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Four-dimensional evaluation and forecasting of marine carrying capacity in China: Empirical analysis based on the entropy method and grey Verhulst model

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ABSTRACT

This study separates marine carrying capacity into four key dimensions, i.e., social, economic, resource, and ecological, and uses the entropy method to evaluate the carrying capacity of China's 11 coastal regions during the period 2007–2016. We then predict the values of marine carrying capacity in the subsequent five years (2017–2021) using the grey Verhulst model. Results reveal a significant disparity in marine carrying capacity among the 11 coastal regions of China, and social and ecological carrying capacities illustrate among the four subcategories. Pearl River Delta in the south has the highest marine carrying capacity value and shows an increasing trend, while Yangtze River Delta and Bohai Rim Region in the north are stable. With regard to the predicted values for 2017–2021, forecasting results illustrate that the industrial structure of China's coastal areas is gradually turning towards the mode of diversified and comprehensive utilization of marine resources.

1. Introduction

Since the 1990s, the ocean has become an increasingly prominent strategic resource due to the entry into force of the United Nations Convention on the Law of the Sea and the implementation of Agenda 21. In addition, development of the marine economy has become an important way to solve the problems facing humankind in the twenty-first century, such as the population explosion, resource shortages, environmental degradation, and climate change. In recent decades, high marine technologies have developed rapidly, new and exploitable marine resources have been discovered, and new marine industrial clusters have been formed (Shao et al., 2020). According to the recently released China Marine Economic Development Report 2019, China's gross ocean product (GOP) reached 8.3 trillion yuan in 2018, with a growth rate of 6.7% per year; GOP accounted for 9.3% of the country's gross domestic product (GDP), providing 36.84 million jobs in coastal areas and contributing nearly 10% to China's overall economic growth. In addition, the added value of China's three marine industries (i.e., primary industry, secondary industry, and tertiary industry) accounted for 4.4%, 37.0%, and 58.6% of the GOP, respectively (NDRC and MENR, 2019).

As land resources diminish in supply and human populations increase, the severity of the deterioration of the ecological environment becomes ever more a concern and the importance of sustainability of the ocean increases (Yin et al., 2018; Shao, 2020). Following the definition of carrying capacity, marine carrying capacity denotes the interaction between the "ocean" as a physical base and "humans". Marine carrying capacity differs from other kinds of carrying capacities, such as urban carrying capacity (Shao et al., 2019; Weng et al., 2020), as the ocean does not merely support human activities by providing resources but also contributes to human activities in various aspects such as improving the ecological environment. Therefore, the provisioning of ocean resources alone cannot entirely convey its carrying capacity; rather, the resilience of ocean resources (self-recovery ability), while under sustainable exploitation, is more important. Therefore, marine carrying capacity can be understood as actually conveying the largest support degree for human activities (Liao et al., 2013; Tian et al., 2020). In this light, two aspects of the connotations of marine carrying capacity can be illustrated: on the one hand, oceans provide many resources necessary to support human society and to build the ocean-related industries, such as marine fisheries, exploitation of oil, gas, and minerals; on the other hand, oceans can accommodate a variety of pollutants.
produced by land-based economies, and this too is an important function provided by oceans (Lai et al., 2020). Further, as marine carrying capacity includes both the productivity of the ocean and management ability, according to the China Sustainable Development Strategy Report 2000 (Niu, 2000), enhancing marine carrying capacity has become a requirement for sustainable development in coastal regions, while the ongoing augmentation of marine carrying capacity facilitates oceans' sustainable development.

However, empirical evidence has confirmed that the resource and environmental carrying capacity of the ocean in China is already overloaded (van den Bergh and Verbruggen, 1999; Di and Zheng, 2017). Marine biodiversity is being destroyed, and the overall water quality of China's seaward rivers is poor. A total of 866.424 million tons (Mt) of sewage were directly discharged to the sea in 2018, with the largest discharge from integrated sewage outlets, followed by industrial sources, and finally domestic sources (MEE, 2018). In addition, populations in coastal areas will continue to increase, industrialization and urbanization will accelerate, and the scale of economic activity will further expand. Against this backdrop, the 13th Five-Year Plan (2016–2020) includes “carrying capacity” of resources and environment as a key point of reference for China's green development (Han et al., 2018). The Outline Development Plan for the Guangdong–Hong Kong–Macao Greater Bay Area also proposes building a modern marine industry system; improving traditional industries, such as marine fisheries and transportation; fostering emerging industries, such as marine biomedicine and marine engineering equipment manufacturing; and accelerating the development of marine services, such as port logistics, coastal tourism, and marine information services (SC, 2019). Therefore, there is an urgent need to study marine carrying capacity, as well as future development trends related thereto, in order to devise better management strategies and more rational use of oceans and ocean resources from the perspective of carrying capacity, and to put forward control measures for preserving a healthy and just relationship between the ocean and humans so as to realize oceans' sustainable development (McKinley et al., 2020; Song et al., 2020).

The entropy weight method and the grey Verhulst model are employed in this study. As Weng et al. (2020, p.20028) indicated, “the entropy method measures the uncertainty contained within each variable for the whole theoretical concept; the approach essentially provides a deeper description of the uncertainty and can eliminate uncertainty in the evaluation analysis to the maximum extent possible, thus making the evaluation more objective”. In addition, the entropy method has been applied in the evaluation of urban carrying capacity (Weng et al., 2020) and marine carrying capacity (Di and Li, 2018), environmental conflict analysis, and the sustainable development capability of agriculture (Li et al., 2019). Following Di and Li (2018), and Liu et al. (2020), this paper uses the entropy method to determine the weight of the specific evaluation indicators of marine carrying capacity for each year. Deng (1982) established the grey theory, which made quantitative prediction of the future by modeling limited original data (Wang and Li, 2019). At present, GM (1,1) model, grey Markov model and grey Verhulst model are widely used in grey forecasting. GM(1,1) model is suitable for sequences with strong exponential laws, but it can only describe the monotonically changing process of data, and the simulation results have low accuracy (Li et al., 2009). The grey Markov prediction model needs to divide the data interval, which is relatively subjective (Zhao et al., 2020). The marine carrying capacity system constructed in this paper is a dynamic system with a certain random fluctuation, which is suitable for the use of grey Verhulst model (Wang et al., 2020).

In light of the above, this study focuses on the 11 coastal regions of China during the period 2007–2016 to evaluate their marine carrying capacity. An index system with four sub-categories (i.e., social, economic, resource, and ecological) is constructed using the entropy weight method, and the values of marine carrying capacity for the subsequent five years (2017–2021) are then forecast using the grey Verhulst model. The main contributions of the study are threefold. First, unlike the regional and single-dimensional analysis conducted in previous research, this study systematically and comprehensively investigates the overall marine carrying capacity of 11 coastal provinces and municipalities, as well as the capacity of the four subcategories in each, from which a comparative analysis is conducted from the perspective of spatial distribution. Second, 30 indicators are selected to construct a more comprehensive marine carrying capacity evaluation system compare to prior studies. Third, prediction analysis shows the future carrying capacity variation trends of China's coastal areas, providing a theoretical basis for policy formulation.

2. Literature review

Based on the theory and practice of environment and resource carrying capacity, and to meet the needs to explore marine resources and develop a marine-based “blue economy” (Jiang et al., 2017; Sangha et al., 2019), researchers have begun to incorporate the ocean into their evaluation frameworks. Some researchers have applied one or more aspects of carrying capacity, such as environment, ecological, or social dimensions. Agmour et al. (2018) indicated that the increase of marine species carrying capacity does not necessarily lead to an increase of catch levels and incomes, using the Atlantic coast of Morocco as case study. By comparison, fisheries in southern Brazil already utilize a large proportion of the marine shelf ecosystem carrying capacity, thus a better ocean governance is need for a long-term sustainable utilization of the sea (Vasconcellos and Gasalla, 2001). Culhane et al. (2020) even developed a systematic framework to evaluate the capacity of supplying ocean ecosystem service in Europe at regional level, despite the quality of data.

Moreover, Liao et al.’s (2013) pioneering study tested the satisfaction levels related to three methods by evaluating the marine environmental carrying capacity of Xiamen Bay, and found that the effectiveness of classical linear optimization, fuzzy optimization, and grey fuzzy optimization have gradually strengthened. Focusing on the ecological aspect of marine carrying capacity in the Dongtou Islands of China, an index system with two objects (carrier and carrying) and three layers (human activities, socio-economic development, and ecological resilience) was constructed by Ma et al. (2017). The results revealed a decreasing capacity value across the research period (2009–2014), with direct pressure coming primarily from coastal reclamation, tourism, and transportation. With regard to social carrying capacity of the oceans, Gonson et al. (2018) used a questionnaire survey to examine the level of social carrying capacity in New Caledonia (a coastal area belonging to France) in order to detect its impact on the spatial distribution of users, which is meaningful for improving recreational use and management approaches to achieve sustainable goals. Kluger et al. (2019) used data collected from the media to analyze changes in social carrying capacity; that is, they considered societal discourse on acceptable levels of aquaculture expansion against different cultural backgrounds for case studies of Casco Bay in the USA, Ría de Arousa in Spain, and Sechura Bay in Peru. Thus, as can be seen, social carrying capacity of the ocean may have different connotations in different contexts, and can be assessed using either quantitative or qualitative methods.

Comprehensive analyses incorporating environmental, ecological, as well as socioeconomic dimensions have been conducted in recent years. For example, Han et al. (2018) constructed an index system including 14 pressure indicators with four layers (coastal disasters, population, coastal pollution, and resource exploitation) that negatively affect marine carrying capacity, as well as 19 support indicators with another four layers (resource, environment, typical habitat, and social support) that have a positive effect, in order to evaluate the marine carrying capacity of Guangxi Province in China during the period 2004–2013. Their results showed a decreasing trend of marine carrying capacity in Guangxi, mainly due to human activities such as land
reclamation, fishing, coastal industry, port construction, and tourism activities. Focusing on another coastal region of eastern China, Jiangsu Province, Liu et al. (2020) constructed a coastal resource–environmental carrying capacity index with three subsystems (i.e., resource, ecological, and socio-economic aspects) to comprehensively evaluate the carrying capacity value, as well as trade-offs between the subsystems from 2000 to 2015, using the entropy weight method and analytic hierarchy process. The results show that, except for the ecological subsystem, the other two subsystems and the overall value continually decreased throughout the research period, and the overall values were low. Since the ecological layer plays an illustrative role regarding the variations of carrying capacity, the authors identified significant driving factors under the layer, such as vegetation coverage, coastal water environmental quality, habitat, and ecological land proportion, which have obvious policy implications. Thus, Liu et al.’s study is of both theoretical and practical value.

In addition, Jiang et al. (2017) considered marine industrial parks in Shandong Province, rather than an administrative district as their research objective, to build an index system incorporating three dimensions (pressure, bearing, and transformation) with 32 indicators to delineate comprehensive carrying capacity values. According to various types of parks, the results indicated that the modern marine service industry and fishery industrial parks perform well in terms of carrying capacity, with an improving development trend. Conversely, the modern marine manufacturing industry and emerging industrial parks, which had greater strategic value, were found to be comparatively underdeveloped and needed more time to develop. In a similar vein, the carrying capacity of recreational fisheries in Ascension Bay of Mexico has been evaluated by estimating the optimum boating density using geographic information system data analysis (Palomo and Hernández-Flores, 2020).

Based on the regional and park-level analyses mentioned above, Du et al. (2020) expanded the research sample to China as a whole to evaluate the carrying capacity of marine resources and environment aspects by employing a comprehensive assessment framework (DPPD) incorporating four specific methods to capture interaction effects among the components. Their results were in line with those of prior studies, as the overall evaluation value of the 11 coastal regions slightly declined, with a poor development trend.

Evaluations of marine carrying capacity evaluation have been conducted towards different uses and aims; thus, various methodologies have been developed. For example, to evaluate the effectiveness of ocean-related environmental policies implemented in the European Union, Culhane et al. (2020) developed a marine ecosystem capacity for service supply assessment (MECSA) framework to assess the current marine ecosystem capacity for service supply and the direction of change in this capacity. By considering three cases, they found that the Mediterranean Sea and the Baltic Sea have unsatisfactory capacity with regard to whale watching and nutrient waste removal service supply, respectively, while the North Sea performs well in commercial fish and shellfish provisioning. The MECSA approach, including its concept, framework, and methodology, can be generalized to other regions and backgrounds. Another function of marine carrying capacity evaluation is to assess beach economic value. Using three recreational Italian beaches with different types and locations as case studies, Rodella et al. (2020) estimated their economic value by multiplying the sustainable carrying capacity of each site with respondents’ related maximum willingness to pay. Their results showed that the values varied from more than 50 million euros per season at a popular urban beach to 1 million euros per season at a remote natural beach. The results are also applicable to other sandy beaches worldwide. Therefore, managers of beaches should pay more attention to, and provide sufficient investment in, this overlooked economic resource. Moreover, with the aim of achieving sustainable beach tourism, a questionnaire survey conducted by Chen and Teng (2016) identified several important concerns for tourists, which indicate management priorities, and calculated the carrying capacity limit according to a focus group discussion.

However, despite the abovementioned discussions, existing research has only focused on marine carrying capacity evaluation of one aspect (e.g., the ecological dimension in Ma et al., 2017), conducted comprehensive analysis in a specific region (e.g., Guangxi Province in Han et al., 2018) or a park (such as marine industrial parks in Jiang et al., 2017), or with a specific assessment aim (e.g., estimation of beach economic value in Rodella et al., 2020). Thus, comprehensive evaluation of marine carrying capacity of multiple dimensions across all 11 coastal regions of China is lacking. Further, prediction analysis of marine carrying capacity is rare in existing literature. To bridge these gaps, this study uses the entropy weight method to build an assessment framework incorporating social, economic, resource, and ecological dimensions to evaluate the carrying capacity of China’s 11 coastal regions during the period 2007–2016, and to predict the values over the subsequent five years (2017–2021) using the grey Verhulst model.

3. Model specification and data selection

3.1. Establishment of a marine carrying capacity index system

3.1.1. Indicator selection

Based on research by Di and Li (2018), Han et al. (2018), and Weng et al. (2020), and following the scientific, availability, and comparability index selection principle, an evaluation index system of marine carrying capacity was built. This system includes a total of four marine criterion layers: social carrying capacity, economic carrying capacity, resource carrying capacity, as well as the ecological carrying capacity. The four layers feature a total of 30 indicators (units), and the number of indicators for this framework exceeds those used in the existing literature. What is worth mentioning, although the addition of additional indicators could make the assessment of marine carrying capacity more comprehensive, we do not believe that the inclusion of indicators that are currently unavailable or difficult to measure would have a significant impact on our assessment results. Taking the marine disaster resistance capacity of coastal provinces and cities as an example, the development of marine industry is conducive to reducing the damage caused by marine disasters. For example, flood levees and related engineering facilities will reduce the damage caused by storm surges, and the development of science and technology can improve the accuracy of disaster early warning. Therefore, indicators such as the development of marine industry and the investment in science and technology can well reflect the disaster resistance ability of the region (Tessler et al., 2015; Liu et al., 2017).

All the data were sourced from the China Statistical Yearbook (CSY, 2019), China Marine Statistical Yearbook (SOA, 2018), and China City Statistical Yearbook (NBS, 2019), from 2008 through to 2017. (See Table 1 for the attributes and summary statistics of all 30 indicators of the four layers.)

3.1.2. Indicator explanations and estimation method

A sample of the 30 indicators is listed below, along with their calculation methods with reference to the relevant standards.

1) Passenger turnover marine volume: This refers to the product of the actual number of passengers transported and the distance transported, with a unit measure of 100 million person-km. Volume of maritime passenger turnover: This conveys both coastal volume of passenger turnover and oceangoing volume of passenger turnover.

2) Volume of marine goods turnover: This is the product of the number of tons handled and the distance shipped, expressed in units of 100 million t-km. Volume of maritime goods turnover: This comprises the coastal volume of goods turnover and the oceangoing volume of goods turnover.

3) Gross ocean product: This is the total value of marine products (both goods and services) produced by permanent resident units of marine
industry departments for a certain time period, thereby reflecting the total results of production and operation activities of the marine industry.

4) Total investment in treatment of environmental pollution: This is the sum of the investments made in urban environment infrastructure facilities, investments in treating industrial pollution sources, and investments in environmental components for “Three-Simultaneity” new construction projects.

3.2. The entropy weight method

The entropy weight method was proposed by Shannon (1948). The concept of entropy is well suited to measuring the relative strength of comparison criterion to represent the average intrinsic information involved in the decision. Following Liu et al. (2020), this study uses the entropy weight method to estimate the weights of indicators and layers. In addition, the Technique for Order Preference by Similarity to an Ideal Solution is used to evaluate the marine carrying capacity in China’s coastal areas (Nilashi et al., 2019). The steps of the model are as follows:

1) Normalize the original data:

Set the original evaluation index matrix of marine carrying capacity as $X(x_i$ is the original value of data), where $i = 1, 2, \ldots, m$ and $m$ is the number of evaluation samples; $j = 1, 2, \ldots, n$, $n$ is the number of evaluation indicators. To obtain the standardized evaluation matrix, this paper uses the extreme value standardization method to process the original index.

Positive indicators:

$$Z_{ij} = \frac{x_{ij} - x_{ij\text{ min}}}{x_{ij\text{ max}} - x_{ij\text{ min}}}$$ (1)

Negative indicators:

$$Z_{ij} = \frac{x_{ij\text{ max}} - x_{ij}}{x_{ij\text{ max}} - x_{ij\text{ min}}}$$ (2)

2) Estimate the weight of indicator $j$:

$$w_j = \frac{(1 - H_j)}{\sum_{j=1}^{n} (1 - H_j)}$$ (3)

$$H_j = -\frac{1}{\ln m} \sum_{i=1}^{m} f_i \ln f_i$$ (4)

where $w_j$ is the weight of indicator $j$, $w_j \in [0, 1]$, $H_j$ is the information entropy, and $f_j$ is an indicators’ weight. The following estimation method is used:

$$p_j = z_j / \sum z_j$$ (5)

3) Estimate the comprehensive marine carrying capacity of a given region:

$$V_i = \sum_{j=1}^{n} w_j p_{ij}$$ (6)

3.3. The grey Verhulst model

3.3.1. Theory behind the grey Verhulst model

Grey prediction modeling is an important part of the grey system theory put forward by Deng (1982), which is expressed via a GM (1, 1) prediction model. More specifically, GM (1, 1) is a long-term forecasting model that has been widely used in both environmental and economic fields. The model is considered reliable in the absence of major market fluctuations.
fluctuations and policy changes (Deng, 1982; Tang et al., 2016). However, the GM (1,1) model is not reliable for predicting nonlinear sequences featuring a saturated state. Due to restrictions of the surrounding environment and the implementation of structural adjustment policies, the development trends of human populations and the marine industry are not monotonous and nonlinear. However, the grey Verhulst model has a strong ability to predict the process underpinning in the data (i.e., S-type process) (Huang et al., 2015). For example, oil production prediction (Ma and Lü, 2018), decoupling state prediction of energy power and industrial electrification (Wang et al., 2020), COVID-19 infection number prediction (Zhao et al., 2020), etc. This model has the advantages of reliable theory, simple method and high prediction accuracy (Wang and Li, 2019).

In recent years, indicators such as the population size and the exploitation of Marine resources (such as the output of sea salt and natural gas) in China's coastal areas show an S-shaped process. Thus, the grey Verhulst model is applied here for reference, with the model improved by using the method of equidimensional grey number incremental prediction. The new predicted value is added to the original sample sequence, and the first data point in the sample sequence removed. The grey Verhulst model is then re-established based on the updated sequence.

1) The original non-negative sequence is: $X^{00} = \{x^{00}(1), x^{00}(2), ..., x^{00}(n)\}$, where the sequence of accumulated generating operation is $X^{(1)} = \{x^{(1)}(1), x^{(1)}(2), ..., x^{(1)}(n)\}$.

2) Set up the sequence matrix $B$ and the data vector $Y$.

$$B = \begin{bmatrix} -Z^{(1)}(2) & (Z^{(1)}(2)) \\ -Z^{(1)}(3) & (Z^{(1)}(3)) \\ \vdots & \vdots \\ -Z^{(1)}(n) & (Z^{(1)}(n)) \end{bmatrix} \quad (7)$$

Thus, the equation can be represented as $Y_a = Bz$. Based on the least-squares fitting method we then obtain the following:

$$\hat{z} = (B^TB)^{-1}B^TY \quad (8)$$

3) The discrete time response function of the grey prediction is thus:

$$\hat{x}^{(1)}(k + 1) = \frac{ax^{(0)}(1)}{hx^{(1)}(1) + (a - bx^{(1)}(1))e^k} \quad (9)$$

4) The sequence of inverse accumulated generating operation is thus:

$$\hat{x}^{(0)}(k + 1) = \hat{x}^{(1)}(k + 1) - \hat{x}^{(1)}(k) \quad (10)$$

where $k = 1, 2, ..., n - 1$.

3.3.2. Model testing

To ensure the applicability and feasibility of the prediction model, we performed an accuracy test to judge whether the prediction results are reasonable. Only a model that passed such a test could be used for prediction. The accuracy of the grey prediction model was tested using the relative error method. Generally, the prediction results are considered valid and realistic when the average relative error is less than 10% (Wang et al., 2020). The average relative error is calculated using

$$rel = \frac{1}{n} \sum_{k=1}^{n} \frac{|ax|}{|x^{(1)}(k)|}$$

4. Empirical analysis and discussion

4.1. Marine carrying capacity evaluation

4.1.1. Calculation of the weights of the indexes of marine carrying capacity

Using the entropy method, the index weights of the evaluation system of marine carrying capacity were calculated; the results are shown in Table 1 according to the social, economic, resource, and ecological carrying capacities (Shao et al., 2020). As can be seen, the contribution of each index to marine carrying capacity varied. According to the calculation results, regardless of the minimal contribution of resource carrying capacity (0.0893), the weight of ecological carrying capacity was 0.4591, making it the most important factor affecting the comprehensive level of carrying capacity in the 11 coastal provinces and municipalities. Among the indicators, marine-type nature reserve area accounts for the largest weight in ecological carrying capacity (0.0936), followed by per capita freshwater (0.0694), which illustrate the essential role of marine reserve area and freshwater in this evaluation framework. Investment in anti-pollution projects as a percentage of GDP was also relatively large (0.0263). Investment in pollution control can improve the marine ecological environment to a certain extent, but it should be matched with an advanced management system to avoid the impediment of low-investment efficiency or corruption induced by excessive investment.

The weight of the social carrying capacity criterion layer was 0.3021; hence, it too is an important factor affecting marine carrying capacity. The number of patents granted by oceanographic institutions accounted for the largest weight (0.0741) of social carrying capacity, followed by the volume of marine goods turnover (0.0633) (Needham et al., 2011). Thus, these two indicators are essential in improving the social carrying capacity. The weight of the number of marine scientific research institutions was relatively small (0.0276); yet, evidences already show that marine scientific research has an obvious positive impact on the utilization of marine resources as well as the sustainable development of a regional marine economy (Shannon, 1948; Di and Li, 2018). In this light, China needs to take measures to maximize the role of science and technology in ocean utilization and marine economic development.

With regard to the economic carrying capacity, marine service industry added value accounted for a large share (0.0434), while the indicators of resource carrying capacity, such as the output of offshore natural gas and sea salt, were relatively small. These findings are consistent with China's current marine industrial structure; that is, development of the marine economy has gradually changed from resource-based to service-oriented—put differently, the share of the service industry as a percentage of GDP is gradually increasing (Han et al., 2018). Reasons for this ongoing shift may be that the poor layout of the marine industry leads to intensive exploitation and inefficient utilization of marine resources, which depletes resources and restricts sustainable development of the overall marine economy. Therefore, as noted previously, "in order to achieve sustainable development, it is necessary to optimize the industrial structure based on the characteristics of marine resources and vigorously develop modern marine service industry" (Sheng et al., 2016, p. 22).

4.1.2. Marine carrying capacity evaluation values of China's 11 coastal provinces and municipalities

Based on the above analyses, we evaluated the comprehensive marine carrying capacity values of the 11 coastal provinces/municipalities. Fig. 1 displays the locations of the 11 coastal regions of China and illustrates their evaluation values of marine carrying capacity in 2016.

As Fig. 2 shows, their respective capacities vary greatly within and across years. Regional standard deviations are presented in parentheses, and show the dispersion of marine carrying capacity in each area. The greater the standard deviation, the greater the dispersion degree of carrying capacity, and the greater the fluctuation. Further, standard deviation values of different regions are very similar, implying that there are no outliers. Across the whole study period, the decline of marine carrying capacity in Tianjin is the most obvious. For those indicators with negative attributes, with the rapid growth of the marine economy in Tianjin in recent years, this city has made great efforts to exploit resources from the sea, and the exploitation of marine crude oil
has increased from 14.845 million tons (Mt) to 29.234 Mt. Meanwhile, positive indicators such as the proportion of investment in environmental pollution treatment in GDP underwent a remarkable decline, from 1.18% to 0.3%, thus negatively impacting the marine environment. To sum up, a declining trend in the marine carrying capacity of Tianjin was illustrated during the study period.

By way of comparison, Guangdong and Jiangsu provinces had the fastest growth rates for marine carrying capacity, at 15.6% and 10.3%, respectively, over the past 10 years. Specifically, Guangdong’s marine carrying capacity gradually declined before 2011; after a stable transition period, it increased on a rapid trajectory from 2013. Two possible reasons for this outcome may be highlighted here. First, relevant indicators of marine scientific research and ecological environment in Guangdong have ranked highly among China’s coastal cities, and Guangdong started the transformation of its marine industry early. Second, the fact that the marine carrying capacity of Guangdong
showed an increasing trend from 2013 suggests that its marine industry developed more steadily following this transformation.

Except for these two areas, Jiangsu had the highest average carrying capacity, at 0.64, followed by Shanghai and Liaoning, whereas Hebei had the lowest carrying capacity, at 0.27. Thus, the economically developed regions always showed a comparatively high marine carrying capacity; this is consistent with research by Di and Li (2018), who found that Guangdong, Shanghai, and Liaoning ranked highly in their marine carrying capacity among coastal areas. The probable reason for this dominance is that well-developed provinces and municipalities, such as Guangdong and Shanghai, enjoy a relatively high level of economic development, large turnover of goods and passengers, and adequate investment in marine research and pollution control. The findings indicate that, in recent years, these regions have achieved some success in developing their marine industrial structure and attaching importance to the ecological environment in a coordinated manner. Hebei province, by contrast, relies heavily on traditional exploitation of marine resources and has no competitive advantage in terms of its social carrying capacity.

4.1.3. Marine carrying capacity evaluation values of three coastal regions

The Yangtze River Delta, Pearl River Delta, and Bohai Rim Region are important growth poles of China’s economy, and also serve as major technological innovation centers (Tang et al., 2016; Li et al., 2019). Among them, the Bohai Rim Region includes Tianjin, Hebei, Shandong, and Liaoning; the Yangtze River Delta includes Shanghai, Jiangsu, and Zhejiang; and the Pearl River Delta includes Fujian, Guangdong, Guangxi, and Hainan. As Fig. 3 shows, the standard deviation for the Bohai Rim Region is slightly higher than those of the other two coastal regions, of which Yangtze River Delta is the lowest. These insights can be seen in the degree of fluctuation of the three lines; the black line (Bohai Rim Region) shows a decrease across the whole research period while the red line (Yangtze River Delta) shows a slight decline before 2011 and then almost returns to its original level.

In 2016, the comprehensive evaluation score of the carrying capacity of Pearl River Delta was as high as 1.98—much higher than those of the other two regions. Although there is little exploitation of marine resources in Fujian, Guangxi, and Hainan, the overall levels of ecological carrying capacity in these areas are relatively high. For example, in 2016 the added value of marine tertiary industry in this region accounted for 39.1% of the total of the 11 coastal provinces and municipalities. Moreover, marine-type nature reserve area, offshore and coastal natural wetland area, and forests in this region account for 53.0%, 52.9%, and 63.9%, respectively, of the total across the 11 coastal provinces and municipalities. On the whole, the structure of the marine industry in the Pearl River Delta has been continuously optimized and upgraded, which explains why the comprehensive evaluation score of its marine carrying capacity in recent years has tended to rise.

4.2. Forecasting results and analysis

4.2.1. Forecasting results of marine carrying capacity for the 11 China coastal regions from 2017 to 2021

According to the grey Verhulst model, the grey system method is more effective for generating short-term prediction results than medium and long-term prediction results (Guillen et al., 2016; Wang and Li, 2019). In this paper, the marine carrying capacity values for China’s coastal areas from 2007 to 2016 were taken as the sample to predict changes in each area from 2017 to 2021. Prediction results are shown in Fig. 4. Further testing the results of the applied Verhulst model produced average absolute errors of the 11 coastal provinces and municipalities that all fell within 10% (see Appendix B). Thus, this model can be regard as having good accuracy and can therefore be used for prediction purposes in addressing practical problems.

As can be seen from Fig. 4, the marine carrying capacity of the Pearl River Delta maintained good development momentum from 2017 to 2021. This result is in line with the China Marine Economic Development Report 2019, which announced that the GDP of the three major marine economic circles in the north, east, and south of China’s coastline increased by 7.0%, 8.0%, and 10.6%, respectively, with the south having strong growth momentum in its marine industry (NDRC and MENR, 2019). This result in turn confirms the validity and feasibility of the model used here.

4.2.2. Forecasting results of the indicators with positive and negative attributes

This section further predicts the values of marine carrying capacity indicators. It should be noted that some indicators are not suitable for forecasting since the values of these indicators barely changed in the past decade. For example, by 2016 the urban sewage treatment rate in coastal areas had approached a saturation level, close to the target of 95% urban sewage treatment in the 13th Five-Year Plan. Moreover, the number of marine nature reserves and marine scientific research institutions are difficult to increase in the short term. In this light, we exclude 8 indicators with slight variations and select 12 negative indicators and 10 positive indicators to predict, please see Figs. 5 and 6.

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2 See http://www.ndrc.gov.cn/fzgggz/fzgh/ghwb/gjgh/201706/t20170605_849988.html
As can be seen, for traditional marine industries, the exploitation of marine crude oil and natural gas maintained an increasing trend across the research period, but the growth rates are gradually slowed down. The yield of marine fishing and sea salt generally decreased in a fluctuating manner. With the continuous improvement of Chinese people’s living standard, the market demand for marine products is rising rapidly, which provides a huge space. Mariculture yield (maricultural production) and marine tourism (number of tourists) are expected to grow during the period of 2017–2021. To meet the increasing demand for marine economic activities, greater opportunities will be created for tertiary industry of the ocean, such as volume of marine goods turnover, passenger turnover marine volume and added value of marine service industry.

In addition, indicators representing marine scientific research capacity, such as number of patents granted by oceanographic institutions, number of marine scientists, have maintained a rapid development trend, indicating that advanced marine technology and innovation are expected to become an important engine to promote the development of marine industry in China. This also suggests that the industrial structure of China’s coastal areas is gradually turning towards the mode of diversified and comprehensive utilization of marine resources.

5. Conclusions and policy implications

5.1. Conclusions

Based on prior studies, by using the entropy method and dividing the marine carrying capacity into social, economic, resource, and ecological carrying capacities, this study evaluated carrying capacities of China’s 11 coastal provinces/municipalities from 2007 to 2016. Employing the grey Verhulst model and selecting 30 indicators related to marine carrying capacity, we also predicted the values of carrying capacities of the regions and indicators for the subsequent five years (from 2017 to 2021). Several conclusions can be summarized here. First, the marine carrying capacity varies greatly across the 11 coastal regions of China; among the four subcategories, ecological and social carrying capacities contribute most to, and have the biggest impact.
upon, the marine carrying capacity. Second, a comparison of the carrying capacity of the Yangtze River Delta, Pearl River Delta, and Bohai Rim Region showed that this was highest in the Pearl River Delta, for which it shows a steady rising trend over time. By contrast, the difference in marine carrying capacity between the Yangtze River Delta and Bohai Rim Region is gradually narrowing. Third, the estimations of the applied grey Verhulst model, from 2017 to 2021, again confirm the dominance of the Pearl River Delta’s marine carrying capacity in China’s coastal areas; the predicted results are consistent with published survey reports and research results, that China’s marine industrial structure shows a trend of diversified development.

5.2. Policy implications

Several policy implications arise from our results. First, further strengthen the role of oceanographic science and technology in enhancing the carrying capacity of oceans. As our results show, the weight of marine science and technology in marine carrying capacity is still relatively small, whereas evidences show that it is an important driving force to improve the marine carrying capacity (Shannon, 1948; Di and Li, 2018). In this context, advanced technologies related to the marine industry should be pursued and developed. In 2017, the Chinese government released the 13th Five-Year Plan for Marine Science and Technology Innovation, which aiming to develop the marine environmental monitoring technology; carry out research on the utilization of marine resources and foster strategic emerging industries of marine biology; and build a system of marine technological innovation with enterprises as the main body.

Second, capacity building of ocean governance should be improved, especially the planning for marine functional zones. It is widely recognized that capacity building is critical to strengthening ocean governance and enhancing scientific and regulatory proficiency (Michalena et al., 2020; Winther et al., 2020). Under China context, the marine functional zones should be strengthened, and its relationships with economic growth, resource exploitation, and environmental protection should be better coordinated, so as to ensure that growth of the marine economy stays within the carrying capacity of the ocean. According to the National Marine Function Regionalization (2011–2020), the sea areas under the jurisdiction of China are divided into eight types of marine functional areas: agriculture and fisheries, port and shipping, industrial and urban sea use, mineral resources and energy, tourism, recreation, marine protection, and special utilization and preservation. Marine functional zones form the basis for marine management to guide and restrict the practice of marine development and utilization, and to ensure the economic, environmental, and social benefits of marine development (Liao et al., 2013).

Third, the marine industrial structure should be optimized, especially by promoting the development of marine secondary industry. Marine industry is different from the land industry. The formation and development of marine industry is built upon the extraction of various resources from the sea; thus, the status of marine secondary industry should be highlighted based on the reasonable utilization of marine resources. In addition, as the land industry system has been fully developed, the marine industry will be hindered in the process of development and cannot form a relatively perfect system. Therefore, it is necessary for the government to give preferential policies on the marine secondary industry. As noted earlier, China’s marine industry is changing from being primarily resource-based to being more service-oriented, meaning that the share of key service sectors, such as coastal tourism and recreational fishing, is expanding; though this is beneficial for the environment, it cannot absorb enough employment and also lacks cutting-edge technologies. Thus, secondary marine industry sectors, such as marine equipment manufacturing and biological medicine, to serve as the foundation of China’s marine economy, warrant greater attention.

5.3. Limitations and future research directions

Limitations remain in this study. Although we scientifically select the evaluation index of the marine carrying capacity, but due to limited data, it fails to include more influencing factors, such as the economic loss caused by marine disasters (Lai et al., 2020) as well as the resilience of coastal areas (Tessler et al., 2015; Liu et al., 2017). Moreover, other commonly-used prediction method could be applied, such as the scenario-based analysis (Niu et al., 2020), it is a method of making predictions about the likely occurrence or consequences of a predicted object on the premise that a phenomenon or trend will continue into the future. Therefore, future research needs to collect more data to improve the accuracy of the model, and multiple methods could be applied. In addition, the extension of marine carrying capacity as a whole index can produce more valuable research. For example, using marine carrying capacity as the outcome variable, the non-linear effects of GOP as well as other factors such as marine technology innovation and foreign direct investment can be examined (Tian and Sun, 2018; Shao, 2020). In addition, whether the sustainable development goals (SDGs) in coastal regions could be realized (Rudolph et al., 2020) and how far the green development could reach under the constraint of marine carrying capacity (Katila et al., 2019) are all valuable subjects worthy of further study.

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CRediT authorship contribution statement

Renqu Tian: Data curation; Methodology; Software; Roles/Writing - original draft.
Qinglong Shao: Conceptualization; Formal analysis; Funding acquisition; Resources; Supervision; Validation; Visualization; Roles/ Writing - original draft; Writing - review & editing.
Fenglan Wu: Funding acquisition; Investigation; Project administration; Supervision; Visualization; Writing - review & editing.
The two joint first authors (Renqu Tian and Qinglong Shao) are contribute equally.

Declaration of competing interest

The authors declare no competing financial interests.
Appendix A. Ecosystem types for the 11 coastal regions of China

| Location | Major Types of Ecosystem |
|----------|--------------------------|
| Liaoning | Estuary and Bay          |
| Hebei    | Estuary                  |
| Tianjin  | Bay                      |
| Shandong | Estuary and Bay          |
| Jiangsu  | Tidal flat and wetland   |
| Shanghai | Estuary                  |
| Zhejiang | Bay                      |
| Fujian   | Bay                      |
| Guangdong| Estuary, Bay and Coral Reef |
| Guangxi  | Coral Reef, Mangroves and Seagrass Bed |
| Hainan   | Coral Reef and Seagrass Bed |

Appendix B. Average absolute errors of the grey Verhulst model (%)

| Location | Average Absolute Error (%) |
|----------|----------------------------|
| Tianjin  | 1.58                       |
| Hebei    | 4.76                       |
| Liaoning | 4.06                       |
| Shanghai | 2.94                       |
| Jiangsu  | 2.51                       |
| Zhejiang | 3.29                       |
| Fujian   | 2.35                       |
| Shandong | 1.97                       |
| Guangdong| 2.94                       |
| Guangxi  | 3.96                       |
| Hainan   | 4.11                       |

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2020.111675.

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