protection of the surrounding environment did not receive enough attention.

Since 2013, the dynamic change of marine ecological carrying capacity has exhibited improvement as the P index gradually improved from 2014. Some variables closely related to industrial pollution, such as waste-water disposal, chemical oxygen demand, SO_2 emission, CO_2 emission, etc., gradually declined, reflecting the enhanced rationality of Shandong provincial government's marine management policies in recent years. In addition, the expanding investment in marine scientific research and environmental protection, as well as the increasing numbers of marine institutions (from 8 in 2008 to 22 in 2017) and construction of marine conservation area (from 220000 km^2 in 2008 to 510000 km^2 in 2017) have all contributed to the establishment of a solid foundation for the improvement of marine ecological conditions and enhancement of the marine ecological carrying capacity. This is consistent with the Chinese government's policy that calls for a balance between economic development and environmental protection based on the ecological civilization construction. Although the carrying capacity increased slightly compared with 2008 (from 0.52 in 2008 to 0.53 in 2017), given both the population (population growth rate was 1.0% in 2017) and the number of tourists (the average growth rate was about 9.8% from 2013 to 2017) have been increasing, it is vital to put more emphasis on environmental protection and resource utilization to promote the improvement of carrying capacity.

Although this article strives to construct a comprehensive and adaptable model for assessing marine ecological carrying capacity, the primary factors and indicators selected in the study article cannot be perfect. Other factors, such as global warming and rising sea levels also affect marine ecosystems to some extent and thus are worth investigating in the future (Ma et al., 2017; Norris et al., 2013). Furthermore, it is difficult to estimate the influence of human activities on the coastal ecology and difficult or impossible to quantify some indicators, thus increasing the complexities of calculating the ecological carrying capacity in coastal zones. Therefore, it is necessary to explore and enrich the marine ecological carrying capacity framework to monitor dynamic changes in the regional carrying capacity.

5. Conclusions

With the rapid development of its marine economy, China has taken many measures to ensure sustainable development. The marine carrying capacity has thus become a crucial principle to evaluate the sustainability of the ocean. In this paper, a marine ecological carrying capacity framework has been developed as an effective model to integrate various complex variables of social-natural coastal ecosystem and identify the interactions between complex pressure and support factors. The proposed model and methods effectively reflect the trends of the marine carrying capacity in the research area. Analysis of specific indicators provided a further understanding of some related key driving factors of the carrying capacity and presented targeted suggestions for coastal management.

The evaluation results show that the marine ecological carrying capacity of the study area was at a low level during 2012-2015. The main reason for the decline is partly due to the intense social and environmental pressure caused by the rapid population growth and the increased number of tourists brought by the tourism development. The other factor in this decline was the various types of pollution brought by industrial development. Government departments and policy makers can adopt reasonable and effective methods to improve the status of these factors, thereby enhancing the carrying capacity.

To enhance the coastal carrying capacity and ensure sustainable development, Shandong province can improve the support and pressure status by putting effort into increasing support and decreasing pressure. To achieve that, three key recommendations are made for overall planning and integrated coastal management: 1) In terms of reducing industrial pollution, it should take green development as an important feature, give importance to the protection of marine environment, and optimize the layout of coastal industries by increasing the proportion of modern service industries and high-tech industries; 2) In order to strengthen the protection of marine ecological environment and maintain biodiversity, and improve the specific environmental protection laws and regulations, the main point is to complete the dynamic monitoring system and the crisis management mechanisms of Shandong province. Simultaneously, it also needs to establish a demonstration zone of marine ecological civilization and increase coastal nature reserves to explore the construction of marine ecological civilization. 3) The government still needs to optimize the population structure further, reasonably control the population growth rate, and increase investment in education and the training of highly educated talents in marine ecology. In the meantime, the local government also needs to vigorously support sustainable ecological tourism and accelerate the construction of protected areas to reduce the impact of intense population pressure on the environment.

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Declaration of interests

we declare that we have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.