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Extension Evaluation of Marine Ecological Carrying Capacity: An Empirical Study Based on the Development of Tropical Marine Island Free Trade Ports in Developing Countries

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Abstract

Today, the global economy presents a leaping economic network centered on coastal areas. Relying on the ocean has become a very important economic development path for many countries and regions. To coordinate and solve the contradiction between the economic development of Hainan Island and the protection of marine ecological environment, this study, based on the matter-element extension evaluation model, examines the marine ecology of Hainan Island considering the construction of a free trade port. This study uses the extension set theory to describe the advantages of the intermediate state and dynamic trend of the transformation of the assessment object to a certain level, to improve the assessment accuracy of marine ecological carrying capacity. The results show that the marine ecological carrying capacity of Hainan Island in 2016 to 2018 is relatively stable, at the transformation grade of N_3, indicating that the marine ecology of Hainan Island is in a medium bearing, sub health state. Focusing on protecting marine ecology, developing a modern service industry, and developing high-tech industry can be effective in improving the ecological carrying capacity of Hainan Island.

Keywords

marine ecological carrying capacity, matter-element extension model, evaluate, free trade port, tropical marine island, Hainan Island

With increasing global population, decreasing land energy and mineral reserves, and the rapid development of science and technology, the marine economy has become the new stage of world economic competition, and countries are now developing marine islands to promote the development of the marine economy. The California Gold Coast, Florida Metropolitan Circle, and the Kanto region, which is the most developed region in Japan, all highlight the strategic significance of marine resources for the development of a country. China is the largest developing country in the world. The importance of oceans to China's economy is increasing. It is particularly important to learn from the development experience of developed countries or regions (such as Japan, Singapore, and Hong Kong) and make rational and scientific use of marine resources of developing countries to help them achieve leapfrog sustainable development.

Hainan Island is a tropical island at the southern end of China and is the second largest island in China after Taiwan Island. Since ancient times, Hainan Island has been crucial to China's marine trade, an important relay port and a safe haven. In April 2018, the Chinese government decided to support the construction of Hainan Island as a free trade pilot area and to explore and

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promote the construction of China's free trade ports, providing Hainan Island with unprecedented historical opportunities. However, the construction of a free trade port is bound to attract large investment and development, which will have a negative impact on the ecological environment of Hainan Island. Therefore, local governments must simultaneously consider technological progress, industrial structure, and policy formulation to deal with environmental problems (Li et al., 2019). To determine the optimal population growth rate and socioeconomic development rate of Hainan Island, find balance between economic development, resource allocation, and marine ecological carrying capacity, and achieve a virtuous cycle of marine ecological system in Hainan Island, it is necessary to undertake a scientific evaluation of its marine ecological carrying capacity.

Research on ecocapacity originates from the use of ecocapacity as the basic estimation of management decision, analyzing the problem of aquaculture environmental carrying capacity and guiding the management of the shellfish aquaculture industry. The ecological carrying capacity of shellfish aquaculture can be calculated by examining the mass balance ecosystem model of the temperate high-water lagoon in Rhode Island (Byron et al., 2011).Using a calibrated fine-resolution physical-biogeochemical model coupled with a dynamic energy budget, a coupled fine-scale numerical model was established to evaluate the ecological carrying capacity of the Bay of St. Lawrence, Magdalen Islands, Canada (Guyondet et al., 2010), and the ridge burro estuary in eastern Canada (Filgueira et al., 2014) for shellfish cultivation. The research on the carrying capacity of urban ecosystem is based on the concept of carrying capacity and the principle of sustainability, establishing the urban carrying capacity load number model, and introducing the spatial decision support system for sustainable environmental planning and management of urban ecosystems (Tehrani & Makhdoum, 2013). According to the research on beach carrying capacity, some scholars believe that the usage pattern of the beach and the user's perception are two important factors. Using on-site counting date, time-lapse photos, and traffic counters, the usage intensity and dynamics of two beaches can be analyzed (Pereira da Silva et al., 2016). Another study used management tools to consider the impact of related water surfing activities on beach carrying capacity, as part of the study of beach carrying capacity (Silva & Ferreira, 2013)). The multiobjective decision model is used to evaluate the water resource carrying capacity of Algeria (Ait-Aoudia & Berezowska-Azzag, 2016). An integrated model based on the system dynamics and cellular automata model was used to evaluate the water environment carrying capacity of Taihu Lake in Changzhou (Zhou et al., 2017). By constructing the energy frame, the energy characteristics of lake water consumption were analyzed to evaluate the carrying capacity of the Erhai river basin in Yunnan (Zhong et al., 2018). A study of the marine ecological carrying capacity of China's coastal cities constructs a technology-environment-resources-economy (TERE) simulation model by dividing the marine ecosystem into four subsystems (Wang et al., 2017) or by applying an system dynamics model, state evaluation model, and multiobjective programming model (Fu, 2009; Jin et al., 2017) to measure the marine ecological carrying capacity of Qingdao and Huizhou.The marine ecological carrying capacity of Tianjin Binhai New Area was evaluated using the analytic hierarchy process to establish an evaluation index from two aspects of pressure and bearing pressure (Fang, 2011). Researchers have studied the marine ecological carrying capacity in Liaoning and Zhejiang from the perspective of ecosystem health (Di et al., 2014; Yu & Hu, 2017). Another study improved and optimized the model of energy ecological footprint and energy ecological carrying capacity and empirically analyzed the change characteristics of the Hainan eco-economic system from 2000 to 2016 (Cao & Sun, 2019). Other studies undertake a horizontal comparison of China's coastal cities. For example, based on the principle of network analysis, an evaluation model of marine ecological carrying capacity can be constructed to examine the correlation and influence relationship between indicators and evaluate the indexes and contributing factors of marine ecological carrying capacity of 11 provinces (cities and districts) in China's coastal areas (Du et al., 2018).

Most existing research on the bearing capacity of marine ecological research quantifies the index, the factor and evaluation considering the objective evaluation indexes in the literature, the evaluation object to a certain level in the middle of the state and the dynamic trend description is unclear. Combined with the free trade port construction status of Hainan Island, evaluating the marine ecological carrying capacity involves factors such as economic system and social support factors such as system conditions. The evaluation index system was designed from the dimensions of resource and environmental carrying capacity, ecological resilience, and human activity potential (Zhang, 2013) to construct a matter-element extension model for the evaluation of marine ecological carrying capacity. Based on empirical data from 2016 to 2018, the marine ecological carrying capacity of Hainan Island in China was evaluated and analyzed.

Methods

Extenics theory is an original interdisciplinary subject put forward by Chinese scholar Cai Wen in 1983, which discusses the possibility of expanding things with a formal model (Cai, 1987). It is a knowledge system, which combines matter-element theory with extension set theory, studies matter element and its changing trend, and attempts to resolve the changing laws of complex problems both qualitatively and quantitatively. An important feature of this theory is that it provides an effective tool for solving incompatibility problems. The variable attributes of elements and sets are represented by correlation functions. The compatibility of research objects or problems can be obtained and the credibility of evaluation improved through the transformation of matter elements and the calculation of extension subsets.

Matter-Element Theory

The matter-element theory regards matter element as its basic unit, and its structure is divided into three parts, that is, given the name of the object of study as O, it may have some characteristics C, and the quantity value of the characteristics is V, which together constitute the ordered triple $M =$ (object, characteristics, value)= (O, C, V), and regard it as the most basic three elements of describing things, referred to as *matter element*. If the research object O has n different characteristics C_i, and the corresponding quantity value of these characteristics is V_i, then the above elements can be combined to form a matrix of n-dimensional matter elements.

Extension Set Theory

The extension set theory is the core of extension theory. It examines the dynamic change classification of things. It can describe the transformation process of things from quantitative change to qualitative change, and it is a quantitative tool to solve the problem of contradiction in things. This is a new set theory based on Cantor set and fuzzy set. However, unlike them, it describes the identification and classification of subjective knowledge of objective things. Its deficiency lies in its lack of considering the changing nature of the elements themselves and its inability to solve the contradictions in the changing process with mathematical ideas and methods such as extension set theory. Extension set theory can describe the mutual transformation between two opposite states of things and the degree to which things have some properties.

Optimization Evaluation Method

Optimization evaluation method is a practical method for comprehensively evaluating the advantages and disadvantages of an object, scheme, strategy, and so on. The optimization evaluation method uses the correlation function to calculate the degree that each measurement condition meets the requirements. Because the value of the correlation function can be positive or negative, the established optimization can reflect the degree of the advantages and disadvantages of an object, making the evaluation more practical.

Construction of Matter-Element Extension Evaluation Model for Marine Ecological Carrying Capacity

The matter-element extension assessment model is a complex and abstract theory that can be transformed to a model of specific, quantifiable, through quantitative values to represent the evaluation results and the correlation between different grade sizes, according to the correlation between sizes, to determine the evaluation matter element in rank, to judge the correlation. The larger the correlation degree is, the better the fitting degree of set is. The steps are as follows:

Step 1: To determine matter-element matrix of marine ecological carrying capacity evaluation. According to the definition of matter element, marine ecological carrying capacity N, characteristic C, and feature vector V jointly constitute matter-element $R = (N, C, V)$, with n evaluation indexes, namely, $c_1, c_2, c_3, \ldots, c_n$, and the corresponding characteristic quantity value is $v_1, v_2, v_3, \ldots, v_n$. The matter-element matrix of marine ecological carrying capacity evaluation can be expressed as Formula 1.

$$R = [N, C, V] = \begin{bmatrix} N & c_1 & v_1 \\ & c_2 & v_2 \\ & \vdots & \vdots \\ & c_n & v_n \end{bmatrix} \tag{1}$$

Step 2: Determination of classical domain and nodal domain of marine ecological carrying capacity evaluation. Classical domain refers to the range of scalar values of each ecological carrying capacity established in different levels of ecological carrying capacity. The following assumptions are made: there are n evaluation indexes for the marine ecological carrying capacity, and the ecological carrying capacity level is divided into m grades. Then, in the matter-element extension evaluation model, the classic domain of the marine ecological carrying capacity index is shown in Formula 2.

$$R_j = (N_j, C_i, V_{ij}) = \begin{bmatrix} N_j & c_1 & v_{1m} \\ & c_2 & v_{2m} \\ & \vdots & \vdots \\ & c_n & v_{nm} \end{bmatrix} \tag{2}$$

$$
= \begin{bmatrix} N & N_1 & N_2 & \cdots & N_m \\ C_1 & V_{11} & V_{12} & \cdots & V_{1\mathrm{m}} \\ C_2 & V_{21} & V_{22} & \cdots & V_{2m} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ C_{\mathrm{n}} & V_{\mathrm{n}1} & V_{n2} & \cdots & V_{nm} \end{bmatrix}
= \begin{bmatrix} N & N_1 & N_2 & \cdots & N_m \\ C_1 & \langle a_{11}, b_{11} \rangle & \langle a_{12}, b_{12} \rangle & \cdots & \langle a_{1m}, b_{1m} \rangle \\ C_2 & \langle a_{21}, b_{21} \rangle & \langle a_{22}, b_{22} \rangle & \cdots & \langle a_{2m}, b_{2m} \rangle \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ C_{\mathrm{n}} & \langle a_{n1}, b_{n1} \rangle & \langle a_{n2}, b_{n2} \rangle & \cdots & \langle a_{nm}, b_{nm} \rangle \end{bmatrix} \quad (2)
$$

In Formula 2, N_j is the $j(j = 1, 2, \dots m)$-th evaluation grade, C_i is the $i(i = 1, 2, \dots n)$-th evaluation index, and V_{ij} is the range of quantity value (i.e., classical domain) corresponding to the evaluation grade N_j standard of Index C_i, which is expressed by $V_{ij} = \langle a_{ij}, b_{ij} \rangle$. a_{ij} and b_{ij} are the lower and upper limits of the classical domain, respectively.

The nodal region refers to the allowable value range of each evaluation index in all levels of marine ecological carrying capacity. Formula 3 shows the nodal region of marine ecological carrying capacity index.

$$
R_p = (N_p, C_i, V_{pi}) = \begin{bmatrix} N_p & c_1 & v_{p1} \\ & c_2 & v_{p2} \\ & \vdots & \vdots \\ & c_n & v_{pn} \end{bmatrix} = \begin{bmatrix} N_p & c_1 & \langle a_{p1}, b_{p1} \rangle \\ & c_2 & \langle a_{p2}, b_{p2} \rangle \\ & \vdots & \vdots \\ & c_n & \langle a_{pn}, b_{pn} \rangle \end{bmatrix} \quad (3)
$$

In Formula 3, N_p is the whole level to be evaluated, $v_{p1}, v_{p2}, \dots, v_{pn}$ is the value range (nodal domain) of N_p on $c_1, c_2, \dots, c_n$, that is, $v_{pi} = \langle a_{pi}, b_{pi} \rangle (i = 1, 2, \dots, n)$ is the value range of N_p on marine ecological bearing capacity evaluation index $C_i(i = 1, 2, \dots, n)$, and a_{pi} and b_{pi} are the lower and upper limits of the nodal domain, respectively.

The evaluation index of the marine ecological carrying capacity to be evaluated and the value of the matter element to be evaluated in the evaluation index are expressed by the matter element, Formula 4 shows the matter-element model to be evaluated.

$$
R_q = (N_q, C_i, T_i) = \begin{bmatrix} N_q & c_1 & t_1 \\ & c_2 & t_2 \\ & \vdots & \vdots \\ & c_n & t_n \end{bmatrix} \quad (4)
$$

In Formula 4, N_q is the marine ecological carrying capacity to be evaluated, $C_i(i = 1, 2, \dots, n)$ is the marine ecological carrying capacity evaluation index, and $T_i(i = 1, 2, \dots, n)$ is the actual value of C_i in each year.

Step 3: The entropy weight method determines the index weight coefficient. The marine ecological carrying capacity is regarded as a system, and each evaluation index is a subsystem. The value of each evaluation object under the index can be regarded as the possible result of the subsystem, and the entropy weight of the index can be calculated according to its probability. According to the definition of entropy, the entropy of n indexes of m evaluation objects is calculated, as shown in Formula 5.

$$
E_i = -\frac{\sum_{j=1}^{m} t_{ij} \ln t_{ij}}{\ln m}, \quad (i = 1, 2, \dots, n; j = 1, 2, \dots m) \quad (5)
$$

where $t_{ij} = \frac{T_{ij}}{\sum_{j=1}^{m} T_{ij}} (t_{ij} \neq 0)$, $t_{ij} = \frac{1+T_{ij}}{\sum_{j=1}^{m} (1 + T_{ij})} (t_{ij} = 0)$, T_{ij} is the value of the i-th index of the j-th evaluation object. The calculation formulas of entropy weight W and weight λ_i of the evaluation index, are Formulas 6 and 7, respectively.

$$
W = (\lambda_i)_{1 \times n} \quad (6)
$$

$$
\lambda_i = \frac{1 - E_i}{n - \sum_{i=1}^{n} E_i} \quad (7)
$$

and satisfy $\sum_{i=1}^{n} \lambda_i = 1$。

Step 4: The determination of the horizontal correlation degree of marine ecological carrying capacity. Correlation degree indicates the extent to which the matter element of marine ecological bearing capacity meets the requirements, when the value of the matter element is taken as a certain point on the real axis, that is, the ownership degree of bearing capacity evaluation index with respect to each evaluation grade j, which is called the extension set correlation degree, expressed by $K_j(T_i)$, and its correlation function is shown in Formula 8.

$$
K_j(T_i) = \begin{cases} \dfrac{-\rho(T_i, V_{ij})}{|V_{ij}|}, & T_i \in V_{ij} \\ \dfrac{\rho(T_i, V_{ij})}{\rho(T_i, V_{pi}) - \rho(T_i, V_{ij})}, & T_i \notin V_{ij} \end{cases} \quad (8)
$$

In Formula 8, $\rho(T_i, V_{ij})$ and $\rho(T_i, V_{pi})$ are the distance between the actual value of the evaluation index and the classical domain and the nodal domain, respectively.

See Formulas 9 and 10 for the calculation formula of the distance.

$$\rho(T_i, V_{ij}) = \left| T_i - \frac{1}{2}(a_{ij} + b_{ij}) \right| - \frac{1}{2}(b_{ij} - a_{ij}) \quad (9)$$

$$\rho(T_i, V_{pi}) = \left| T_i - \frac{1}{2}\left(a_{pi} + b_{pi}\right) \right| - \frac{1}{2}\left(b_{pi} - a_{pi}\right) \quad (10)$$

where $\left|V_{ij}\right| = b_{ij} - a_{ij}$ is the size of the classical field $\langle a_{ij}, b_{ij} \rangle$ related to the i-th index and the j-th grade. If $K_j(T_i) = \max\{K_j(T_i)\}(j = 1, 2, \ldots, m)$, the evaluation index T_i belongs to grade j.

Step 5: The calculation of the comprehensive correlation degree of the marine ecological carrying capacity and the determination of its grade. As shown in Formula 11, correlation degree between each evaluation index and the grade standard is weighted and summed to obtain the value of the weighted correlation degree.

$$k_j(R_q) = \sum_{i=1}^{n} \lambda_i K_j(T_i) \quad (11)$$

If $k_j(R_q) = \max\{k_j(R_q)\}(j = 1, 2, \ldots, m)$, the assessment of marine ecological carrying capacity is j.

The meaning of relevance degree in the matter-element extension model is more abundant than the membership degree in fuzzy theory. If $k_j(R_q) < -1$, the marine ecological bearing capacity does not belong to grade j and does not have the conditions to meet the grade standard. The smaller the value, the greater the difference; if $-1 \leq k_j(R_q) \leq 0$, the marine ecological bearing capacity does not belong to grade j but has the conditions to convert to the grade; the greater the value, the easier the conversion; if $k_j(R_q) > 0$, the marine ecological bearing capacity meets the requirements of grade j, and the greater the value, the higher the degree of conformity.

Study Area

Hainan Island is a tropical island at the south end of China, with a plane of pear shaped ellipse, a long axis from northeast to southwest, length of 240 kilometers, width of 210 kilometers, area of 34,000 square kilometers, and sea area of 2 million square kilometers. It is the second largest island in China after Taiwan Island. Hainan Island is bounded by Qiongzhou Strait and Guangdong in the north, the Beibu Gulf in the west, Guangxi and Vietnam, the South China Sea in the East, Taiwan, and the Philippines, Brunei and Malaysia in the South China Sea in the southeast and south. Hainan Island has a tropical monsoon climate with pleasant beaches, lush vegetation, and fresh air. It is regarded as China's *Florida*. By the end of 2018, there were 9.3432 million permanent residents, 483.205 billion yuan of gross domestic product (GDP) and 52,000 yuan of per capita GDP.

Data Collection

The marine ecological carrying capacity generally refers to the maximum supply capacity and the pollutant carrying capacity of marine resources and environment subsystems, as well as the maximum supporting capacity for the scale of socioeconomic development and the corresponding population in the coastal area, within the scope of the elastic limit conditions of marine ecosystems, and under the requirements of certain living standards and environmental quality (Miao et al., 2006). The concept includes two aspects: One is the supply capacity of marine resources and environment system, subsystem, and the self-sustaining and self-protection capacity after the system is destroyed; the other is the relationship between human production and living activities and the marine resources and environment in coastal areas. Based on the explanation of concept and connotation, marine ecological carrying capacity can be divided into three parts: the supply capacity of marine resources and the capacity of marine ecological accommodation, the elastic capacity of the marine ecosystem, and the interaction between human activities and the marine ecosystem.

The assessment of marine ecological carrying capacity requires constructing a set of index system with rich contents, clear levels, and strong pertinence. To ensure that the system is scientific, the following principles should be followed in the construction of the index system:

Combination of Comprehensiveness and Saliency. The selected indicators should not only comprehensively reflect the resources, environment, social, and economic aspects of the carrying capacity of the sea area but also highlight its main characteristics and status.

Combination of Dynamics and Stability. Indicators should be continuous in time not only to evaluate the current situation accurately but also to better describe and measure past situations and future development trends.

Combination of Independence and Comparability. Independence means that each evaluation index should avoid repeated calculation and be independent of each other. The selected indicators should be accurate and standardized, with a large amount of information, easy to understand, and with strong comparability.

Based on the above selection principle of indicators, and combining the concept, connotation, and index characteristics of marine ecological carrying capacity, this study analyzes the marine ecosystem considering the construction of a free trade port in Hainan Island, China. According to the matter-element theory, the marine ecological carrying capacity is the object of analysis, and the factors influencing the assessment of marine ecological carrying capacity, including natural factors and human factors, are analyzed using the extension theory to expand thinking and divergent thinking. Combining the supply capacity of marine resources with the capacity of marine ecology, the influencing factors can expand the utilization of marine resources and environmental quality. Combined with the resilience of the marine ecosystem, the influencing factors can expand ecological quality and environmental governance. Combined with the interaction between human activities and marine ecosystems, the influencing factors can expand the level of science and technology, quality of life, level of education, and systematic communication. Using the expanded influencing factors of marine ecological carrying capacity and referring to the existing literature (Gai et al., 2018; Sun et al., 2014; Zhang, 2013), this study constructs a multilevel classification evaluation index system of marine ecological carrying capacity. It also determines the weight of the evaluation index using the entropy weight method and obtains the results shown in Table 1.

Determination of Classical Domain and Nodal Domain. According to the matter-element model and extension evaluation method, the marine ecological carrying capacity of Hainan Island in China considering the free trade port development will be divided into five grades, namely, N_1,N_2,N_3,N_4,N_5. It is described as strong bearing, trend strong bearing, medium bearing, trend weak bearing, and weak bearing. The strong bearing indicates that the marine ecosystem is in a healthy state and maintains its natural attributes. The biodiversity and ecosystem structure are basically stable. The main service functions of the ecosystem are playing normally. The ecological pressures such as environmental pollution, man-made destruction, and unreasonable development of resources are within the bearing capacity of the ecosystem. The medium bearing indicates that the marine ecosystem is in a sub healthy state. Essentially, it has its own natural attributes, biodiversity and ecosystem structure have changed to some extent; however, the main service functions of the ecosystem can still play. Environmental pollution, man-made destruction, unreasonable development of resources, and other ecological pressures exceed the carrying capacity of the ecosystem. Weak carrying indicates that the marine ecosystem is in an unhealthy state, and the natural attributes of the ecosystem have changed significantly. Great changes have occurred in the biodiversity and ecosystem structure, the main service functions of the ecosystem have been seriously degraded or lost, and ecological pressures such as environmental pollution, man-made destruction, and unreasonable development of resources exceed the carrying capacity of the ecosystem. Referring to the average level of each indicator in each coastal region of China and each administrative region of Hainan Island, the background value of the research object and expert opinions, the grade standard value of

$$R_j = \begin{bmatrix} N & N_1 & N_2 & N_3 & N_4 & N_5 \\ C_1 & \langle 0.31, 0.54\rangle & \langle 0.17, 0.31\rangle & \langle 0.09, 0.17\rangle & \langle 0.05, 0.09\rangle & \langle 0.01, 0.05\rangle \\ C_2 & \langle 384.12, 1026\rangle & \langle 143.82, 384.12\rangle & \langle 53.85, 143.82\rangle & \langle 20.16, 53.85\rangle & \langle 2.8, 20.16\rangle \\ C_3 & \langle 463.5, 672.8\rangle & \langle 276.7, 463.5\rangle & \langle 93.87, 276.7\rangle & \langle 19.78, 93.87\rangle & \langle 4.8, 19.78\rangle \\ C_4 & \langle 24.86, 59.55\rangle & \langle 10.38, 24.86\rangle & \langle 4.35, 10.38\rangle & \langle 1.81, 4.35\rangle & \langle 0.3, 1.81\rangle \\ C_5 & \langle 11160, 28460\rangle & \langle 4375, 11160\rangle & \langle 1716, 4375\rangle & \langle 673, 1716\rangle & \langle 103, 673\rangle \\ C_6 & \langle 80683, 231115\rangle & \langle 28167, 80683\rangle & \langle 9834, 28167\rangle & \langle 3433, 9834\rangle & \langle 418, 3433\rangle \\ C_7 & \langle 0, 3\rangle & \langle 3, 8\rangle & \langle 8, 14\rangle & \langle 14, 20\rangle & \langle 20, 32\rangle \\ C_8 & \langle 91, 100\rangle & \langle 78, 91\rangle & \langle 52, 78\rangle & \langle 32, 52\rangle & \langle 18, 32\rangle \\ C_9 & \langle 11, 67\rangle & \langle 67, 166\rangle & \langle 166, 411\rangle & \langle 411, 1017\rangle & \langle 1017, 2516\rangle \\ C_{10} & \langle 95, 100\rangle & \langle 75, 95\rangle & \langle 55, 75\rangle & \langle 40, 55\rangle & \langle 25, 40\rangle \\ C_{11} & \langle 3367, 5623\rangle & \langle 1895, 3367\rangle & \langle 934, 1895\rangle & \langle 426, 934\rangle & \langle 107, 426\rangle \\ C_{12} & \langle 496, 625\rangle & \langle 352, 496\rangle & \langle 167, 352\rangle & \langle 83, 167\rangle & \langle 25, 83\rangle \\ C_{13} & \langle 82417, 151078\rangle & \langle 44961, 82417\rangle & \langle 24527, 44961\rangle & \langle 13880, 24527\rangle & \langle 3980, 13880\rangle \\ C_{14} & \langle 1.7, 5\rangle & \langle 1.2, 1.7\rangle & \langle 0.7, 1.2\rangle & \langle 0.2, 0.7\rangle & \langle 0, 0.2\rangle \\ C_{15} & \langle 39.77, 58.94\rangle & \langle 23.05, 39.77\rangle & \langle 11.83, 23.05\rangle & \langle 6.75, 11.83\rangle & \langle 1.62, 6.75\rangle \\ C_{16} & \langle 450, 630\rangle & \langle 270, 450\rangle & \langle 130, 270\rangle & \langle 45, 130\rangle & \langle 5, 45\rangle \\ C_{17} & \langle 2.5, 3\rangle & \langle 2, 2.5\rangle & \langle 1.5, 2\rangle & \langle 1, 1.5\rangle & \langle 0, 1\rangle \\ C_{18} & \langle 25, 30\rangle & \langle 30, 35\rangle & \langle 35, 40\rangle & \langle 40, 45\rangle & \langle 45, 50\rangle \\ C_{19} & \langle 480.5, 620.5\rangle & \langle 310.5, 480.5\rangle & \langle 190.5, 310.5\rangle & \langle 70.5, 190.5\rangle & \langle 10.5, 70.5\rangle \\ C_{20} & \langle 130, 225\rangle & \langle 50, 130\rangle & \langle 20, 50\rangle & \langle 5, 20\rangle & \langle 0, 5\rangle \\ C_{21} & \langle 34955, 54316\rangle & \langle 20831, 34955\rangle & \langle 9523, 20831\rangle & \langle 1227, 9523\rangle & \langle 145, 1227\rangle \end{bmatrix}$$

$$R_p = \begin{bmatrix} N_p & C_1 & \langle 0.01, 0.54\rangle \\ & C_2 & \langle 2.8, 1026\rangle \\ & C_3 & \langle 4.8, 672.8\rangle \\ & C_4 & \langle 0.3, 59.55\rangle \\ & C_5 & \langle 103, 28460\rangle \\ & C_6 & \langle 418, 231115\rangle \\ & C_7 & \langle 0, 32\rangle \\ & C_8 & \langle 18, 100\rangle \\ & C_9 & \langle 11, 2516\rangle \\ & C_{10} & \langle 25, 100\rangle \\ & C_{11} & \langle 107, 5623\rangle \\ & C_{12} & \langle 25, 625\rangle \\ & C_{13} & \langle 3980, 151078\rangle \\ & C_{14} & \langle 0, 5\rangle \\ & C_{15} & \langle 1.62, 58.94\rangle \\ & C_{16} & \langle 5, 630\rangle \\ & C_{17} & \langle 0, 3\rangle \\ & C_{18} & \langle 25, 50\rangle \\ & C_{19} & \langle 10.5, 620.5\rangle \\ & C_{20} & \langle 0, 225\rangle \\ & C_{21} & \langle 145, 54316\rangle \end{bmatrix}$$

Table 1. Evaluation Index System of Marine Ecological Carrying Capacity of Hainan Island in China.

Primary indicators	Composition and influencing factors	Secondary indicators	Secondary indicator description	Weight
Resource and environment carrying capacity index A_1	Utilization of marine resources	C_1: Per capita sea area	Sea area/total population, km^2/person	0.0448
		C_2: Per capita output of sea water products	Sea water product output/total population, kg/person	0.0467
		C_3: Total output value of fishery	Annual total fishery output value, 100 million yuan	0.0246
		C_4: Proportion of marine economy in GDP	Total marine economy/real GDP,%	0.0455
		C_5: Per capita marine economy	Output value of marine industry/total number of people, yuan/person	0.0283
		C_6: Economic density of coastline	real GDP/coastline length, 10,000 yuan/km	0.0627
	Environmental quality	C_7: Waste water discharge of 10,000 yuan GDP	Total wastewater discharge/real GDP, t/ 10,000 yuan	0.0320
		C_8: Urban domestic sewage treatment rate	Urban domestic sewage treatment capacity/urban domestic sewage discharge capacity, %	0.0406
		C_9: Industrial solid waste production	Annual output of industrial solid waste, 10,000 tons	0.0431
		C_{10}: Comprehensive utilization rate of solid waste	Utilization amount of solid waste/ production amount of solid waste, %	0.0246
Ecological elastic force index A_2	Ecological quality	C_{11}: Coastline length per capita	Coastline length/total population, m/10,000 person	0.0615
		C_{12}: Wetland area per capita	Total wetland area/total population, km^2/person	0.0923
		C_{13}: Mariculture area	Annual mariculture area, hectare	0.1144
	Environmental governance	C_{14}: Proportion of environmental protection investment in GDP	Environmental protection, expenditure/real GDP, %	0.0520
Human activity potential index A_3	Level of science and technology	C_{15}: Science and technology expenditure in coastal areas	Science and technology expenditure, 100 million yuan	0.0198
		C_{16}: Per capita marine scientific research fund	Expenditure on marine scientific research/ total number of people, yuan/person	0.0595
		C_{17}: Proportion of science and technology investment in GDP	Science and technology expenditure/real GDP, %	0.0523
	Quality of life and education	C_{18}: Engel coefficient	Proportion of total food expenditure in total personal consumption expenditure, %	0.0208
		C_{19}: Education funds	Education expenditure, 100 million yuan	0.0833
	System exchange	C_{20}: Number of berths for production of ports above designated size	Number of berths for port production above designated size, Unit	0.0390
		C_{21}: Port cargo throughput	Port cargo throughput, 10,000 tons	0.0130

GDP = gross domestic product.

each indicator for the evaluation of marine ecological carrying capacity was determined, and the following classic domain R_j and node domain R_p obtained.

Determination of Matter Element to be Evaluated. T_i in Formula 4 is the matter element to be evaluated in the assessment of marine ecological carrying capacity of Hainan Island in China. There are 21 secondary indicators in the assessment index system. These data are primarily from the China statistical yearbook, Hainan statistical yearbook, China marine statistical yearbook, China ocean yearbook, China environment statistical yearbook, China city statistical yearbook, and marine environment bulletin of Hainan Province. Thus, we can obtain the original data of the evaluation index system of marine ecological carrying capacity, that is, the matter element to be evaluated.

Results

According to the value $T_i(i = 1, 2, \ldots, n)$ and Formulas 8 to 10 of each evaluation index $C_i(i = 1, 2, \ldots, n)$ in 2016 to 2018, we can obtain the correlation function value (correlation degree) of all the secondary indexes of marine ecological carrying capacity evaluation of Hainan Island in terms of evaluation grade. By judging that the actual value $T_i(i = 1, 2, \ldots, n)$ of the matter-element R_q to be evaluated tends to the adjacent level $N_j(j = 1, 2, \ldots m)$, we can understand the trend of change in the level of the matter element to be evaluated. Table 2 shows the correlation degree and grade of the secondary indicators for the assessment of marine ecological carrying capacity of Hainan Island in 2016 to 2018.

Substituting the weight of each index in Table 1 and the correlation degree of each index in Table 2 into Formula 5, we can obtain the correlation degree and the grade of primary indicators of the marine ecological carrying capacity evaluation of Hainan Island in 2016 to 2018 and the comprehensive correlation degree of the marine ecological carrying capacity of Hainan Island in 2016 to 2018. Tables 3 and 4 show the results.

Data Analysis

As shown in Table 2, the correlation degree of indicator C_1 in 2016 is $K_1 = -0.3064$, $K_2 = 0.3434$, $K_3 = -0.1877$, $K_4 = -0.3810$, $K_5 = -0.4468$; therefore, it can be determined that indicator C_1 belongs to grade N_2. Among the 21 secondary indicators, 11 belong to grade N_3, accounting for the largest proportion, indicating that these indicators are in the middle bearing level. There are five indicators in grade N_2, namely, per capita sea area, per capita sea water product output, total fishery output value, proportion of environmental protection investment in GDP, and number of berths for port production above designated size. There are two indexes in

Table 2. Correlation Degree and Grade of Secondary Indicators of Marine Ecological Carrying Capacity Evaluation of Hainan Island, China From 2016 to 2018.

	2016						2017	2018
Indicators	N_1	N_2	N_3	N_4	N_5	Grade	Grade	
C_1	–0.3064	0.3434	–0.1877	–0.3810	–0.4468	N_2	N_2	N_2
C_2	–0.5612	0.1095	–0.1359	–0.4100	–0.4726	N_2	N_2	N_2
C_3	–0.2842	0.3022	–0.1467	–0.4215	–0.4883	N_2	N_2	N_2
C_4	0.0934	–0.1044	–0.3893	–0.4607	–0.4860	N_1	N_1	N_1
C_5	0.0728	–0.0927	–0.3951	–0.4650	–0.4882	N_1	N_1	N_1
C_6	–0.6747	–0.0591	0.0895	–0.3900	–0.4694	N_3	N_3	N_3
C_7	–0.4200	–0.2093	0.4799	–0.2229	–0.4560	N_3	N_3	N_3
C_8	–0.3784	–0.0417	0.0385	–0.5208	–0.6618	N_3	N_2	N_2
C_9	–0.4519	–0.3395	0.3306	–0.2025	–0.6829	N_3	N_4	N_4
C_{10}	–0.4628	–0.2347	0.4470	–0.1987	–0.3990	N_3	N_4	N_4
C_{11}	–0.5218	–0.1280	0.2382	–0.3195	–0.4430	N_3	N_2	N_2
C_{12}	–0.3476	–0.0111	0.0167	–0.3972	–0.4906	N_3	N_3	N_3
C_{13}	–0.8235	–0.6622	–0.3263	0.3703	–0.2217	N_4	N_4	N_4
C_{14}	–0.2647	0.1000	–0.0385	–0.3056	–0.4565	N_2	N_3	N_3
C_{15}	–0.6311	–0.3434	0.3442	–0.2153	–0.3885	N_3	N_3	N_3
C_{16}	–0.9723	–0.9534	–0.9012	–0.6914	0.3086	N_5	N_5	N_5
C_{17}	–0.8451	–0.8064	–0.7419	–0.6129	0.3871	N_5	N_5	N_5
C_{18}	–0.4500	–0.2667	0.2000	–0.0833	–0.3529	N_3	N_3	N_3
C_{19}	–0.5665	–0.3209	0.1319	–0.1044	–0.4137	N_3	N_3	N_3
C_{20}	–0.1260	0.2000	–0.3657	–0.4585	–0.4955	N_2	N_2	N_2
C_{21}	–0.5333	–0.2147	0.3927	–0.2971	–0.4828	N_3	N_3	N_3

grades N_1 and N_5, respectively, and the remaining one belongs to N_4. According to the bulletin on the marine environment of Hainan Province, the environmental conditions of the sea areas adjacent to some key sewage outlets in Hainan Island are generally poor, affecting the environmental quality; therefore, these indicators are at N_3 level. In 2017, there were five secondary indicators of grade change, namely, C_8, C_9, C_{10}, C_{11} and C_{14}, among which C_8 and C_{11} increased from N_3 level to N_2 level, from medium load to strong load. This is because in 2017, the number of excessive emissions from land-based sewage outfalls into the sea significantly reduced, the environmental condition of the marine dumping area improved, and the water quality of the offshore area was in good condition. However, the grades of indicators C_9, C_{10}, and C_{14} have declined, C_9 and C_{10} have declined to weak bearing, and C_{14} to medium bearing. This is because the production of industrial solid waste in Hainan Island has increased much more than in 2016; however, utilization efficiency has not improved. In addition, the investment in environmental protection has not increased correspondingly, which makes the marine ecological bearing capacity grades of the above three indicators higher than that in 2016. However, there are some adverse changes. The level of all secondary indicators in 2018 has not changed significantly compared with 2017.

From the distance between the highest value and the second highest value of the correlation degree K_j of each index C_i, we can find the key influencing factors in the index. Taking 2016 as an example, among all 21 indicators, the distance between the highest K_j value and the second highest K_j value of indicators C_6, C_8, C_{12}, and C_{14} is relatively small. The key factors influencing the marine ecological carrying capacity in 2016 are these four indicators, specifically the economic density of coastline, treatment rate of urban domestic sewage, wetland area per capita, and the proportion of environmental protection investment in GDP. However, the key influencing factors in each year are different. The key influencing factors in 2017 are C_9, C_{12}, C_{14}, and C_{15}. The key influencing factors in 2018 are C_2, C_9, C_{12}, and C_{14}. It can be seen that C_{12} and C_{14} are the key influencing factors in the past 3 years, which means that the key to improve the marine ecological carrying capacity is to develop the green economy under the limited resource conditions, protect the existing wetland resources, and ensure the normal level of environmental protection expenditure.

From Table 3, in 2016, the first-level indicator resource and environment carrying capacity A_1 belongs to grade N_3, while the correlation between ecological resilience A_2 and human activity potential A_3 is negative, and the value is between –1 and 0, indicates that although it does not belong to a certain grade, it has the potential to transform to that grade; therefore, A_2 belongs to the grade of transformation to N_3, and A_3 belongs to the grade of transformation to N_5. Compared with 2016, in 2017 and 2018, A_1 changed into transformation to N_2, while A_3 did not change, while A_2 changed from transformation to N_4 to transformation to N_3. Hainan Island has a good natural resource endowment; therefore, we should focus on maintaining a good ecological environment and normal environmental governance level, especially the improvement of science and technology education level and the improvement of residents' quality of life.

Table 4 shows that the correlation degree of each level from 2016 to 2018 is negative, the value is between –1 and 0, and the maximum value of each year falls in level N_3, which is the level of transformation to N_3, indicating that the marine ecological carrying capacity of Hainan Island in these 3 years is basically at the medium bearing level, and the marine ecosystem is in the sub healthy state.

Discussion

Hainan Island was established as a special economic zone of China in April 1988 and was proposed to be an international tourism island in 2009. The state has repeatedly issued dividends to promote the economic development of Hainan, which indicates the importance of Hainan. Over the past 30 years, Hainan has gone through the *Yangpu free port* because of the failure of *too advanced*, the bursting of the real estate bubble and a painful bad debt process. By 2017, the per capita GDP of Hainan dropped to about 83% of the national level.

Although Hainan Island has more than 1,500 kilometers of coastline, because of frequent typhoons in

Table 3. Correlation Degree and Grade of Primary Indicators for the Evaluation of Marine Ecological Carrying Capacity of Hainan Island, China, From 2016 to 2018.

	2016						2017	2018
Indicators	N_1	N_2	N_3	N_4	N_5	Grade	Grade	
A_1	–0.3629	–0.0304	0.0013	–0.3743	–0.5094	N_3	Transformation to N_2	Transformation to N_2
A_2	–0.5376	–0.2482	–0.0723	–0.0931	–0.3798	Transformation to N_3	Transformation to N_4	Transformation to N_3
A_3	–0.6359	–0.4622	–0.2767	–0.3811	–0.1268	Transformation to N_5	Transformation to N_5	Transformation to N_5

Table 4. Comprehensive Correlation Degree and Grade of Marine Ecological Carrying Capacity of Hainan Island, China, From 2016 to 2018.

Year	N_1	N_2	N_3	N_4	N_5	Grade
2016	–0.4977	–0.2244	–0.1023	–0.2865	–0.3582	Transformation to N_3
2017	–0.4945	–0.2126	–0.1481	–0.2754	–0.3665	Transformation to N_3
2018	–0.4814	–0.1977	–0.1279	–0.3052	–0.3737	Transformation to N_3

the East, and the need for ecological maintenance (mangrove) and offshore aquaculture in some coastlines, the sandy coastline suitable for real estate and tourism development is only 785.7 kilometers. Considering the limited resources, all parties pay little attention to their ecological environment. Sanqionghai City and Changjiang County illegally encroached on the coastal zone, felled coastal defense forest, and developed mariculture in a disorganized manner, which led to the deterioration of local water quality. Haikou, Danzhou, Chengmai, and other municipal and county water departments failed to promote the construction of sewage treatment projects, resulting in the direct discharge of massive quantities, and serious pollution of the surrounding coast. More than 5 million square meters of real estate projects were halted because of noncompliance or violation of two temporary procedures; multiple compliance, coastal zone protection, and other policies were shut down. From 2012 to 2017, tourism in Hainan Island has increased to 67.45 million, and it is estimated that it will receive 110 million tourists in 2020. The exploitable coastline of Hainan Island has exceeded its own ecological environment load, which directly affects the island's marine ecological carrying capacity and is not conducive to the sustainable development of the island's economy.

Hainan Island was established as a free trade port by China in 2018, because of its unique natural and ecological conditions and superior location advantages. Hainan Island is located in the forefront of the South China Sea, which itself is the focus of and challenge for China's security strategy and its *one belt and one road* initiative. Hainan Island, as an important strategic base for the Pan South China Sea Economic Cooperation circle, is an important opening door for China to India and the Pacific Ocean. Different from the free trade area, the free trade port is an all-round opening of goods, capital, people flow, data, and so on. Its system is designed to be exclusive to the free trade port and the highest level of globalization such as Hong Kong, Singapore, and so on.

Hainan was selected as China's first free trade port construction area, which is different from the 11 domestic free trade areas in nature, mainly for building a free trade port with Chinese characteristics. With opening up as the first step, for both land and sea, and green development as an important feature, we should develop Hainan's unique ecological advantages, giving importance to the protection of marine ecology, consolidate the economic foundation, and develop a modern service industry and high-tech industry. Building a free trade port through a comprehensive opening of the region, should consider its marine ecological carrying capacity, establish a construction system in line with the actual and natural laws, and achieve green and sustainable development of Hainan Island.

Importance to the Protection of Marine Ecology

Reasonable Utilization of Marine Resources. In building and developing free trade ports, marine resources should be used responsibly to prevent resource depletion. Although natural gas, ilmenite, and other resources in Hainan Island rank very high in China, some of them are nonrenewable resources. To diversify resource utilization, we should not rely on one type of marine resource. Fossil energy should go hand in hand with renewable clean energy such as wind and water energy. Meanwhile, the sustainable development of Hainan's marine economy should be promoted by utilizing tourism resources in coastal areas, with greater investment in new tourism modes and projects.

Improve Marine Ecological Construction. In terms of marine ecological protection, maintaining biodiversity and increasing investment in environmental protection will have a significant impact on the marine ecosystem of Hainan Island. Hainan should increase the area of coastal shelter forests and establish marine nature reserves to maintain the original appearance and biodiversity of the ocean. Simultaneously, the establishment of marine ecological civilization construction demonstration zone, and reducing noise pollution in the ocean, provide useful references for exploring the construction of a marine ecological civilization. Damaged beaches can be restored by vegetation sand fixation and other means. For islands with serious ecological damage, we can learn from the repair experience of Qiaoshan Island, create an environment suitable for plant growth, and restore them by plant remediation and other means.

Strengthen the Management of Marine Scientific Research. The level of science and technology plays an important role in improving marine ecological carrying capacity, pollution control, marine environmental monitoring, and early warning. It is crucial to strengthen the training of marine professionals and the research and development of technology and to focus on the scientific research of marine environmental pollution control. However, it is also important to focus on monitoring the marine environment. In marine management, online monitoring equipment should be installed in key bays, bending rivers and sewage outlets, the dynamic monitoring system of marine environment should be improved, and monitoring, control, early warning, and crisis management mechanisms should be established.

Developing Modern Service Industry

Promote the Construction of International Tourism Consumption Center. To build an international tourism consumption center, we should focus on expanding the supply of international tourism products and related services, targeting mature tourism destinations favored by European and American tourists such as Bali, Phuket, and so on. We should also expand the tourism consumption space, cultivating new hotspots of tourism consumption, creating several international level tourism theme parks (parks), and further implementation of tax-free shopping policies.

Developing Medical and Health Industry. Hainan Island should be the destination for the medical and health industry. The Boao Lecheng International Medical Tourism Pioneer Area should be developed into a global medical innovation *Silicon Valley*, so that research and related technological innovation of international high-end medical services, such as stem cells and anti-aging, can be pioneered in Lecheng, and develop Hainan into an important contact for national medical and health consumption. This not only helps in cultivating and developing Hainan's medical and health industry but also attracts global medical and medical services. Senior pharmaceutical talents and professionals will travel to Hainan, developing the conditions for innovation and entrepreneurship.

Accelerating the Opening of the International Education Market. The increase in the acceleration and efficiency of international education, international conferences, and exhibitions is important for the development of Hainan, helping reduce the dependence on the real estate industry and embark on a high-quality development path. It is very important to improve the level of education, its quality, the quality of workers, innovation and entrepreneurship talent, and create a foundation for medium- and long-term innovation and the future development of Hainan.

Developing High and New Technology Industry

The Hainan Ecological Software Park is an important platform for the development of high-tech industry in Hainan Island. Many scientific and technological enterprises have establishments here including Baidu, 360 blockchain, Xunlei, and other well-known Chinese enterprises. In recent years, blockchain has attracted much attention. The integration and application of blockchain technology play a very important role in the new industrial revolution. On October 8, 2018, Hainan Province granted a license to the Hainan Ecological Software Park to build a *Hainan free trade port blockchain test area*, which is the first official blockchain test area in China.

Implications for Conservation

To formulate and improve technical standards, it is necessary to implement laws and regulations for marine ecological environment monitoring, investigation, protection, and management to ensure that marine governance is reasonable and legal. It is necessary to control the total amount of pollutants entering the sea and implement the red line system of marine ecology, and the permit system of marine sewage discharge. We should strengthen marine supervision and law enforcement, examine the pollution situation in factories, investigate and punish illegal acts, revoke pollutant discharge permits and business licenses in serious cases, and eliminate disorderly discharge.

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