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Fishery Resources, Ecological Environment Carrying Capacity Evaluation and Coupling Coordination Analysis: The Case of the Dachen Islands, East China Sea

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Impacts of human activity on the sustainable development of marine fisheries have been greatly concerned, and the carrying capacity with theoretic and practical meanings has become a focused area over the past two decades. More importantly, there are few studies on the fishery resources and environment compound system. In this study, based on the investigation data in Dachen Islands during 2019–2021, we proposed the evaluation method of fishery resources and ecological environment carrying capacity (FRCC & MEECC) and analyzed the coupling coordination degree between the fishery resources and environment. The results showed that (1) the MEECC of Dachen Islands was in the critical overload state and fluctuated significantly among seasons and the winter voyage of 2021 was the worst. (2) The nekton index of Dachen Islands was basically stable, the fish eggs and juvenile index dropped markedly, and the FRCC was also critically overloaded. (3) The fishery resources and marine environment were moderately balanced. Further, the development was relatively synchronized in autumn of 2019 and 2020, while the fishery resources in spring of 2021 lagged behind the marine environment.

Keywords: marine ecological environment carrying capacity, fishery resources carrying capacity, coupling and coordination, index system method, Dachen Islands

1 INTRODUCTION

The concept of carrying capacity was first put forward in the research of human ecology (Park and Burgess, 1921), which referred to the maximum number of organisms in existence under given circumstances. The connotation of carrying capacity continuously expanded with the research objects from living organisms, natural systems, to human society. To achieve the sustainable development of the marine economy, Di et al. (2004) first proposed the notion of marine carrying capacity. Early studies mainly concentrated on the resource supply and environmental capacity in specific sea areas and ignored the critical role of coastal space and resources on the coastal economy

(Lai et al., 2021). Currently, there is no uniform classification of the marine carrying capacity. Scholars focused attention on a single research direction, instead of comprehensive research, such as fishing capacity (Gómez and Maynou, 2020), carrying capacity of coastal tourism (Ahyuni and Nur, 2017), beach carrying capacity (Cisneros et al., 2016), recreational waters carrying capacity (Dato et al., 2019), and aquaculture carrying capacity (Outeiro et al., 2018; Smaal and Van Duren, 2019). Chinese researchers divided the marine carrying capacity into coastal zone carrying capacity (including coastal tourism carrying capacity, industry carrying capacity, and water environmental carrying capacity), fishery resources carrying capacity (carrying capacity of mariculture and fishing), and marine ecological environment carrying capacity (Han and Luan, 2008).

With the development of the retrieval technique of the computer, bibliometric methods were performed to trace the research trends and hotspots. The data were extracted from the Web of Science Core Collection from 2000 to 2021. The search query was proposed as follows: All Fields (marine ecological environment carrying capacity) or All Fields (fishery resources carrying capacity). A total of 423 matching records were retrieved. Keywords were extracted and ranked with Bibexcel; those with the highest frequency are shown in **Table 1**. Obviously, carrying capacity, aquaculture, fisheries, and conservation were all current hotspots. The frequency of keywords related to fishery resources carrying capacity (FRCC) was higher than that of marine ecological environment carrying capacity (MEECC). These studies widely used the Ecopath model and GIS technology and focused on the structure of marine ecosystems, including morphological and nutrient structure. Pajek software was applied to visualize the keyword co-occurrence network (occurrence greater than 3), as shown in **Figure 1**. Carrying capacity, aquaculture, fisheries, climate change, Ecopath, conservation, etc., suggested more co-occurrences. The thick lines indicated the high frequency and relevance of the research fields: carrying capacity & aquaculture, sustainability; aquaculture & Ecopath; and climate change & adaptation. There are state-space method (Sang and Liu, 2019), ecological footprint method (Romadhon et al., 2014), system dynamics approach (Nugroho et al., 2019), index system method, etc., in the evaluation methods of marine carrying capacity. The MEECC was chiefly constructed based on the pressure-and-support perspective (Du and Wang, 2021). The FRCC was still at an exploratory stage and focused on the estimation of fished stock (Perry and Schweigert, 2008) and aquaculture carrying capacity (Outeiro et al., 2018).

In general, the distribution of fish populations has a certain relationship with ecological, environmental, hydrological, and other objective factors. The abundance of fish larvae showed a negative correlation with coastal distance and suspended matter concentration in the middle Elbe River (Oesmann, 2003). The Bransfield Strait and adjacent waters represent the important areas of larval retention, seawater temperature, salinity, and sampling depth which were the primary factors determining the spatial distribution of fish (La Mesa et al., 2016). The spatial distribution of fish in the Hongchaojiang Reservoir was influenced by biological factors (fish bait, escape from predators, etc.) and abiotic factors such as chlorophyll a and TP (Zhou et al., 2021). At the same time, fish populations respond to environmental stressors. For example, light has a certain regulatory effect on the fish behavior, feeding, growth, and endocrine system. The increase in temperature can significantly affect the normal physiological processes of fish and adjust their own physiological processes and life history strategies. Changes in distribution, abundance, phenological characteristics, and body size are a marine fish community in response to a warming environment (Greve et al., 2005; Cheung et al., 2013).

There appeared to be a lack of comprehensive research on the coupling system of fishery resources and the oceanic ecological environment. Present studies developed a comprehensive marine ecological environment evaluation system, while the coupling and coordination relationship with fishery resources was ignored (Li et al., 2014; Ma et al., 2017), or considered fishery resources but selected single indicators (Shen et al., 2016), or the period time of resource investigation was insufficient (Gao et al., 2013). Therefore, taking the Dachen Islands as an example, it was a new attempt to establish a comprehensive index system of fishery resources and ecological environment. The main objectives were

TABLE 1 | Evaluation system of the MEECC.

Target layers	Element layers	Index layers	Unit	Level I	Level II	Level Ⅲ
Environmental capacity	Water quality	X_1 (DIN)	mg/L	≤0.2	(0.2,0.4)	≥0.4
		X_2 (PO_4-P)		≤0.015	(0.015,0.030)	≥0.030
		X_3 (COD)		≤2	(2,4)	≥4
		X_4 (BOD)		≤1	(1,4)	≥4
		X_5 (SS)		≤10	(10,100)	≥100
		X_6 (petroleum hydrocarbons)		≤0.05	(0.05,0.30)	≥0.30
		X_7 (heavy metal pollution indices)		≤0.7	(0.7,1.0)	≥1.0
	Sediment quality	X_8 (sulfide)	mg/kg	≤300	(300,500)	≥500
		X_9 (organic carbon)		≤2	(2,3)	3
		X_{10} (heavy metal pollution indices)		≤0.7	(0.7,1.0)	≥1.0
Ecosystem health	Ecosystem structure	X_{11} (bottom dissolved oxygen)	mg/L	≥6	(4,6)	≤4
		X_{12} (Chl-a)	μg/L	5 ± 2.5	(1,2.5)∪(7.5,10)	≤1∪≥10
		X_{13} (phytoplankton diversity indices)		≥3.5	(3.5,1.6)	≤1.6
		X_{14} (zooplankton diversity indices)		≥3.5	(3.5,1.6)	≤1.6

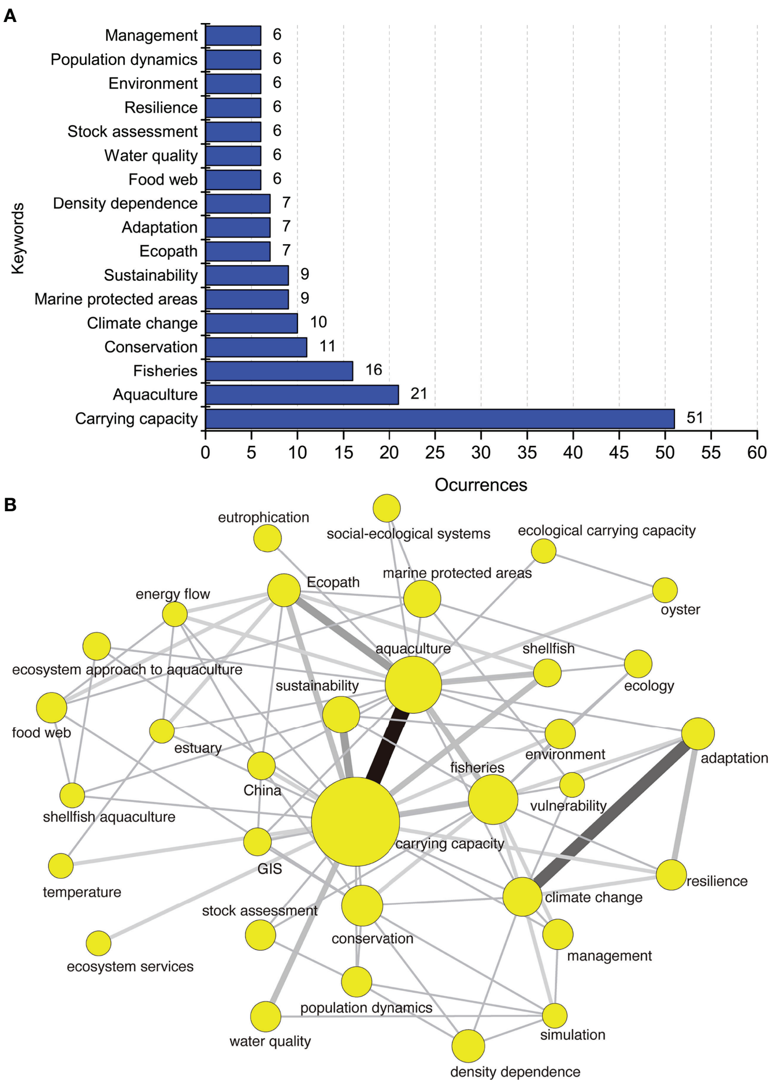

FIGURE 1 | Frequency of top topics related to fishery resources, ecological environment carrying capacity **(A)** and keyword co-occurrence network **(B)**.

set as follows: (1) to establish the evaluation system of MEECC & FRCC in the Dachen Islands; (2) to quantitatively calculate carrying capacity; (3) to assess their coupling coordination; and (4) to enlighten managers about the protection of the fishery resources and environment in the Dachen Islands.

2 MATERIAL AND METHODS

2.1 Study Area and Survey Method

The Dachen Islands (121°44′55″–121°55′10″E, 28°23′24″–28°37′02″N) are located in the southeast waters of Taizhou Bay, 52 km away from Jiaojiang District. The total land area of the Dachen islands is about 14.6 km^2, including Shang Dachen Island, Xia Dachen Island, Zhuyao Islet, Huang Islet, and Zhu Islet, and the coastline extends more than 98.85 km. The Dachen Islands are dominated by a subtropical monsoon with the northerly wind in winter and the opposite in summer. It exhibits the regular semi-diurnal tide and has high wave and tidal resources, as well as excellent recharge conditions. The high saline oceanic waters and the low saline coastal waters converge, with fertile water and rich fishery resources, making Dachen the second major fishing port in Zhejiang Province. The traditional Dachen fishing ground was rich in hairtail, and the average output reached 57,700 tons in the fishing season during the 1960s and 1970s (Lu, 2017). Affected by historical overfishing and environmental degradation, the fishing season disappeared, reef fishery resources declined seriously in the past four decades, and the traditional fishing industry was in deep waters.

A total of 20 sample sites (**Figure 2**) were selected in the Yangqi sea area of Xia Dachen Island (121°48′~121°60′E, 28°22′12″~28°28′12″N);. We monitored environmental parameters in November 2019 (autumn), September 2020 (summer), January

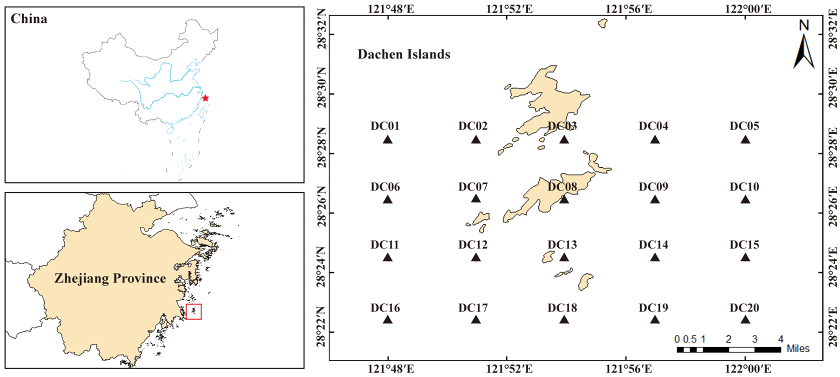

FIGURE 2 | Location of Dachen Islands with 20 sampling sites.

2021 (winter), and April 2021 (spring) and conducted fishery resource surveys respectively in November 2019, November 2020, and April 2021. Maritime survey and monitoring were carried out according to *Specifications for Oceanographic Survey* (GB/T 12763-2007) and *The Specification for Marine Monitoring* (GB 17378-2007). Fish eggs and larvae were collected with a shallow water type I plankton net, fixed in 5% formalin solution on-site, and brought back to the laboratory for microscopic examination and identification. Catches were harvested by bottom trawl (net size: 3 m high × 5 m wide mouth opening; 30–60 mm mesh) and towed at a mean speed of 3.0 km for 20 min on each site.

2.2 Modeling Approach

2.2.1 Model Structure of Marine Carrying Capacity

We viewed the marine ecological environment as the main carrier and reflected the size and change of the MEECC with its self-purification and regeneration capabilities. The evaluation system of the MEECC of Dachen Islands was constructed through the submodules of water quality, sediment quality, and ecosystem structure (**Table 1**), first using the grading index method (Bricker et al., 2003; Li et al., 2014) to standardize these indicators from raw usability data, then applying principal component analysis (PCA) to distinguish the primary and secondary degrees of factors, and, finally, employing the overall entropy method (Li and Chen, 2021) for assignment, and calculating the results through the linear weighted sum method. The grading standards were determined by relevant research (Jin and Zhang, 1980; Jia et al., 2003) and China's technical guidelines and standards, such as Sea Water Quality Standard (GB 3097-1997) and Marine Sediment Quality (GB18668-2002). The marine ecological environment carrying capacity grades were divided into level I (loadable), level II (critical), and level III (overloaded), corresponding to the assignment of (0.66,1], (0.33,0.66], and [0,0.33].

$$E_q = \sum_{i=1}^{n} E_i \times W_i \tag{1}$$

where E_q is the MEECC; E_i is the value of the standardized index; and W_i means the corresponding weight of the index.

Referring to Technical Methods of Early-warning of Resource and Environmental Carrying Capacity (Trial Implementation; No. 2043 of the National Development and Reform Commission; Fan, 2016), the Guidance for the Assessment of Coastal Marine Ecosystem Health (HY/T 087-2005), and related research (Ye et al., 2018), the evaluation system of FRCC (**Table 2**) was established. The FRCC (F) was obtained from the weighted average of the nekton index (F_1) and fish eggs and juvenile index (F_2). The variation index of catch species richness (SR), the average stock density (T_{CPUE}), the trophic level of catch (TL), Shannon's diversity index (SDI), and the density of fish eggs and larvae (F_{EL}) were used as the evaluation indexes for the FRCC. The FRCC state can be described as overloaded when F <1.5, critically overloaded when 1.5 ≤ F< 2.5, and loadable when F ≥ 2.5. The formulas were as follows:

$$F_1 (SR + T_{CPUE} + TL + SDI)/4 \tag{2}$$

$$F = F_1 \times 0.6 + F_2 \times 0.4 \tag{3}$$

2.2.2 Coupling Coordination Degree Model

Coupling was originally a physical concept. It refers to the phenomenon in which two or more systems influence each other through interaction. Based on the coupling theory, this paper established the coupling degree model of the MEECC and FRCC. The coupling degree model was difficult to reflect the coordinated development degree of internal factors, so the coupling coordination degree model (CCDM) was introduced.

$$C = \left\{ f(x) \times g(y) / \left[\frac{f(x) + g(y)}{2} \right]^2 \right\}^{1/2} \tag{4}$$

$$T = \alpha f(x) + \beta g(y) \tag{5}$$

$$D = \sqrt{C \times T} \tag{6}$$

TABLE 2 | Evaluation system of the FRCC.

Target layers	Element layers	Index layers	Threshold range	Assignment
Fishery resources	Nekton index (F_1)	Trophic level of catch, *TL*	>5%	1
			3%~5%	2
			≤3%	3
		Variation index of catch species richness, *SR*, SA	>20%	1
			5%~20%	2
			≤5%	3
		The average stock density, T_{CPUE}	>30%	1
			10%~30%	2
			≤10%	3
		Shannon's diversity index, *SDI*	<1.5	1
			1.5~2.5	2
			≥2.5	3
	Fish eggs and juvenile index (F_2)	Density of fish eggs and larvae, F_{EL}	≤35	1
			5~50	2
			>50	3

TL, SR, and T_{CPUE} are assigned according to the variation between the monitoring value and the multiyear average.

where C is the coupling degree, which is divided into low-level coupling∈(0, 0.3], antagonistic coupling∈(0.3, 0.5], grinding-in period∈(0.5, 0.8], and high-level coupling (0.8, 1); $f(x)$ and $g(y)$ refer to the standardized MEECC and FRCC; and T represents the comprehensive evaluation index between MEECC and FRCC (the two subsystems are equally important; thus, they are given the same weight, that is, $\alpha = \beta = 0.5$); and D denotes the coupling coordination degree. The grading of D is shown in **Table 3**, and the relative development degree evaluation model was used to judge the relative development level (Deng et al., 2019).

3 RESULTS

3.1 Evaluation of MEECC

3.1.1 Marine Ecological Environment

No sulfides and volatile phenols were detected. The seawater of the Dachen Islands contained high concentrations of nutrients, with high intensity of water exchange and supersaturated dissolved oxygen. COD, BOD, and petroleum hydrocarbon contents generally met the second-class standards; however, suspended solid, nitrogen, and phosphorus contents exceeded the quality standards (**Table 4**).

TABLE 3 | The standard of the coupling coordination degree.

Level	Degree	f(x)/g(y)≤0.9	0.9<f(x)/g(y) <1.1	f(x)/g(y)≥1.1
0.8<D ≤ 1.0	High balanced	Fishery resources advance	Synchronous development	Fishery resource lag
0.6<D ≤ 0.8	Moderate balanced			
0.4<D ≤ 0.6	Basically balanced			
0.2<D ≤ 0.4	Moderate unbalanced			
0<D ≤ 0.2	Serious unbalanced			

TABLE 4 | The monitoring results of ecological environment in Dachen Islands.

Index	2019.11	2020.09	2021.01	2021.04	Standards
X_1	0.350 ± 0.111	0.256 ± 0.094	0.370 ± 0.032	0.415 ± 0.058	0.30
X_2	0.066 ± 0.034	0.056 ± 0.027	0.065 ± 0.038	0.047 ± 0.027	0.030
X_3	1.09 ± 0.52	0.87 ± 0.24	0.58 ± 0.30	0.86 ± 0.73	3
X_4	0.28 ± 0.12	0.98 ± 0.27	1.07 ± 0.27	1.16 ± 0.56	3
X_5	51.44 ± 34.60	52.61 ± 38.81	33.66 ± 15.90	22.11 ± 9.19	10
X_6	0.022 ± 0.023	0.020 ± 0.014	0.037 ± 0.020	0.018 ± 0.014	0.05
X_7	0.53 ± 0.28	0.48 ± 0.35	0.68 ± 0.17	0.59 ± 0.37	1
X_8	85.94 ± 75.28	39.68 ± 26.53	41.31 ± 52.42	72.53 ± 78.98	500
X_9	1.30 ± 0.36	1.17 ± 0.42	1.76 ± 0.35	0.98 ± 0.21	3
X_{10}	0.29 ± 0.06	0.30 ± 0.03	0.31 ± 0.06	0.43 ± 0.50	1
X_{11}	6.89 ± 0.35	7.55 ± 0.13	10.31 ± 0.31	9.47 ± 0.11	5
X_{12}	0.83 ± 0.41	3.27 ± 3.16	0.53 ± 0.23	3.15 ± 1.22	1.7
X_{13}	2.46 ± 0.39	3.49 ± 0.50	3.41 ± 0.22	1.75 ± 0.60	1.6
X_{14}	3.09 ± 0.48	2.52 ± 0.43	0.84 ± 0.35	0.95 ± 0.59	1.6

Refer to the second-class of quality standards in China and related documents.

Heavy metal pollution indices of surface seawater indicated that the water was slightly contaminated, with high concentrations only in a few sites. The sulfide and organic carbon contents fluctuated from 1.10 to 320.70 mg/kg, 0.67% to 2.38%, which met the requirements of the second class of the sediment quality standards. The marine ecological indicators showed obvious seasonal variations. The plankton community structure suggested unhealthy in spring 2021 and winter 2021. In autumn 2019 and winter 2021, Chl-a content was relatively low and uniform.

3.1.2 Indicator Screening and Weight Calculation

Results showed that the Kaiser–Meyer–Olkin (KMO) test value of the standardized data was 0.569 (greater than 0.5), and the Bartlett spherical test value was equal to 0.000. In other words, there was a certain correlation between the variables. Six principal components were extracted to explain 74.200% of the total variance, and the variance contribution rate was 22.268%, 16.478%, 10.197%, 9.547%, 8.220%, and 7.491%, respectively. Factor analyses were conducted on the standardized data, and factor loadings were adjusted by rotation. The new set of rotated loading matrices is shown in **Table 5**. The absolute values of the loadings in that component represented the closeness between factors and principal. A frame was added to the factors of higher load in each principal component, and sulfide in sediment was not considered in the evaluation of MEECC because of its low load. The overall entropy method was employed for assignment (**Figure 3**) after the index screening.

3.1.3 Temporal and Spatial Distributions of the MEECC

The MEECC of the Dachen Islands in summer was the highest (0.581 ± 0.056), followed by spring (0.567 ± 0.046) and autumn (0.528 ± 0.029), whereas the winter voyage was the lowest (0.432 ± 0.026). The MEECC fluctuated between years, but there was no significant difference between summer and spring voyages ($P > 0.05$). The mean value of MEECC was between 0.33 and 0.66; that is, the evaluation result was critical overload, indicating that human social activities exerted pressure on the ecological environment of the Dachen Islands and there was a large space for improvement. Winter voyages had the lowest mean MEECC due to the poor health of the marine ecosystem. The MEECC showed spatial heterogeneity (the value difference was greater than 0.1): (1) The MEECC of the remote reef sites during the autumn voyage was relatively high; (2) DC13 and DC15 during the summer voyage reached the appropriate load level; and (3) the MEECC of winter and spring voyage decreased from west to East (**Figure 4**).

3.2 Evaluation of FRCC

3.2.1 Nekton Index

In view of China's summer moratorium of marine fishing, the annual mean of fishery resources was calculated based on the statistics of surveys during spring and autumn voyages. A total of 148 nekton species were collected on the three voyages, and 105, 106, and 80 species were identified in autumn 2019, autumn 2020, and spring 2021, respectively. The values in autumn 2019 and autumn 2020 were higher; thus, the *SR* was assigned a value of 3. While the number of the nekton species in spring 2021 dropped by 17.53%, the *SR* received a value of 2.

The weight and individual density of nektons in autumn 2019 were 1,265.46~4,625.68 kg/km^2 and (103.89~383.03) × 10^3 ind./km^2, and the resource density of nektons in autumn 2020 accounted for 1,360.74~5,831.72 kg/km^2 and (112.41~370.63) × 10^3 ind./km^2. The spatial heterogeneity of the relative resource density of nektons increased in spring 2021, with a fluctuation range of 321.65 ~5,011.26 kg/km^2 and (26.57~347.67) × 10^3 ind./km^2. The values in autumn 2019 and autumn 2020 were higher than the multiyear average; thus, T_{CPUE} was assigned a value of 3. However, the weight and individual density of nektons in spring 2021 dropped by 24.97% and 22.38%, respectively, and T_{CPUE} was given a value of 2.

In this study, the trophic levels of catch are referred to the *TL* of adult fish in the relevant literature, and the average *TL* of fishery organisms in the offshore waters of southern Zhejiang was 3.57 as a benchmark value (Gao et al., 2020). In autumn 2019, autumn 2020, and spring 2021, the average trophic levels of catch in the Dachen Islands sea area were 3.54, 3.52, and 3.53, respectively. The *TL* of the catch was basically stable, and the decrease of *TL* was less than 3%, so the assignments were both 3.

In autumn 2019, autumn 2020, and spring 2021, Shannon's diversity indices of nekton in different survey stations were 1.77–

TABLE 5 | Component matrix of factors.

Index	F_{i1}	F_{i2}	F_{i3}	F_{i4}	F_{i5}	F_{i6}
Zscore (X_4)	0.928	-0.038	-0.141	0.065	0.036	-0.147
Zscore (X_{11})	-0.849	-0.144	-0.345	-0.002	0.111	-0.161
Zscore (X_{14})	0.760	0.070	0.436	-0.163	-0.254	0.168
Zscore (X_9)	0.038	0.783	0.074	0.017	0.085	-0.003
Zscore (X_{12})	-0.391	0.769	0.041	-0.206	0.041	0.204
Zscore (X_6)	0.186	0.629	-0.004	0.077	-0.088	-0.054
Zscore (X_{13})	-0.093	-0.603	0.511	0.258	-0.076	-0.035
Zscore (X_1)	0.212	0.050	0.877	0.044	0.099	-0.033
Zscore (X_{10})	0.166	-0.115	0.153	0.802	0.090	-0.016
Zscore (X_3)	-0.411	-0.016	-0.058	0.740	-0.117	-0.115
Zscore (X_8)	-0.228	-0.272	0.217	-0.387	0.110	-0.338
Zscore (X_2)	-0.010	0.048	0.282	-0.085	0.831	0.041
Zscore (X_5)	-0.176	-0.003	-0.415	0.083	0.659	0.017
Zscore (X_7)	0.009	-0.003	0.004	-0.072	0.065	0.947

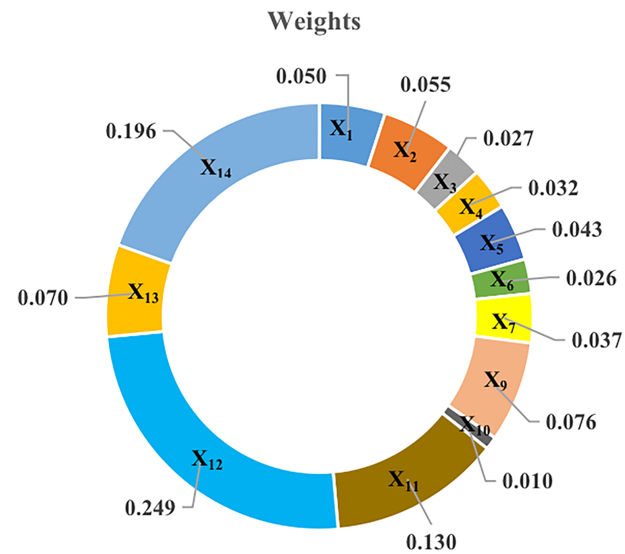

FIGURE 3 | Index weights of the MEECC.

3.55, 1.96–3.83, and 0.98–3.72, respectively. In autumn 2019 and 2020, the *SDI* was at a high level, with a value of 3. The average value of *SDI* in spring 2021 was 2.42, which was between 1.5 and 2.5, and was assigned a value of 2. Based on the evaluation results of *SR*, T_{CPUE}, *TL*, and *SDI*, the nekton index F_1 in autumn 2019, autumn 2020, and spring 2021 are 3, 3, and 2.25, respectively.

3.2.2 Fish Eggs and Juvenile Index

In autumn 2019, 4 species of fish eggs and larvae were collected, and the density of fish eggs and larvae was 0.292 ind./100 m^3; in autumn 2020, 5 species were collected, with the density of 0.842 ind./100 m^3; and during the spring 2021 voyage, 2 species were collected, with the density of 0.748 ind./100 m^3. The densities of fish eggs and larvae in the three voyages were far less than the grading standard of 5 ind./m^3, so fish eggs and juvenile index F_2 were all assigned a value of 1, indicating a significant drop.

3.2.3 Comprehensive Index of Fishery Resources

The comprehensive index of fishery resources was calculated by combining F_1 and F_2. The values in autumn 2019, autumn 2020, and spring 2021 were 2.2, 2.2, and 1.75, respectively, which were evaluated as a critical overload of fishery resources.

3.3 Coupling Coordination Degrees

The MEECC of the Dachen Islands was highly coupled with the fishery resource system (**Table 6**). Coupling coordination degrees were between 0.6 and 0.8, showing the type of moderate balance.

The order parameters of the ecological environment changed from relatively backward to ahead of the order parameters of fishery resources in terms of time series. In the autumn of 2019 and 2020, the two systems were synchronous, but the fishery resources in the spring of 2021 lag behind the environment.

4 DISCUSSIONS

The overall entropy method distributed the weight of each indicator according to the variation degree. The MEECC of critical overload was affected by the high-weight ecological factors, indicating that the marine ecological health of the Dachen Islands needed to be improved. Phytoplankton diversity indices (X_{13}) were low in the spring voyage, and *Noctiluca scintillans*, *Melosira sulcata*, and *Prorocentrum donghaiense* were the dominant species, implying the risk of red tides. Zooplankton diversity indices (X_{14}) were unhealthy in winter and spring voyages. The winter voyage was due to fewer zooplankton species, while the spring voyage was dominated by *Calanus sinicus*. According to Yamada's seawater eutrophication standards (Li and Liu, 2000), the studied areas in autumn 2019 and winter 2021 were oligotrophic (Chl-a <1.7 μg/l), and those in the remaining voyage were eutrophic (1.7–10 μg/l). The low chlorophyll content (X_{12}) in Dachen Islands greatly affected

TABLE 6 | Coupling and coordination degree of marine ecological environment and fishery resources in Dachen Islands.

Year	Ecological environment	Fishery resources	C value	D value	Types
Autumn 2019	0.528	0.567	0.9994	0.740	Moderate balanced-synchronous development
Autumn 2020	0.581	0.567	0.9999	0.758	Moderate balanced-synchronous development
Spring 2021	0.567	0.417	0.9882	0.697	Moderate balanced-fishery resource lag

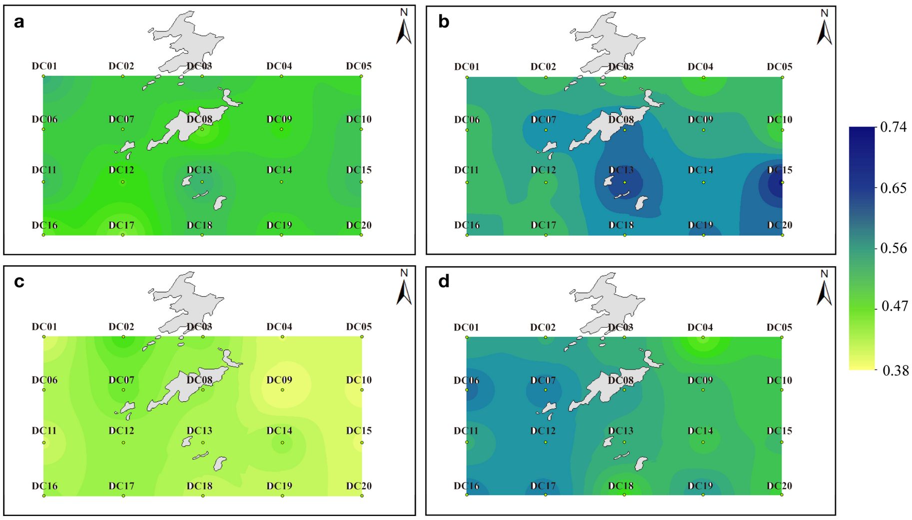

FIGURE 4 | The interannual variation of the MEECC in **(A)** November 2019, **(B)** September 2020, **(C)** January 2021, and **(D)** April 2021.

primary productivity. Generally, the higher the nutrients in the survey area, the richer the phytoplankton and Chl-a concentration, but this is not the case. Low light and temperature in winter are not conducive to the growth of phytoplankton.

The factors of contaminants receiving with low scores included inorganic nitrogen (X_1), phosphate (X_2), and suspended solids (X_3). The Dachen Islands and the adjacent Sanmen Bay both showed high suspended solid concentration (Nie et al., 2018), which was related to strong water exchange. High turbidity reduced the fish predation pressure (Toepfer et al., 1998) but also affected the survival and distribution of planktivorous fish. The contents of inorganic nitrogen and phosphate of the Dachen Islands exceeded the second class of seawater quality standards by 15.94% and 95.82%, respectively, and high concentrations of nutrients were influenced by aquaculture activities and pollutants directly into the sea. The fishermen started the cage culture of *Pseudosciaena croce* at the Dachen Islands since 1998, and the scale increased yearly so that it became a pillar industry. Meanwhile, pollutants directly into the sea affected the water quality of the Dachen Islands, and Taizhou even saw 43 red tides in its coastal waters from 2009 to 2017. Until 2018, the pilot implementation of ecological compensation in the Jiaojiang River system improved the environmental quality of the offshore zone. Marine pasture is a new type of marine fishery production method, which is based on the ecological principle and adopts artificial reef construction, restocking, and stock enhancement. The Dachen Islands basically met the standards for the construction of marine ranching; that is, the water quality reached the second class of seawater quality standards (except for inorganic nitrogen and phosphate). It can make full use of the seaweed bed to store and regulate the high nutrients in Dachen Islands, improve the marine ecological structure, and realize the conservation of biological resources.

To facilitate the restoration and revitalization of fisheries, the Dachenyang spawning ground reserve (121°56′–122°25′E, 28°23′–28°35′N) adjacent to the study area was established by the Zhejiang Provincial Ocean and Fisheries Bureau in August 2017, and the fishing ban period was advanced to April. A recent survey showed that the density of fishery resources in this reserve increased significantly, and the abundance and biomass of fish communities in November 2018 were 10.4 times and 8.1 times higher than those in November 2017 (Rui et al., 2021), which was consistent with the good evaluation results of the nekton index in this study. As explained above, the current protection measures assumed an increasingly important role in the restoration and protection of economic species. Meanwhile, fish eggs and juvenile index should be concerned. During the 13th Five-Year Plan period (2016–2020), most of the monitored bay and estuarine ecosystems were in a sub-healthy state, and the density of fish eggs and larvae was generally low, according to the Bulletin on China's Marine Ecological Environment in 2020. The number and species richness of fish eggs and larvae in Yueqing Bay (Liu et al., 2019), Oujiang Estuary (Du et al., 2016), and Daiquyang (Fan et al., 2020) of Zhejiang Province showed a downward trend in spatial pattern. Specifically, the average density of fish eggs and larvae in the middle of Zhejiang Province coastal waters in November 2018 was 3.08 ind./100m^3 (Fan, 2020). On the one hand, the resources of fish eggs and larvae in Zhejiang coastal waters are declining due to the rapid development of coastal industries and high-intensity fishing. On the other hand, water temperature, salinity, and reproductive characteristics are the main factors leading to resource changes. Commercial fishes in Zhejiang coastal waters presented a peak of spawning activity from May to June (Zhou et al., 2013; Zheng et al., 2014). Liu et al. (2021) found highly significant differences ($P < 0.01$) among the average density of fish eggs in Zhoushan fishing grounds in April (0.76 ind./100 m^3) and May (31.51 ind./100m^3) from 2017 to 2019. In summary, the low density of fish eggs and larvae during spring and autumn voyages in the Dachen Islands was affected by human activities and the non-peak spawning season.

The basically stable fishery resource indicators will get a higher value, but the MEECC evaluation value is 0.66 when the ecological environment factors all reach the first class of seawater quality standard, which may suggest that the grading index method has a stricter evaluation of the ecological environment. In this respect, the standardization process of directly comparing FRCC with 3 before coupling and coordination analysis might be unreasonable. 1.5 and 2.5 simply corresponded to the critical points of carrying the status of fishery resources with reference to the Technical Methods (Trial Implementation). In this paper, a more reasonable liner normalization formula was employed: FRCCstandardized = 1/3* FRCC -1/6, which obtains 1/3 and 2/3 by substituting 1.5 and 2.5, respectively. The coupling degrees of MEECC and FRCC of the Dachen Islands were higher than 0.8, which was the high-level coupling, indicating the strong interaction intensity and coupling relationship. After a slight recovery in 2020, the coupling coordination degree decreased again, and the coupling coordination type of the three voyages was moderately balanced, showing that the development of coordination needed to be further improved. The coupling coordination was the result of the combined interaction of the two subsystems. The autumn voyage in 2020 obtained the best results of carrying condition assessment, conveying that human disturbance was minimal, the ecological environment quality was excellent (only the phosphate was overloaded), and the nekton indicators all enjoyed relative stability. The plankton community structure was healthy in autumn 2019, but high weight and low assigned Chl-a significantly reduced the MEECC. In spring 2021, each indicator of fishery resources was lower than the multiyear average.

The background investigation of resources and environment in the Dachen Islands was planned for different seasons. The fishery resource survey in September 2020 was postponed to November 2020 due to the fishing ban. Generally, the changes in the overall marine ecological environment in adjacent months were not significant (Wang et al., 2021). The time of environmental monitoring and fishery resource survey was not completely synchronized, which will affect the coupling coordination degree in autumn 2020, but within a reasonable range. The marine environment developed synchronously with fishery resources in autumn 2019 and 2020, while the fishery resources lagged behind the marine environment in spring 2021. Contaminant receiving and ecological effect factors called status and response indicators are the direct reflections of the overall health status. The FRCC is not only affected by the dynamic changes in fisheries, but also by the environment, and social and economic activities. The effect of external factors on the FRCC is not instantaneous, so the changes in the ecological environment and fishery resources are not synchronized with each other. Although the ecological environment of the Dachen Islands provided suitable growth conditions for the fish population, the growth rate of fishery resources in spring lagged behind the fishing intensity due to human disturbance. It can be seen that Taizhou continuously strengthened the protection of fishery resources and the ecological environment and achieved a certain degree of success. Meanwhile, there was still plenty of room to improve the MEECC and FRCC, and we must be alert to the risks of marine resources and the environment.

The widely used index system method has the advantages of simple and objective calculation, clear evaluation, strong systematisms, etc. The calculation of MEECC considered the indicator screening process compared to previous studies. The index of FRCC was further expanded and applied compared to Trial Implementation. Most importantly, coupling coordination analysis of fishery resources and ecological environment carrying capacity was the first attempt. However, the coupling coordination degree can only represent the status of the corresponding voyage. Data need to be improved, and long-term data can better grasp the changing trend of carrying capacity and make scientific predictions.

5 CONCLUSIONS

Marine carrying capacity evaluation is an effective means of rational developing and utilizing marine resources and early warning of marine ecological problems. Taking the Dachen Islands as a case, we discussed the development status of MEECC and FRCC from the perspective of coupling and coordination. The carrying capacity of fishery resources and ecological environment in the Dachen Islands fluctuated with no obvious continuous increasing or decreasing trend, both of which were critically overloaded and needed to be improved. The two subsystems were high-level coupling, the coupling coordination degrees were moderately balanced, and the relative development levels were synchronous or fishery resource lag. The local government should strengthen the protection of the ecological environment and conserve the fishery resources of the Dachen Islands to improve the carrying capacity of fishery resources and the ecological environment.

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

HH: supervision, conceptualization, methodology, writing—review and editing, resources and funding acquisition. ZuW: investigation, data curation, original draft. YL: investigation, data curation. XZ: investigation, data curation. ZhW: investigation, writing—review and editing. XC: investigation. All authors contributed to the article and approved the submitted version.

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