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# Evaluation of the ecological carrying capacity of Wailingding marine ranching in Zhuhai, China by high-resolution remote sensing

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Evaluation of the ecological carrying capacity of marine ranching is a prerequisite and guarantee for ensuring the sustainable development of aquaculture activities, protecting and maintaining the stability and security of marine ecosystems. Based on high-resolution satellite remote sensing data and survey data of Wailingding marine ranching in Zhuhai from 2006 to 2021, this study constructed a marine ecological carrying capacity (MECC) index system with three levels: resources, environment, and ecology. A combination of the analytic hierarchy process (AHP) method and entropy method was applied to assign values to indexes, and then, the MECC of marine ranching was evaluated based on the state-space model and the weighted Bonferroni mean (WBM) model. Results showed that the MECC of Wailingding marine ranching increased from 0.49 (2006) before the marine ranching construction to 0.79 (2021) after the marine ranching construction. Marine ranching had elevated MECC from a loadable state to a fully loaded state. The intertidal subsystem, with a weight of 52.51%, dominates the MECC of marine ranching, in which resource and environmental factors are the major influencing factors. The increased rate of the state-space model (61.73%) was higher than that of the WBM model (44.34%), indicating that the state-space model is more feasible for the MECC assessment of Wailingding marine ranching.

## KEYWORDS

marine ecological carrying capacity, marine ranching, high-resolution remote sensing, Wailingding, three-dimensional state-space model, weighted Bonferroni mean

## 1 Introduction

Marine ranching is a new type of fishery model based on the principle of marine ecosystem, taking measures such as putting artificial reefs, stocking and releasing in specific sea areas to build or repair the places needed for the growth, baiting, enemy avoidance, and reproduction of marine organisms, so as to achieve the purpose of stocking and conserving fishery resources and improving the ecological environment of the sea area, thereby realizing the sustainable protection of fishery resources (Chen et al., 2013). Compared with the traditional ones aimed at fishery production, modern marine ranching integrates modern engineering technology and management theories, developing from relying solely on ecological engineering to systematically managing biological resources, ecological environment, fishery production, and related cultural and leisure activities, forming a comprehensive system of people, fish, land, and sea. It is an effective carrier of the primary, secondary, and tertiary industries, with a greater emphasis on ecological attributes, environmental protection, ecological restoration, and resource conservation, covering seedling expansion and ecological development (Yang et al., 2019). It directly affects the carrying capacity of the marine ecosystem by changing the structure of food webs and their potential productivity (Vasconcellos and Gasalla, 2001). It is of great significance in carbon sequestration in the ocean, improving the seabed observation network, and promoting the construction of comprehensive marine pastures (Yang et al., 2018a; Chen, 2020). A responsible stock enhancement should not only increase total production and stock abundance, but also consider the potential impacts on ecosystem structure and function. Therefore, assessing the ecological carrying capacity of marine ranching, identifying potential environmental and ecological risks, and predicting factors that may influence the ecological environment are necessary prerequisites and safeguards to ensure the sustainable development of stock enhancement and to preserve the stability and security of marine ecosystems.

Marine ecological carrying capacity (MECC) is a synthesis of resource carrying capacity and environmental carrying capacity, which refers to the ability or limit of the ocean to support the coordinated development of population, environment, and economy within a certain period time, based on the principle of sustainable utilization of marine resources and the non-destruction of the marine ecosystem through the ocean's self-regulation and self-maintenance under the material standard of living that meets the current stage of socio-cultural norms, while marine resources can be sustainably utilized and marine ecological environment is not destroyed (Di et al., 2014). It can be divided into resource supply capacity, environmental constraint capacity, ecological elasticity, and human influence. Initially, the focus of marine carrying capacity was primarily on determining sustainable thresholds for fish, shellfish, and other marine resources (Suo et al., 2023). Later, with the continuous development and utilization of marine resources and environment, studies gradually expanded from single factor to comprehensive carrying capacity (Chapman et al., 2013; Borja et al., 2022; Theodora and Spanogianni, 2022), and also included marine ecosystem service function study (Ma et al., 2019)

and marine ecosystem health study (Zhao et al., 2016). At present, the state-space method, supply–demand analytical method, and system dynamics method are the major approaches to evaluate the MECC quantitatively. The state-space method evaluates the ecosystem carrying capacity by establishing an index system, such as the Pressure-State-Response (PSR) model. On this basis, the model had been extended as the Driver-Pressure-State-Impact-Response (DPSIR) model (Li et al., 2023b), the Pressure and Support-Destructiveness and Resilience-Degradation and Promotion (PS-DR-DP) model (Ying et al., 2022), and the Driver-Pressure-State-Ecosystem Service-Response (DPSIR) model (Chapman et al., 2013), among others. Since ecological carrying is often assessed based on supply–demand conditions of the resource environment, the supply–demand analytical method uses the difference relationship between them to build a model. For example, a three-dimensional ecological footprint model has been successfully applied to assess the MECC of coastal urban agglomerations (Wang et al., 2020). The system dynamics method simulates MECC through mathematical calculation models. The MERAMOD model offers the possibility to simulate and predict the impact of the environment on the carrying capacity of marine fish farms (Yucel-Gier et al., 2019). In addition, some scholars have explored the use of a multidimensional approach. Du created the DPPD evaluation model, based on driving-pressure-state-impact-response (DPSIR), Principal Component Analysis (PCA), Path Analysis (PA), and Decision Making Trial and Evaluation Laboratory (DEMATEL), being applied to the MECC evaluation of 11 coastal areas in China (Du et al., 2020). Some new technologies, like image video processing and video sequence algorithms, have also been applied to the assessment of MECC (Huamantincó Cisneros et al., 2016), offering a fresh perspective for MECC evaluation. During the evaluation process, the methods to determine the weight of index can be categorized into subjective methods, objective methods, and a combination of both (Li et al., 2023b). Among them, subjective methods include the analytic hierarchy process (AHP) (Wang et al., 2017; Du and Gao, 2020; Zhang et al., 2023) and expert judgment (Du et al., 2022), while objective methods include the entropy weight method and PCA method (Du et al., 2020). Subjective methods were influenced by the subjective factors of the evaluator in the selection of criteria and the distribution of weights. Objective analysis relies on the information of the data itself. The combination of both can improve the accuracy of the evaluation to a certain extent.

Although previous studies have laid the foundation for the evaluation of MECC of marine ranching, there are still some problems. Spatially, major focus has been on large-scale coastal areas (Huamantincó Cisneros et al., 2016; Du et al., 2020; Wang et al., 2020; Ying et al., 2022) or islands (Nam et al., 2010), with a lack of understanding of the adjacent or embedded areas of islands. In terms of time, the main focus was on the ecological effects at the beginning of marine ranching construction, neglecting long-term monitoring and early warning (Huamantincó Cisneros et al., 2016; Zhao et al., 2016; Long et al., 2019). Regarding influencing factors, the major consideration was the *in situ* investigation of fishery resources and ecological environments (Liao et al., 2013; Wang et al., 2018; Feng et al., 2021; Feng et al., 2023), while many key

hydrodynamic factors were rarely observed or continuously monitored at the same time or in the same location as biological surveys. As the construction of marine ranching is a regional comprehensive development, the ecological carrying capacity evaluation based on a large-scale, long-term, and comprehensive survey is a prerequisite. High-resolution remote sensing has advantages of long duration, high accuracy, and full coverage, which makes it possible to continuously monitor the dynamic variations of the geographical and habitat factors of marine ranching.

In this study, the MECC of the Zhuhai Wailingding National Marine Ranching Demonstration Zone was evaluated based on high-resolution satellite remote sensing. Furthermore, major factors affecting the MECC were analyzed. Results will contribute to a better understanding of the ecological variations of marine ranching and provide theoretical support for the scientific planning and sustainable development of modernized marine ranching.

## 2 Materials and methods

### 2.1 Research area

Wailingding Island is located in the Pearl River estuary, where seawater and freshwater intermingle. This island spans from 114°1'20.26"E to 114°3'5.91"E and 22°5'17.87"N to 22°6'46.24"N (Figure 1). It is part of the Wanshan Archipelago with an area of approximately 4.23 km<sup>2</sup>. The National Marine Ranching Demonstration Zone of Wailingding Island was established in the eastern sea area. Artificial reefs were first deployed in the Wailingding National Marine Ranching Demonstration Zones between February 2007 and February 2009, followed by a second placement in 2021. The area currently hosts 2,937 artificial reefs. According to the distance to the artificial reef area, 12 survey stations were set (indicated by S1, S2, S3, S4, S5, S6, S7, S8, S9, C1, C2, and C3 in Figure 1). Field investigation was conducted during the pre-artificial reefs deployment period in August 2006 and the post-artificial reefs deployment period in August 2009,

September 2016, April 2020, September 2020, and September 2021, respectively. Among them, water quality, sediment, environmental factors, and fishery resources surveys were conducted at stations S1–S6, S8, and S10–S12, water quality surveys were conducted at stations S7 and S9, while the intertidal benthos investigation were undertaken at stations C1–C3.

### 2.2 Data process

All investigations, analysis, and identification were carried out following the Specification for Marine Monitoring (GB17378-2007) and the Specification for Oceanographic Survey-Marine Biological Survey (GB12763.6-2007). The survey data included seawater quality [temperature, depth, and salinity (‰)], dissolved inorganic nitrogen (DIN), reactive phosphate (PO<sub>4</sub><sup>3</sup>-P), marine organism (intertidal organisms, phytoplankton, zooplankton, benthic organisms, swimming organisms, fish larvae, and so on), and chlorophyll a concentration (Chl-a). Satellite remote sensing data included sea surface Chl-a, current, and intertidal data. In this study, as the high-resolution satellite was launched in 2018, Chl-a in 2006, 2009, and 2016 were survey data, and Chl-a in 2020 and 2021 were satellite remote sensing data. Among them, the Chl-a were obtained from the China HY-1 C satellite (<https://osdds.nsoas.org.cn/>), with a temporal resolution of 1 day and a spatial resolution of 50 m. The current data were from Global Ocean Physical Reanalysis Product of the Copernicus Marine Environment Management Service (CMEMS, <http://marine.copernicus.eu/>). Five remote sensing images were used to extract the intertidal area (Table 1).

MATLAB software were used to extract Chl-a information, removing the invalid value and calculating the monthly average Chl-a. Coastline length was extracted by high-resolution remote sensing data (Table 1). ENVI software was applied to preprocess the coastline length (the land area between A1 and A2 of box A in Figure 1), including reading, radiometric calibration, atmospheric correction, and image fusion. The FVCOM tidal model was used to compute the elevation when the satellite passed, and then it was

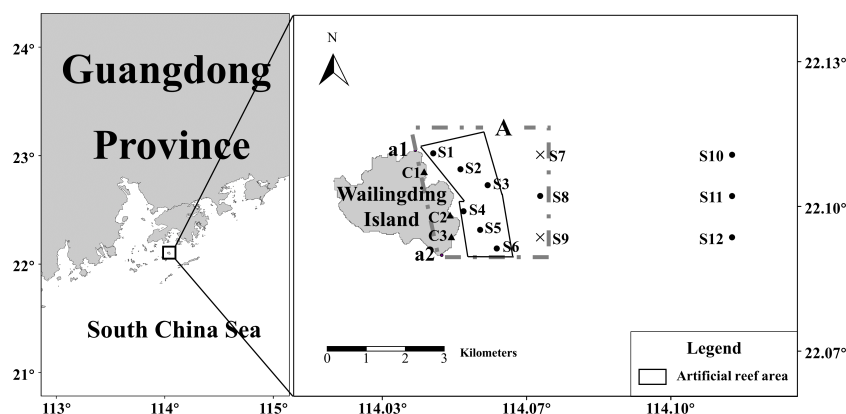


FIGURE 1

Research area and survey stations (box A is the area of satellite remote sensing data, and the land part between A1 and A2 is the area of remote sensing data of intertidal area).

TABLE 1 Remote sensing data.

Number	Name	Date	Data Source	Spatial Resolution
1	Chl-a	2019.01–2022.10	HY-1C	50 m
2	Current	2006 2009 2016 2020 2021	Global Ocean Physical Reanalysis Product of the Copernicus Marine Environment Management Service	0.083°× 0.083°
3	Intertidal data	2006.11.10	Landsat-5 TM	30 m
4	Intertidal data	2009.08.23	Landsat-5 TM	30 m
5	Intertidal data	2016.03.27	BJ-2	0.8 m
6	Intertidal data	2020.07.22	GF-1	2 m
7	Intertidal data	2021.11.28	BJ-3	0.5 m

inserted into the tidal level calculation formula (Wang and Chu, 2005) to get the extent of the intertidal zone. Finally, the length of the coastline and the area of the island and beach were calculated in ArcGIS 10.3 (Esri, Redlands, CA, USA).

## 2.3 Methods

### 2.3.1 Marine ecological carrying capacity index system

According to the concept of MECC, it should include resource supply capacity, environmental constraint capacity, ecological elasticity, and human influence (Fu et al., 2009; Di et al., 2014). Compared to land studies, as a small and medium-sized sea area, MECC of marine ranching is relatively simple. Therefore, the carrying capacity of the ocean on the actual population was not considered in the present study. Indicators of resource supply capacity were mainly considered by the supply level of various types of marine resources. Indicators of environmental constraint capacity were selected from the quality of the marine environment and the capacity of the marine environment, respectively. Ecological elasticity indicators were selected from biodiversity and taxa structure. The marine ranching ecosystem integrates characteristics of wetlands and marine ecosystems (Song, 2006). In order to construct a comprehensive and unbiased evaluation model, the select indexes were based on the characteristics of different subsystems, and the marine ranching ecosystem was divided into the intertidal subsystem and the nearshore subsystem (Zhao et al., 2016; Du et al., 2020; Borja et al., 2022; Bui and Tran, 2022). The evaluation system was constructed by factors from three levels: resource, environment, and ecology, respectively (Carneiro, 1960) (Figure 2). The index system was divided into four layers, namely, the target layer (A), system layer (B), factor layer (C), and index layer (D). The target layer (A) was the MECC of the marine

ranching layer, while the system layer (B) was the intertidal subsystem layer and the nearshore subsystem layer. The factor layer (C) included the resource layer, environment layer, and ecology layer. The index layer consisted of 24 indexes. Indexes were divided into a positive index, a negative index, and a moderate index. The positive index means the effect is promoting, and the larger the index value, the better. The negative index means the effect is inhibitory, and the smaller the index value, the better. A moderate index means there is a reasonable range of the ideal value, which should not be too high or too low.

The positive index included natural shoreline (D1, shoreline between A1 and A2 in box A in Figure 1), beach retention rate (D2), island area (D3), vegetation coverage (D4), biomass (D5), biodiversity index (D6), artificial reef area (D8), species of fish eggs and larvae (D15), benthic biomass (D16), benthic biodiversity index (D17), zooplankton biomass (D18), zooplankton biodiversity index (D19), phytoplankton density (D20), phytoplankton biodiversity index (D21), nekton density (D22), and nekton diversity index (D23). The negative index included open aquaculture area (D7), dissolved inorganic nitrogen concentration (D9), and reactive phosphate concentration (D10). The moderate index included temperature (D11), salinity (D12), depth (D13), current velocity (D14), and Chl-a (D24).

### 2.3.2 Calculation of index

#### (1) Beach retention rate

The beach retention rate ( $T_i$ ) is used to indicate the variation of the intertidal zone (Su et al., 2018), which is calculated as follows:

$$T_i = \frac{S_i}{S_{1990}} \quad (1)$$

where  $S_i$  is the intertidal area in  $i$  year;  $S_{1990}$  is the intertidal area in 1990.

#### (2) Vegetation coverage

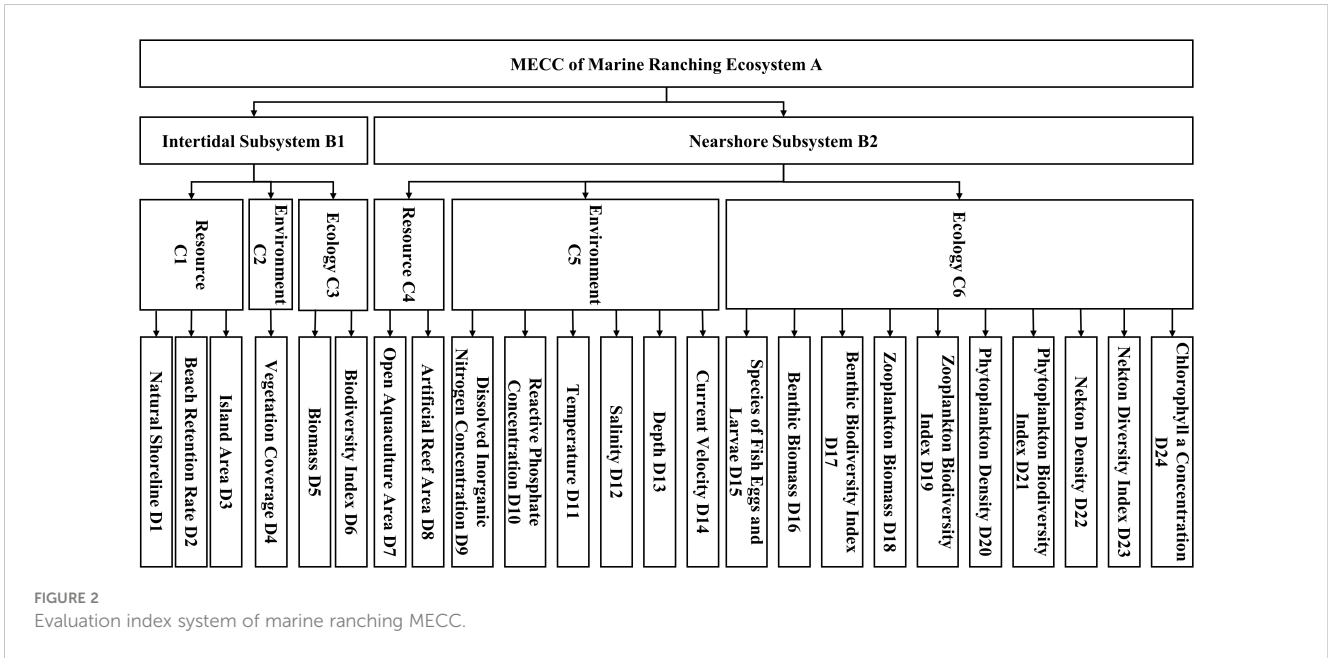


FIGURE 2 Evaluation index system of marine ranching MECC.

Vegetation coverage (VC) is one of the important indexes that indicate the change of beach environment, and the Normalized Different Vegetation Index (NDVI) is used to extract the vegetation area from remote sensing data (Chen et al., 2001). Wailingding Island is located in the subtropical monsoon climate area, where VC varies little from season to season (Xie et al., 2022; Wu et al., 2022b).

$$VC = \frac{S_V}{S_I} \tag{2}$$

where  $S_V$  is the area covered by vegetation;  $S_I$  is the area of island.

(3) Diversity index

The Shannon–Weaner index ( $H'$ ) (Wilhm, 1968) is used to indicate species diversity of organisms, which is calculated as follows:

$$H' = -\sum_{i=1}^S P_i \log_2 P_i \tag{3}$$

where  $S$  is the total number of species captured at each station and  $P_i$  is the ratio of the number of individuals of the  $i$ th species to the total number of individuals of all species.

(4) Data standardization

Owing to the different nature, units, and quantity level of index, standardization is required to eliminate the effect of the scale between the raw data (Wang, 1999). In order to avoid the occurrence of value 0 after normalization, an adjustment index  $k$  was added. The moderate index was standardized by introducing ideal values, which were obtained from the opinions of local experts, scholars, government decision-makers, or existing international and domestic standards. The reduction of calculation errors can be achieved by employing diverse methods tailored to specific index types (Yue et al., 2020; Yu and Du, 2023).

$$X_i = \frac{x_i - x_{min}}{x_{max} - x_{min}} \times 1 - k + k \tag{4} \text{ (positive index)}$$

$$X_i = \frac{x_{max} - x_i}{x_{max} - x_{min}} \times (1 - k) + k \tag{5} \text{ (negative index)}$$

$$X_i = \frac{x_i}{x_i'} \times (1 - k) + k \tag{6} \text{ (moderate index)}$$

where  $X_i$  is the standardized value of each index,  $x_i$  is the original value of each index,  $x_i'$  is the ideal value of each index,  $x_{max}$  and  $x_{min}$  are the maximum and minimum values of each index, respectively, and  $k$  is the adjustment coefficient of 0.01.

2.3.3 Index weighted

In order to avoid the bias caused by subjective factors and data itself, the weights calculated by AHP (Saaty and Kearns, 1985) and entropy method (Zou et al., 2006) were integrated, which is calculated as follows:

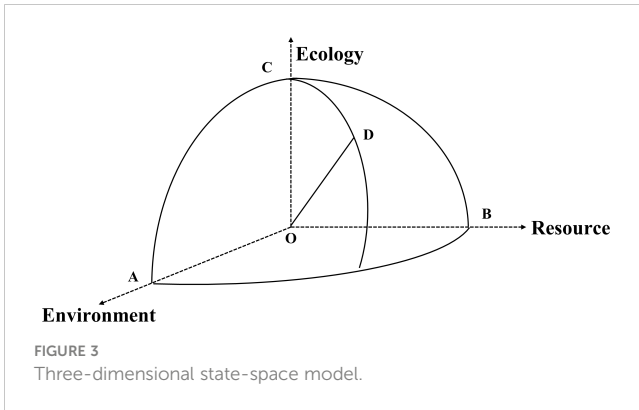
$$\omega_j = \frac{C_j W_j}{\sum_{j=1}^n C_j W_j} \tag{7}$$

where  $\omega_j$  is the combined weight,  $C_j$  is the weight calculated by AHP, and  $W_j$  is the weight calculated by the entropy method.

2.3.4 Evaluation model

(1) Three-dimensional state-space model

The three-dimensional state-space model is an evaluation method that uses vector modes (e.g., OD) composed of the origin point and system state points in a coordinate system to represent the ecological carrying capacity value (Mao and Yu, 2001). In the three-dimensional state space, each point represents the spatial combination of the resource environment at a certain moment, and the position of the point in space is used to determine the carrying capacity of the ecosystem (Figure 3). There is a surface ABC corresponding to resource, environmental, and ecological



allocation at any point on the surface reach a balance. When the point is lower than the ABC surface, it indicates that MECC is loadable; when the point is higher than the ABC surface, it indicates that MECC is overloaded.

$$MECC=|M|=\sqrt{\sum_{i=1}^n W_i R_i^2 + \sum_{i=1}^m W_i I_i^2 + \sum_{i=1}^p W_i E_i^2} \quad (8)$$

where  $n$  is the number resource indexes,  $m$  is the number of environmental indexes,  $p$  is the number of ecological indexes,  $R_i$  is the standard value of each resource index,  $I_i$  is the standard value of each environmental index, and  $E_i$  is the standard value of each ecological index.

The range of the standard value is 0–1, then the ideal value of MECC is:

$$MECC=|M|=\sqrt{\sum_{i=1}^n W_i x_i^2}=1 \quad (9)$$

The vector mode of MECC when overloaded is larger than that of the ideal state; in contrast, the vector mode of MECC when loadable is smaller than that of the ideal state. Based on the ecosystem complexity and fluctuation of its development, the tolerance of criterion was set to 0.3 (Wang, 2007). The evaluation criteria were as follows:

- When  $MECC \geq 1.2$ , overloaded;
  - When  $0.9 \leq MECC < 1.2$ , fully loaded;
  - When  $MECC < 0.9$ , loadable.
- (2) Weighted Bonferroni mean

The weighted Bonferroni mean (WBM) was applied to evaluate MECC through the iterative algorithm (Xia et al., 2012). It uses standardized results of each index as attribute variables and the combined weights after the multiplication of subjective and objective weight as the weight vector of variables, and calculates

MECC through an iterative algorithm.

$$S_i = \sqrt[p+q]{\sum_{i,r=1}^m \omega_i X_i^p \omega_r X_r^q} \quad (10)$$

Where  $S_i$  is the value of MECC,  $m$  is the number of index, and  $p = q = 1$ .

## 3 Results

### 3.1 Beach retention rate

ENVI and ArcGIS software were applied to process the high-resolution remote sensing images of Wailingding Island (Figure 4), and the length of natural shoreline, the area of the island, the beach retention rate, and the vegetation coverage were calculated (Equations (1) and (2), Figure 5). Results showed a small change in the area of the island during 2006–2021, with a mean value of 4.58 km<sup>2</sup> and a gap of 0.28 km<sup>2</sup> between the maximum and minimum values (Figure 5A). The average length of the natural shoreline was 4.28 km, with a maximum value of 4.81 km in 2020 and similar values in other years (Figure 5A). The beach retention rate of Wailingding Island remained at a consistently high level, with an average value of 86.8%. Notably, beach retention was greatest in 2021 at 92%, with a slight decline in 2009 and 2016 (Figure 5B). Vegetation coverage rate reached its maximum in 2009 at 83% and the minimum in 2016 and 2020 at 78%. It fluctuated approximately 80% between 2006 and 2021 (Figure 5B).

### 3.2 Evaluation system and combined weight

Biodiversity index is calculated according to Equation 3, the raw data of the positive index, negative index, and moderate index in the MECC system were dimensionless, according to Equations (4–6) (Table 2).

The weight of each index was calculated using AHP and the entropy weight method, respectively. Then, the results were integrated according to Equation (7). Combined weights of each index are as follows (Table 3). The intertidal subsystem dominated the MECC of marine ranching with a weight of 52.51%, followed by the nearshore subsystem with a weight of 47.49%. In the factor level, resource factor is the major influencing factor with a weight of 37.54%, followed by environmental factor (35.13%) and ecological factor (27.33%). In the



FIGURE 4  
High-resolution remote sensing images of Wailingding Island, 2006–2021.

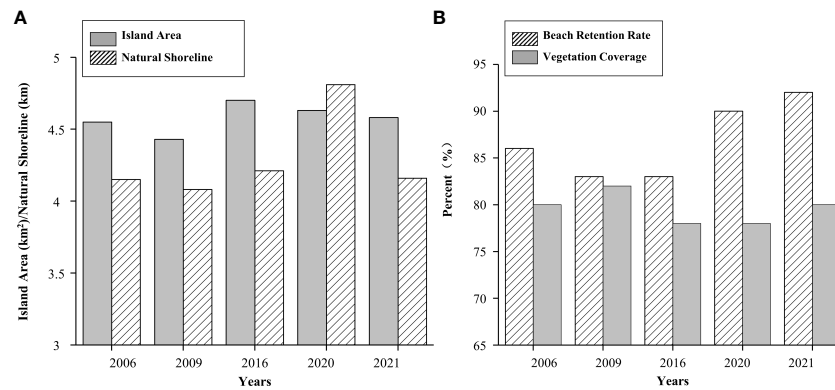


FIGURE 5 (A) Island area and natural shoreline of Wailingding Island, 2006–2021. (B) Beach retention rate and vegetation coverage of Wailingding Island, 2006–2021.

TABLE 2 Dimensionless results.

Index (D)	2006	2009	2016	2020	2021
Natural shoreline (D1)	0.1056	0.0100	0.1779	1.0000	0.1103
Beach retention rate (D2)	0.4254	0.0100	0.0697	0.8211	1.0000
Island area (D3)	0.4447	0.0100	1.0000	0.7260	0.5386
Vegetation coverage (D4)	0.4498	1.0000	0.1555	0.0100	0.4233
Biomass (D5)	0.0298	0.7282	0.0100	0.3790	1.0000
Biodiversity index (D6)	0.8180	1.0000	0.0100	0.9090	0.7816
Open aquaculture area (D7)	0.0100	0.4379	0.8129	1.0000	1.0000
Artificial reef area (D8)	0.0100	0.5014	0.5014	1.0000	1.0000
Dissolved inorganic nitrogen concentration (D9)	0.8791	0.7229	1.0000	0.8430	0.0100
Reactive phosphate concentration (D10)	1.0000	0.0100	0.8920	0.8839	0.9142
Temperature (D11)	0.9164	0.9401	0.8704	0.8299	0.8079
Salinity (D12)	0.8175	0.7758	0.9130	0.8989	0.9041
Depth (D13)	0.1701	0.1724	0.2533	0.1712	0.4711
Current velocity (D14)	0.4622	0.8975	0.8408	0.6906	0.6539
Species of fish eggs and larvae (D15)	0.3636	0.0100	0.3636	0.4343	1.0000
Benthic biomass (D16)	0.6620	1.0000	0.0100	0.1143	0.7380
Benthic biodiversity index (D17)	0.0694	1.0000	0.0100	0.1676	0.4328
Zooplankton biomass (D18)	1.0000	0.0100	0.4590	0.3244	0.8429
Zooplankton biodiversity index (D19)	0.0100	0.6805	0.2828	0.5032	1.0000
Phytoplankton density (D20)	0.8844	1.0000	0.5951	0.4599	0.0100
Phytoplankton biodiversity index (D21)	0.0100	0.0148	0.4189	0.5310	1.0000
Nekton density (D22)	0.8039	1.0000	0.0150	0.0100	0.2446
Nekton diversity index (D23)	0.4332	0.2702	1.0000	0.3105	0.0100
Chl-a (D24)	0.1387	0.7109	0.1809	0.5169	0.8049

TABLE 3 Index weights.

Index(D)	AHP	Entropy weight method	Combined weights
Natural shoreline(D1)	2.90%	5.00%	3.47%
Beach retention rate (D2)	9.96%	4.48%	10.66%
Island area (D3)	5.63%	4.06%	5.46%
Vegetation coverage (D4)	18.48%	4.34%	19.18%
Biomass (D5)	8.73%	4.60%	9.62%
Biodiversity index (D6)	4.34%	3.97%	4.12%
Open aquaculture area (D7)	10.44%	4.06%	10.13%
Artificial reef area (D8)	8.01%	4.08%	7.82%
Dissolved inorganic nitrogen concentration (D9)	1.53%	3.97%	1.45%
Reactive phosphate concentration (D10)	1.60%	3.96%	1.52%
Temperature (D11)	6.41%	3.50%	5.36%
Salinity (D12)	4.29%	3.50%	3.59%
Depth (D13)	2.35%	3.71%	2.08%
Current velocity (D14)	2.28%	3.55%	1.94%
Species of fish eggs and larvae (D15)	1.33%	4.18%	1.33%
Benthic biomass (D16)	1.09%	4.32%	1.13%
Benthic biodiversity index (D17)	1.55%	4.74%	1.76%
Zooplankton biomass (D18)	1.04%	4.15%	1.03%
Zooplankton biodiversity index (D19)	1.44%	4.15%	1.43%
Phytoplankton density (D20)	1.03%	4.05%	1.00%
Phytoplankton biodiversity index (D21)	1.57%	4.65%	1.74%
Nekton density (D22)	1.36%	4.78%	1.55%
Nekton diversity index (D23)	1.73%	4.27%	1.77%
Chl-a (D24)	0.91%	3.91%	0.85%

index level, vegetation coverage (D4) held the highest weighting (19.18%), followed by beach retention rate (D2, 10.66%), open aquaculture area (D7, 10.13%) and biomass (D5, 9.62%). The index with the smallest weighting was Chl-a (D24) at 0.85%.

### 3.3 MECC of marine ranching

The state-space model and WBM were used to calculate MECC score of Wailingding marine ranching ecosystem Equations (8–10),

as well as the intertidal subsystem and the nearshore subsystem, respectively. Results from the WBM and the state-space model were also compared (Figure 6).

The MECC of the Wailingding marine ranching ecosystem remained within the safe carrying range for the period 2006–2021 (Figure 6A). It showed a steady upward trend in every year except 2016. Evaluation of the state-space model indicated that the maximum was 0.79 in 2021, indicating that MECC was close to being fully loaded. From 2006 to 2021, the MECC increased by 61.73%. Evaluation from WBM showed that the maximum was 0.50 in 2021, and the minimum was 0.35 in 2006. The increase of MECC between 2006 and 2021 was 44.34%. These showed that results calculated by WBM were lower than those obtained from the state-space model.

Based on the state-space model, the MECC of the nearshore subsystem fluctuated at a higher level and increased from 0.55 in 2006 to 0.85 in 2021. This indicated that MECC gradually moved from being loadable to full, but remained within the safe loadable range (Figure 6B). The minimum and maximum of MECC for the intertidal subsystem were 0.31 (2016) and 0.74 (2021), respectively.

## 4 Discussion

### 4.1 Marine ranching improves MECC

After the construction of marine ranching, fishery, benthic biomass, and species diversity have increased, and the MECC increased from 0.49 (pre-artificial reefs) in 2006 to 0.79 (post-artificial reefs) in 2021 (Figure 6A), indicating a slow fluctuating growth toward ideal carrying pattern. Studies had shown that after the deployment of artificial reefs, the community structure remained stable, with an even interspecific ratio (Feng et al., 2021), and the biomass and diversity indexes of phytoplankton, zooplankton, and zoobenthos more than doubled before reefing (Table 2). Indexes such as the biodiversity were at a medium-high level, and there was an increase in intertidal biomass and species diversity as well (CN-SC, 2015). This was consistent with the studies on marine ranching in Daya Bay (Liao et al., 2013) and Zhelin Bay (Ma et al., 2019). On the one hand, upwelling is generated near the artificial reefs, which carries nutrient-rich bottom water to the well-lit euphotic zone through the process of resuspension and diffusion, thereby accelerating nutrient circulation (Lin and Zhang, 2006). On the other hand, the flow field effect, feeding effect, and shelter effect produced by artificial reefs not only provided habitat, spawning, and shelter for organisms (Chen et al., 2002), but also offered rich bait for fish, shrimp, and shellfish, resulting in fish-gathering effect and enhancing the biodiversity of marine ranching ecosystem along with the complexity of food web. Moreover, Chl-a increased year by year after reefing, reaching a maximum in 2021 (Table 2). Primary producers define the extent of ecosystems, due to the presence of bottom-up energy regulation (Del Monte-Luna et al., 2004). Chl-a serves as an indicator of the current phytoplankton stock (Culver and Smith, 1989). As the initial (Yu et al., 2015) in the marine food chain, phytoplankton further affects the stock density of fishery through influencing the feeding, habitation, and reproduction of



fish, shrimp, and shellfish in the sea (Yu et al., 2015). Fishing methods such as trawling are limited by the deployment of artificial reefs, thereby reducing the fishing pressure in the reef areas (Zeng et al., 2021). This increase in biomass and biodiversity enhances the stability and carrying capacity of the ecosystem in the marine ranching, as well as its ability to resist external changes and restore after damage (Broman and Robert, 2017). Seaweed farms have the potential to expand the environmental capacity of grazing areas (Han et al., 2021). Major seaweed in Wailingding marine ranching were *Sargassum* (*Sargassum henslowianum*, *Sargassum hemiphyllum*, and *Hizikia fusiforme*) and *Caulerpa lentillifera*. These macroalgae are able to improve the local ecological environment by absorbing inorganic salts, heavy metal, etc (Zhang et al., 2019). They can also enhance the primary productivity by converting CO<sub>2</sub> to organic carbon in the seawater (Jiang et al., 2013; Yu et al., 2021). In addition, there are *Reishia clavigera*, *Saccostrea echinata*, *Nodilittorina (N.) trochoides*, and *Septifer bilocularis* in the Wailingding marine ranching. Shellfish has a well-developed filter-feeding system, which enhances seawater exchange and control of phytoplankton biomass, and promotes a balanced distribution of nutrients to alleviate eutrophication and improve water quality (Wang et al., 2018). Environmental capacity is the constraint of MECC, and increased resource and ecological improvement are the material foundation and support conditions (Fu et al., 2009). The improvement of marine ranching environment provides suitable habitats for organisms and reduces the impact of pollutants (Fu et al., 2009), which, in turn, improves the MECC.

It was found that MECC values of Wailingding marine ranching decreased in 2016 (Figure 6A) to 0.54, which slightly exceeded the pre-construction level value. This decline may be due to the development of tourism projects on Wailingding Island in 2009 occupied wetland resources (Li, 2017). With the increase of human flow on the island, the discharge of domestic sewage had also increased. The trumpet-shaped geographical form of Lingdingyang Estuary weakened the dilution of pollutants (Zeng et al., 2020), leading to high nutrient concentration in the waters. Increased DIN and PO<sub>4</sub><sup>3-</sup>-P, reduced intertidal area, decreased the beach retention to 83%, decreased the vegetation coverage from 82% to 78%

(Figure 5B), and slightly decreased the intertidal biomass and diversity index. Studies showed that 64% of the 11 marine ranching in the Bohai and Yellow Seas had very low ecosystem security status (Du and Gao, 2020). Increased discharges of pollutants due to human activities may lead to higher nutrient concentrations in the sea area and a reduction in the local MECC. In addition, artificial reefs have a certain service life (Lin and Zhang, 2006), and the physical stability of reef can affect its ecological effects. It has been more than 10 years since the first reef was deployed in 2007 in Wailingding marine ranching, and the long duration of reefing is also one of the reasons affecting the decrease in the MECC in 2016. Marine ranching ecosystems have the ability of self-regulation (Wang et al., 2010). Although the deployment of artificial reefs breaks the original ecological environment of the Wailingding water, a new ecosystem balance will be established after the buffer of ecosystem's self-regulation ability. This is why after the second reefing in 2020, MECC of Wailingding marine ranching improved from 2016, rising to 0.79 in 2021, close to ideal full capacity.

## 4.2 Resource and environment factors affecting MECC of marine ranching

Intertidal ecosystem and nearshore ecosystem have close material and energy exchanges, and they interact with each other. Reclamation projects or nearshore pollutants can bring substantial changes in hydrodynamics, estuarine circulation, and solute transport, which can have considerable environmental impacts on estuarine ecosystems (Yang et al., 2018b; Hu et al., 2021). Studies on the MECC of marine ranching ecosystems cannot be limited to nearshore ecosystems and need to incorporate the impacts of intertidal subsystems. Studies have shown that intertidal subsystems play an important role in the MECC of marine ranching, in which resource and environmental factors are the major influencing factors. The MECC of the nearshore subsystem has been far higher than that of the intertidal subsystem, except in 2009 (Figure 6B). However, in the MECC evaluation index system, the weight of the intertidal subsystem accounted for 52.51%

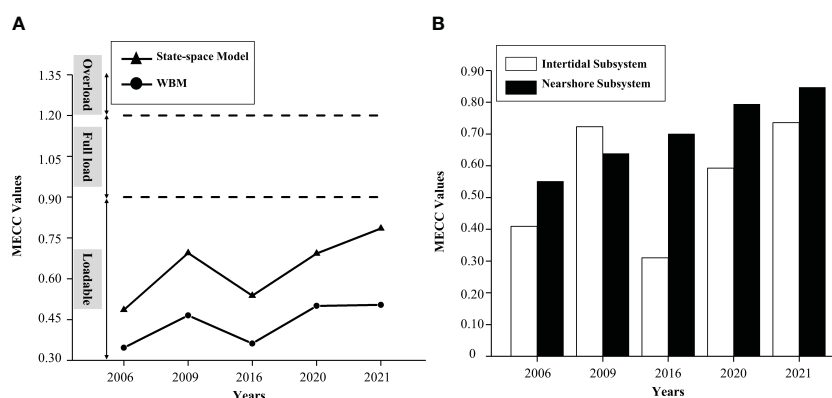


FIGURE 6 MECC values of the Wailingding marine ranching from 2006 to 2021. (A) Marine ranching ecosystem. (B) Marine ranching subsystem.

(Table 3), which had the greatest impact on the MECC of the Wailingding marine ranching. The intertidal subsystem is in the sensitive transitional region of ocean–land atmosphere interaction, rich in biomass and biodiversity (Li et al., 2023a). It provides habitat and food resources for marine organisms and also plays an important role in the stabilization and regulation of the marine environment. The complexity of the geographic location makes the ecology of the region very sensitive and fragile (Wang et al., 2015).

The construction marine ranching has an effect on increase of benthic biomass (Wang et al., 2018) and conservation of intertidal resources. Intertidal biomass reached its maximum in 2021 (Table 2). Studies have shown that the geographic location of island and their habitats affect the species composition of intertidal communities, and salinity and hydrodynamic changes affect the distribution of communities, of which changes in flushing and siltation directly affect the intertidal benthic biodiversity and distribution characteristics (Zhu and Lu, 2003). Factors affecting the hydrodynamic processes of the intertidal area include tidal currents and waves, and the deployment of reefs changes regional tidal wave and tidal patterns, bringing about erosion and resuspension of the sedimentary substrate (Lin and Zhang, 2006). In this study, the intertidal subsystems with higher weights were vegetation coverage (D4) with a weight of 19.18%, and beach retention (D2) with a weight of 10.66% (Table 3), indicating that resource and environmental factors are the major factors limiting MECC of the intertidal subsystems. Resources and environmental conditions play a decisive role in the stability of ecosystems and the diversity and distribution of fish and other biological groups in the region (Lv et al., 2014), affecting the regional ecological carrying capacity (Del Monte-Luna et al., 2004). They provide habitats and foods, purify water, and maintain ecosystem stability.

### 4.3 Selection of MECC methods for marine ranching

Considering the uniqueness of marine ranching ecosystems, it is a challenge to assess the MECC. Although previous studies have provided a variety of referable methods (Chapman et al., 2013; Di et al., 2014; Wang et al., 2017; Du and Gao, 2020; Du et al., 2020; Wang et al., 2020; Borja et al., 2022; Bui and Tran, 2022; Ying et al., 2022; Suo et al., 2023), the rationality and practicality of their applications in marine ranching still need to be further explored and improved.

The most popular conceptual model for quantitative evaluation of MECC is the PSR model, from which the evaluation system based on the concept of MECC is evolved (Wu et al., 2022a). However, the causal relationship between indexes in this model is not accurate enough. Compared with this, the establishment of the evaluation index system from the concept can provide a clearer idea for the classification of the assessment indexes. Studies have shown that the assessment of carrying capacity of fishery is based on the theory of the food chain/food web and energy flow (Suo et al., 2023). As a small-scale energy system, marine ranching does not have standardized and comprehensive access to energy flow data, as is

the case for global or national systems, and there are uncertainty of sources, which reduces the credibility of the calculations (Du et al., 2022). The study of ocean carrying capacity should not be limited to a single carrying capacity, but should also include the coastal zone and surrounding waters, seabed and bottom, etc. Its application to relatively closed marine ecosystems requires a clearer understanding of the ability of the water to allow pollutants to enter without causing long-term deterioration or pollution. The MECC of small-scale areas is the carrying capacity under dominant function determination and needs to take into account physical processes (such as dilution, dispersion, sedimentation, and evaporation) as well as all chemical and biological processes. Therefore, in this study, temperature, salinity, depth, current velocity, and other hydrodynamic factors were added to construct the model to make the evaluation system more complete. AHP and the entropy method are the combination of expert experience and objective data, eliminating subjectivity and ambiguity in the evaluation process (Wu et al., 2022a). Combing through the multiplicative integration (Equation 7) makes the results of weight allocation more objective, and the influence of each index can be revealed as well.

The state-space model solved the difficulties in determining the ideal index value of MECC, based on the evaluation criteria of the conservation effect of marine ranching. Survey data are processed according to national standards. Remote sensing data extraction information had been used in many ecological studies (Su et al., 2018; Pan et al., 2020; Zhu et al., 2022) and is consistent with survey data. These data conformed to the spatial scale and time frame required for our research. Therefore, the data were reliable, and methods can reduce the systematic error in the evaluation process (Yu and Du, 2023). The evaluation system in this study consists of 24 indexes in four levels. WBM has excellent performance in processing multi-criteria decision-making, where the optimal solution is selected from multiple schemes, or synthesizing the performance of each scheme under multi-criteria to obtain its ranking (Xia et al., 2012). Therefore, introducing WBM in the evaluation of MECC can deal with the situation where there is a link between the criteria in multi-criteria decision making. In this study, the two methods show a similar trend of change, with an overall upward trend in MECC scoring value from 2006 to 2021, and a significant decline in 2016 (Figure 6A). It can be considered that both methods are feasible. The difference is that the calculation results of WBM are significantly lower than those of the state-space model, and the variation of the state-space model is 61.73%, while the change in the WBM is 44.34%, which is relatively gentle compared to the state-space model. That is, results of WBM showed that MECC of Wailingding marine ranching was at a low level, and there was little change in the MECC after and before the deployment of artificial reefs. This was partly associated with the iterative operation of WBM that weakened the correlation between the indexes (Yang et al., 2020). The MECC of the marine ranching ecosystem is a relatively single in terms of the carrying objects, which leads to the possibility of strong correlations between various indexes. Furthermore, MECC is mainly influenced by resources and environmental factors (Woodworth-Jefcoats et al.,

2017), and biomass is considered a dynamic component of MECC (Del Monte-Luna et al., 2004). The key resource elements in this study, such as beach retention rate and artificial reef area, have increased significantly compared to the pre-reefing period (Table 2). Environmental factors such as temperature, salinity, and current velocity remain relatively constant over the same period of time. As biomass and Chl-a increased, it is reasonable to predict that the MECC should be at a higher level, and there is a significant change from the initial state. Results of the state-space model were relatively high, which was a significant improvement and was closer to the actual situation than that of the WBM. Therefore, the state-space model is more optimal and suitable for Wailingding marine ranching.

## 5 Conclusion

An evaluation index system from three levels was constructed, based on high-resolution satellite remote sensing and survey data. Two methods of the state-space model and WBM were used to comprehensively evaluate the MECC of Wailingding marine ranching. Results provide new ideas for the construction of modern marine ranching. Firstly, attention needs to be paid to the protection and restoration of the intertidal areas near the marine ranching. Measures such as designation of protected areas and restrictions on fishing can be taken to increase investment in resource protection. The health and integrity of intertidal resources can be protected and the MECC of the intertidal system can be enhanced through planting mangroves, *Tamarix chinensis* Lour, *Suaeda glauca* (Bunge) Bunge, etc. Secondly, the management of pollutant discharge should be strengthened and the scale of coastal reclamation should be controlled. A healthy ecosystem is a prerequisite for enhancing MECC. Thirdly, a digital platform that can monitor the ecological environment and fishery variations of marine ranching should be built. Early warning of ecological safety and environmental security, and big data processing and analysis for resources and environments should be considered as well. An effective assessment of marine ranching MECC provides data references for determining appropriate scale, establishing reasonable fishery quotas and protective measures, and implementing risk management in the construction of modern marine ranching (Wang and Du, 2023). The research has expanded the application of high-resolution satellite remote sensing in nearshore waters, and enriched marine ranching ecological carrying capacity assessment.

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## Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

## Author contributions

ZW: Writing – original draft, Writing – review & editing. LY: Writing – review & editing. JY: Writing – review & editing. PC: Writing – review & editing. ZL: Writing – review & editing. WY: Writing – review & editing.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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