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The beibu gulf biodiversity and sustainability: Baselines, impacts and solutions

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Published in
Frontiers in Marine Science

ISSN 1664-8714
ISBN 978-2-8325-4003-9
DOI 10.3389/978-2-8325-4003-9

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The beibu gulf biodiversity and sustainability: Baselines, impacts and solutions

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Citation
Yang, B., Kwan, K. Y., Lin, P., Peng, S., Cai, S., eds. (2023). *The beibu gulf biodiversity and sustainability: Baselines, impacts and solutions*. Lausanne: Frontiers Media SA. doi: 10.3389/978-2-8325-4003-9

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frontiers | Frontiers in Marine Science

TYPE Original Research
PUBLISHED 23 September 2022
DOI 10.3389/fmars.2022.996202

OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Marine Conservation and Sustainability, a section of the journal Frontiers in Marine Science

RECEIVED 17 July 2022
ACCEPTED 07 September 2022
PUBLISHED 23 September 2022

CITATION
Zhu Z, Wei H, Guan Y, Zhang L, Sun P and Zhang Q (2022) Spatial and seasonal characteristics of dissolved heavy metals in the seawater of Beibu Gulf, the Northern South China Sea. *Front. Mar. Sci.* 9:996202. doi: 10.3389/fmars.2022.996202

Spatial and seasonal characteristics of dissolved heavy metals in the seawater of Beibu Gulf, the Northern South China Sea

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Heavy metal contaminations in the marine environment are of considerable attention because of their high potential ecological effects and public concern for human health. However, the influencing factors for the large-scale distributions of heavy metals in Beibu Gulf, a newly developing industry and port in South China, are still unclear due to the lack of large-scale investigation. Here, a total of 871 samples in the 127 stations in the seawater of Beibu Gulf during spring, summer, fall and winter in 2020-2021 were analyzed for dissolved heavy metal concentrations and physicochemical parameters. The concentrations of heavy metals in the Beibu Gulf ranked following the order of Zn > Cu > Cr > As > Pb > Hg > Cd. Compared to other regions, the concentrations of Hg were at relatively higher levels, which were mainly influenced by the input of the transportation of water masses from the local and other regions; whereas the other heavy metals were at relatively lower levels. Seasonally variations in the concentrations of heavy metals were observed in the gulf, which is mainly influenced by human activities (i.e., shipping and mariculture activities) and seasonally hydrological conditions. Seasonal changes in the spatial distribution of heavy metals have been found in the gulf. The higher concentrations of heavy metals mainly occurred in the coastal bays or areas in summer whereas the higher concentrations were observed in the offshore areas during the other three seasons. This is mainly related to the seasonal changes of the water masses that affect the seawater of Beibu Gulf, which exhibits the dominant contribution of coastal current from the northern Beibu Gulf in summer, and the dominant contribution of west-Guangdong coastal current and SCS water during the other three seasons. The potential ecological risk index revealed that Hg is the main ecological risk factor in the gulf, and the heavy metal contamination in the gulf seems to be noticeable. This study highlights the seasonal changes of the water masses that affect the seawater of Beibu Gulf greatly affecting the large-scale distributions of heavy metals in the gulf.

KEYWORDS

heavy metals, seasonal and spatial variation, water mass, ecological risk assessment, Beibu Gulf

Introduction

Since the 1950s, public hazard caused by heavy metal pollution, such as the mercury-caused Minamata disease in Japan and the occurrence of the cadmium Itaiitai disease, has been of great concern due to their persistence, high toxicity, non-degradability, and vast sources (Wang et al., 2013). Particularly in the marine environment, with the rapid economic and social development, large quantities of anthropogenic sources of heavy metals are discharged into the coastal environment, and those metals can be bioaccumulated by the marine organisms and biomagnified through the food chain, and ultimately endanger human health (Rainbow and Luoma, 2011; Kumar et al., 2019; Lao et al., 2019a; Liu et al., 2020; Huang et al., 2021). Thus, a better understanding of the current status of heavy metal contamination in marine ecosystems has a significant implication for the sustainable development of marine ecosystems, the seafood industry, and public concerns (Wang et al., 2013; Zhu and Zheng, 2017a; Zhu and Zheng, 2017b; Zhu and Zheng, 2018; Liu et al., 2020; Lao et al., 2022a).

Many researches have been increasingly concerned about the heavy metals in the marine environment. For example, increasing anthropogenic inputs of heavy metals into the seawater of mariculture areas have been reported due to the continuous expansion of the mariculture scale for the past decades (Wang et al., 2019; Liu et al., 2020; Lao et al., 2022a; Mohsen et al., 2022). Moreover, the coastal currents play an important role on the distribution of materials, and greatly impact on the local marine environment (Dong et al., 2012; Li et al., 2018; Lv et al., 2021; Hu et al., 2022; Lao et al., 2022b; Lao et al., 2022c). Once the heavy metals input into the seawater, they can transport along with ocean currents to other areas, resulting in the wide spread of heavy metals in the marine environment (Li et al., 2018). Environmental change, such as ocean acidification and seasonal hypoxia, could change heavy metal status in the marine environment (Atkinson et al., 2007; Chakraborty et al., 2016; Ma et al., 2016; Lao et al., 2019a; Lao et al., 2022a). For example, the decrease of pH value in the marine environment leads to the re-release of heavy metals from sediments into the overlying water with linkage variation of metal concentrations in seawater and sediment environment, resulting in the decrease of heavy metals in sediments and the increase in seawater (Lao et al., 2022a).

Beibu Gulf, located in the northwestern South China Sea (SCS), is a newly developing industry and port in South China (Lao et al., 2021a). Additionally, the gulf is an important mariculture base and one of the most important fishing grounds in China because of its high productivity and rich biological diversity (Liu et al., 2020; Xu et al., 2020; Xu et al., 2021; Chen et al., 2022a). This is mainly because there is a stable external nutrient input to the Beibu Gulf from different water masses to maintain marine production (Lao et al., 2021b; Lao et al., 2022c). However, the ecosystems of the Beibu Gulf, particularly in the northern coastal bays, are now facing many environmental issues (Kaiser et al., 2016; Lao et al., 2019a; Lao et al., 2021a; Lao et al., 2021b; Zhang et al., 2021a; Cai et al., 2022; Chen et al., 2022a), such as the aggravating seawater acidification (Lao et al., 2022a) and eutrophication over the past years due to intensive human activities (Lao et al., 2021b; Cai et al., 2022). In addition, heavy metal contaminations have also been widely reported in coastal areas or bays around the northern Beibu Gulf. For example, the contamination of heavy metals and other pollutants in both seawater and sediment showed an increasing trend in the northern coastal bays over the past decades (Chen et al., 2018; Lao et al., 2019a; Liu et al., 2020; Zhu et al., 2021; Zhang et al., 2021b; Lao et al., 2022a; Zhang et al., 2022a), which also increased the proportions of bioavailable metals in the environment of the gulf (Kang et al., 2017; Chen et al., 2022a). Moreover, the heavy metals in the coastal wetland sediment cores of the northern Beibu Gulf also exhibited an increasing trend from 1985 to 2008 (Gan et al., 2013). The pH value in the seawater decreased by 4.7% over the past two decades, which greatly impacts the distribution of heavy metals in the seawater and sediment (Lao et al., 2022a). According to the assessment of potential ecological risk index (ERI) (Hakanson, 1980), Hg is the dominant risk factor in the coastal bays of northern Beibu Gulf due to intensive human activities, such as mariculture, agricultural, shipping and industrial activities (Lao et al., 2019; Liu et al., 2020; Lao et al., 2022a). In addition, there are several water masses, namely the coastal current, SCS water, and West-Guangdong coastal current that affecting the seawater in the Beibu Gulf (Figure 1) (Lao et al., 2022c). These water masses will

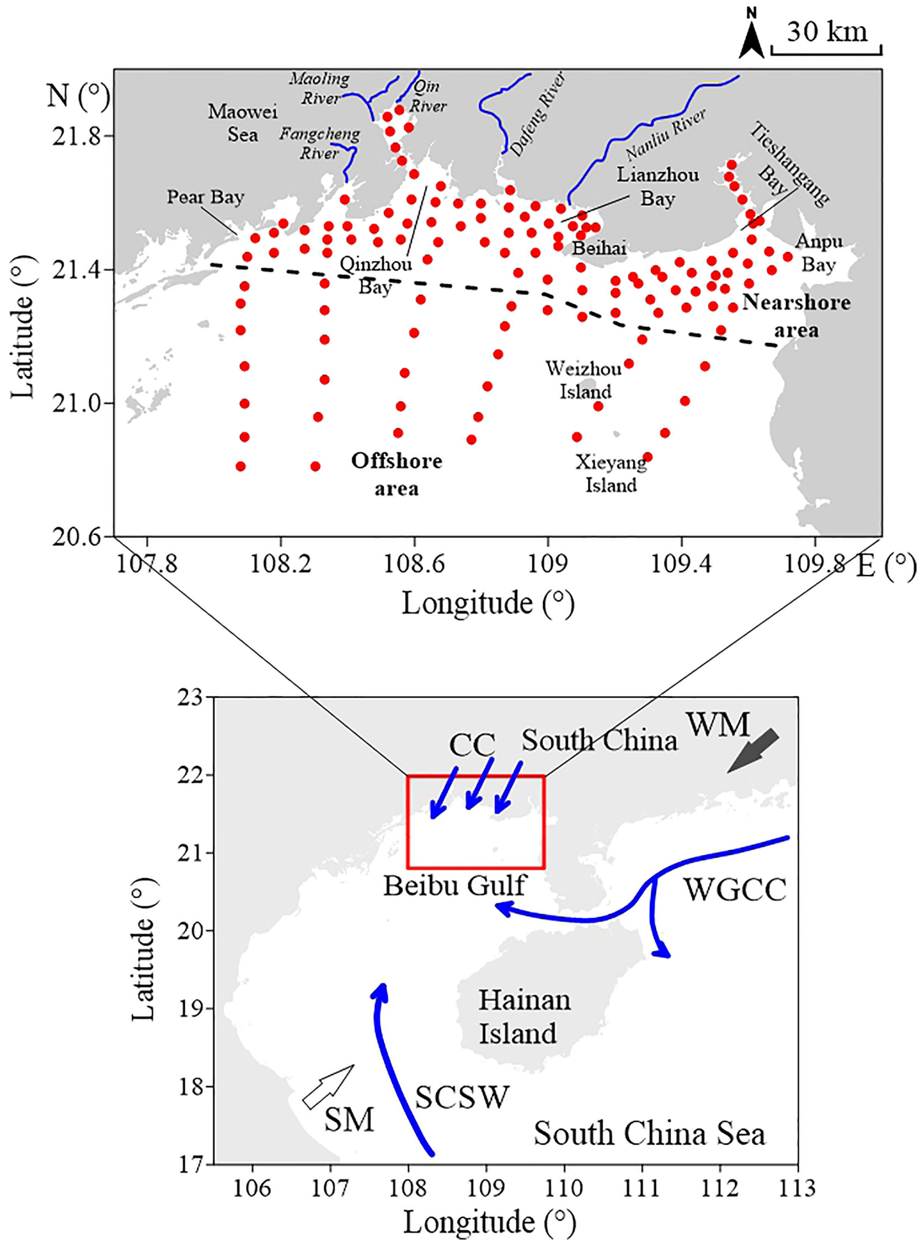

FIGURE 1
The study area and sampling sites (red blots) in Beibu Gulf. The dotted line is the dividing line between the nearshore and offshore area in the study area; the blue arrows in the below figure represent the water masses that affect the water in the gulf, which is modified from Lao et al. (2022c). WGCC, West-Guangdong coastal current; SCSW, South China Sea water; CC, coastal current from the Guangxi Province. The black and white arrows represent monsoons, SM, summer monsoon; WM, winter monsoon.

input rich materials into the Beibu Gulf (Chen et al., 2019; Lin et al., 2020; Lao et al., 2022c). Particularly the West-Guangdong coastal current, which originated from the diluted Pearl River and flows along the western coast of Guangdong Province with high contaminants into the Beibu Gulf through the Qiongzhou Strait (Chen et al., 2019; Lao et al., 2019b; Lin et al., 2020; Lao et al., 2022b; Lao et al., 2022c). However, the study on heavy metals in the Beibu Gulf is mainly on the nearshore or the coastal bays (Xia et al., 2011; Zhu and Zheng, 2013; Gu et al., 2015; Yang et al., 2015; Lao et al., 2019a; Liu et al., 2020; Yang et al., 2020; Lin et al., 2021; Lao et al., 2022a), and the characteristics of large-scale heavy metal contamination and distribution in the Beibu Gulf are still unclear. We speculate that the seasonal changes in water mass transportation in the

Beibu Gulf (Lao et al., 2022c) may have a great impact on the local heavy metal contaminations and distributions.

In this study, seasonal concentrations of seven heavy metals (Cu, Cd, Pb, Zn, As, Hg and Cr) and other physicochemical parameters in seawater in the large-scale Beibu Gulf were investigated to (1) analyze the seasonal distributions of heavy metals and their relationship with other related environmental parameters, (2) reveal the impact of seasonal intrusion of different water masses on the distribution of heavy metals and the possible behaviors and transition processes of those heavy metals in the gulf.

Materials and methods

Study area and sampling

The Beibu Gulf is a semi-enclosed bay with an average depth of 42 m and an area of about 130,000 km^2 located in the northwestern SCS. The gulf is surrounded by the coast of Guangxi Province in the north, Vietnam in the west, the Leizhou Peninsula in the east, and Hainan Island in the southeast (Figure 1). The west-Guangdong coastal current originates from the diluted Pearl River and flows along the coast of western Guangdong Province. After reaching the coastal area on the east side of Leizhou Peninsula, a tributary of the current enters into Beibu Gulf through Qiongzhou Strait. In addition, many rivers flow from the coast of Guangxi Province in the north into the northern coastal bays (e.g. Qinzhou Bay, Lianzhou Bay), with the higher runoff of the rivers in the rainy seasons (132.51 × 10^8 m^3) whereas lower runoff in the dry seasons (20.39 × 10^8 m^3) (Lao et al., 2020; Lao et al., 2022c). The runoff in the northern Beibu Gulf formed a coastal current that affects the seawater in the gulf, which become the dominant contributor to the seawater of the gulf in the rainy season (43% in summer and 45% in fall) due to the high runoff in the northern gulf during these periods (Lao et al., 2020; Lao et al., 2022c), while the dominant contributor to the seawater of the gulf changed to the intrusion of SCS water (57%) with high salinity through the coast of western Hainan Island during the dry season (winter) due to sharp drop of runoff (Lao et al., 2020; Lao et al., 2022c). However, the contribution of the west-Guangdong coastal current to the seawater of Beibu Gulf was relatively stable throughout the year (24-31%) (Lao et al., 2022c). Beibu Gulf is influenced by the East Asian monsoon, with the southwestern monsoons prevailing in summer and the northeastern monsoons prevailing in winter. The annual rainfall in the gulf is 1775 mm, with the dominant precipitation in the rainy season (April-October, 1579 mm) due to a large amount of rainfall brought by frequent typhoons and high rainfall frequency during this period (Chen et al., 2021; Luo et al., 2022). In this study, the study area is covering all northern Beibu Gulf, including the coastal bays in the north and the offshore area extending to the central gulf (Figure 1).

Four cruises were conducted during summer (July 2020), fall (September 2020), winter (January 2021), and spring (May 2021) in the Beibu Gulf. A total of 127 stations were set up in each season. Only surface water was collected when the depth is less than 10 m, and surface and bottom water were collected when the depth is greater than 10 m. A total of 217, 221, 215, and 208 seawater samples were collected using a rosette sampler fitted with 10 L Niskin bottles (Acid cleaned using 25% trace metal grade HNO_3) during spring, summer, fall, and winter, respectively. The profiles of salinity, temperature, and depth were determined using a calibrated Sea-Bird 911/19 plus CTD unit (USA). The seawater samples for total suspended particulate matter (TSM) were filtered by pre-weighed mix cellulose membranes (47 mm diameter and 0.45 μm pore size). The dissolved oxygen (DO) and pH were measured on-site using a calibrated multi-parameter water quality analyzer (Proplus, YSI, USA). The seawater samples for heavy metals were filtered using acid-cleaned cellulose acetate filters (47 mm diameter and 0.45 μm pore size, Entegris, China), and the filtrate was transferred into an acid-cleaned polyethylene bottle (250 mL), and then added HNO_3 (Trace metal grade, CNW, Germany) to the filtrate to achieve a pH<2. The filtrate of the heavy metal sample was stored at -20°C until analysis.

Sample analysis

The seawater samples for the analysis of Cu, Pb, Zn, Cd, and Cr concentrations were diluted 20-fold using 2% HNO_3 and then determined using an inductively coupled plasma mass spectrometer (ICPMS, ThermoFisher iCAP RQ, Bremen, Germany) by external calibration method. The samples for the analysis of As were pretreated with HCl (Trace metal grade, CNW, Germany) and thiourea-anticyclic acid (GR, Sinopharm, China) reducing agent for 30min. The samples for Hg were digested with sulfuric acid potassium persulfate (GR, Sinopharm, China) for 24 hours and then added with hydroxylamine hydrochloride (GR, Sinopharm, China) solution. The concentrations of As and Hg were determined using an atomic fluorescence spectrophotometer (AFS, Haiguang HGF-V2, Beijing, China) by an external calibration method. The method detection limits (Detailed in the supplementary materials) of Cr, Cu, Pb, Zn, Cd, Hg and As were 0.004 μg L^{-1}, 0.003 μg L^{-1}, 0.008 μg L^{-1}, 0.005 μg L^{-1} and 0.001 μg L^{-1}, 0.001 μg L^{-1}, 0.01 μg L^{-1}, respectively.

Quality control

Milli-Q water and trace metal-grade ultra-pure acids were used throughout the analysis. All labware was soaked with nitric acid (25%) for 7d and then cleaned with Milli-Q water before use. Procedure blanks were prepared by filtrating Milli-Q water and acidified to pH< 2 during the cruises. To ensure high precision and accuracy, blanks, duplicate samples, and certified reference materials (CRMs) were prepared with each batch of test samples (20 samples a batch). Seawater trace metal CRM GBW(E)080040 (For Cr, Cu, Pb, Zn, Cd, Second Institute of Oceanography, Ministry of Natural Resources, Hangzhou, China) was used for ICPMS analysis validation, CRM GBW(E) 080042 (For Hg, Second Institute of Oceanography, Ministry of Natural Resources, Hangzhou, China) and CASS-5 (For As, National Research Council Canada, Ottawa, Canada) was used for AFS analysis validation. The relative standard deviation (RSD) of the determination methods was< 6%, and the recoveries were ± 10%, further analytical figures of merit were detailed in the supplementary materials. The metal concentrations were all blank-corrected in this study.

Heavy metal pollution assessment

The ERI proposed by Hakanson (1980) was used to conduct the risk assessment of heavy metal pollution in seawater of the Beibu Gulf. This method not only takes into account the heavy metal pollution coefficient obtained by the single factor pollution index method, but also introduces the toxicological response coefficient of heavy metals. The calculation formula of the ERI is as follows:

$$\mathrm{ERI} = \sum_{i=1}^{N} E_r^i = \sum_{i=1}^{N} T_f^i \times \frac{C_i}{C_o} \quad (1)$$

where C_i and C_o denote the measured value of a heavy metal element in seawater (both surface and bottom water samples) and a standard value, T_f^i denotes toxic response factor (TRF), E_r^i denotes each metal potential ERI. In this study, C_o obtained from the National Standard of China for Seawater Quality GB 3097-1997, Grades I, and T_f^i of Hg, As, Cr, Cu, Pb, Zn, and Cd were 40, 10, 2, 5, 5, 1, and 30 (Liu et al., 2020; Lao et al., 2022a). To assess the potential ecological risk, the ERI could be classified into five grades (Table 1) (Liu et al., 2020; Lao et al., 2022a).

Statistical analysis

The data in this study were statistically analyzed by the IBM SPSS Statistics (Version 19.0). The spatial distributions of heavy metals were formed using Ocean Data View (Version 4.0). The analysis of Student's *t*-test of the difference between the parameters in the two groups were performed using the IBM SPSS Statistics (Version 19.0). The correlations analysis and principal component analysis (PCA) between metals and other environmental factors were also performed by the IBM SPSS Statistics (Version 19.0). Notably, One-way ANOVA was carried out to verify whether the data had homogeneous variances (F-test) before the application of Student's t-test.

Results

Physicochemical parameters in the Beibu Gulf

The physicochemical parameters in the seawater during the four seasons were illustrated in Figure 2. The temperature ranged from 12.70 to 33.70 °C. The salinity varied greatly in the gulf, and the values ranged from 2.20 to 34.21, with higher salinity in the dry seasons (winter (an average of 31.00) > fall (an average of 29.94), *t*-test, $p < 0.001$) and lower salinity in the rainy seasons (spring (an average of 27.56) > summer (an average of 26.94), *t*-test, $p < 0.01$) (Figure 2). The DO levels ranged from 3.40 to 10.30 mg L^{-1}, with a decreased level of winter > fall > spring > summer (*t*-test, all $p < 0.001$). The pH values ranged from 7.46 to 8.90. The concentrations of TSM varied greatly with seasons, and the concentrations ranged from 0.01 to 99.32 mg L^{-1}, with a decreased concentration of fall > summer > winter > spring (*t*-test, all $p < 0.001$).

Heavy metals in the seawater of Beibu Gulf

The concentrations of the seven heavy metals in the Beibu Gulf during the four seasons were presented in Table 2. The seasonal variations of heavy metals in Beibu Gulf were presented in Figure 3.

TABLE 1 The relationship between ecological risk index and pollution degree.

E_r^i	ERI	Pollution level
$E_r^i<40$	ERI<150	Low ecological risk
$40\le E_r^i<80$	150≤ERI<300	Moderate ecological risk
$80\le E_r^i<160$	300≤ERI<600	High ecological risk
$160\le E_r^i<320$		Very high ecological risk
$E_r^i\ge 320$	ERI≥600	Extremely high ecological risk

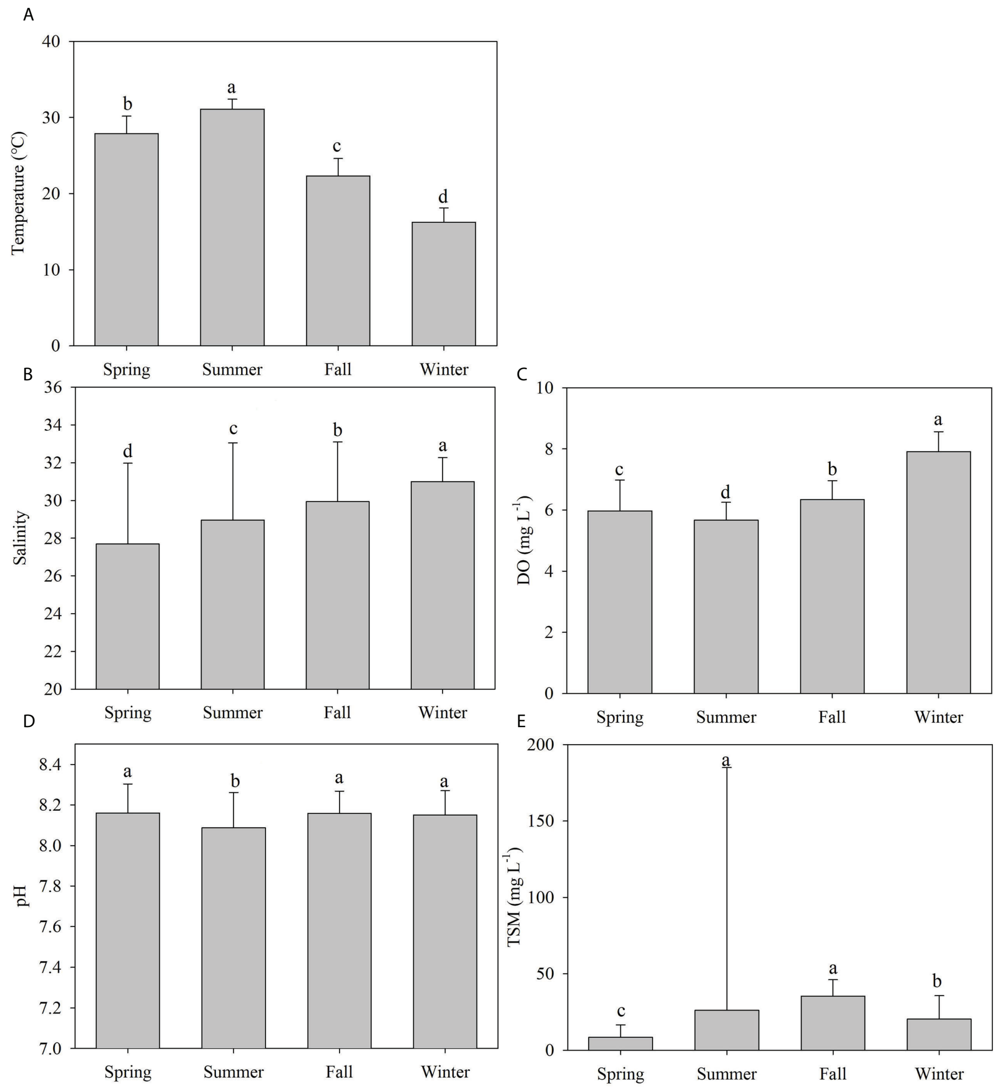

FIGURE 2
Seasonal variations of physicochemical parameters in the seawater of Beibu Gulf. The same letters in the bar chart denote significant differences; different letters in the bar chart denote significant differences. **(A)** Temperature; **(B)** Salinity; **(C)** DO; **(D)** pH; **(E)** TSM.

The concentrations of Cr, Cu, Cd, Pb, Zn, As, and Hg in the whole Beibu Gulf (both surface and bottom water) during the four seasons ranged from not detected (ND) to 6.81 $\mu g\ L^{-1}$, ND to 7.74 $\mu g\ L^{-1}$, ND to 0.26 $\mu g\ L^{-1}$, ND to 5.77 $\mu g\ L^{-1}$, ND to 74.87 $\mu g\ L^{-1}$, ND to 1.18 $\mu g\ L^{-1}$ and ND to 0.36 $\mu g\ L^{-1}$, respectively, which ranked following the order of Zn (12.12 $\mu g\ L^{-1}$) > Cu (1.06 $\mu g\ L^{-1}$) > Cr (0.65 $\mu g\ L^{-1}$) > As (0.62 $\mu g\ L^{-1}$) > Pb (0.23 $\mu g\ L^{-1}$) > Hg (0.08 $\mu g\ L^{-1}$) > Cd (0.03 $\mu g\ L^{-1}$). The seasonal variations of heavy metals are quite different in the gulf (Figure 3 and Table 2). Generally, the concentrations of Cr, Cd, Zn in winter and spring were significantly higher than that in summer (*t*-test, all $p< 0.001$) and fall (*t*-test, all $p< 0.001$). By contrast, concentrations of Cu, As and Hg in summer were significantly higher than that in the other three seasons (*t*-test, all $p< 0.05$). The concentrations of Pb in winter were significantly higher than in other seasons (*t*-test, all $p< 0.001$). The seasonal variation of different heavy metal concentrations indicates that their sources and factors affecting their distribution could be different. Spatially, the higher concentrations of Cu in summer were observed in the northern coastal bays (*t*-test, all $p< 0.01$) (Figure 4B), whereas the higher concentrations in other seasons were observed in the offshore areas (*t*-test, all $p< 0.01$). The higher concentrations of Pb were observed in the offshore areas during fall (*t*-test, $p< 0.001$) (Figure 4G) and winter (*t*-test, $p< 0.01$) (Figure 4F). However, the concentrations of Pb were lower in the gulf during spring and summer (*t*-test, all $p< 0.01$) except for a higher concentration in Weizhou Island during spring and in the

TABLE 2 Concentrations of heavy metals in seawater of the Beibu Gulf during different seasons (μg L^{-1}).

Heavy metal		Spring		Summer		Autumn		Winter	
		Range	Average	Range	Average	Range	Average	Range	Average
Cu	Surface	0.46-4.66	1.04 ± 0.51	0.32-4.82	1.54 ± 0.90	0.10-4.68	0.90 ± 0.61	0.06-5.88	1.00 ± 0.79
	Bottom	0.30-3.28	0.94 ± 0.48	0.30-5.79	1.11 ± 0.85	ND-7.53	0.93 ± 1.07	0.10-7.74	0.96 ± 1.00
	All	0.30-4.66	1.00 ± 0.50	0.30-5.79	1.36 ± 0.90	ND-7.53	0.91 ± 0.83	0.06-7.74	1.56 ± 6.00
Pb	Surface	ND-1.58	0.10 ± 0.19	ND-5.77	0.21 ± 0.63	ND-2.64	0.25 ± 0.35	0.04-3.32	0.51 ± 0.62
	Bottom	ND-0.34	0.08 ± 0.07	ND-0.56	0.11 ± 0.12	ND-2.01	0.24 ± 0.34	0.04-2.49	0.45 ± 0.47
	All	ND-1.58	0.09 ± 0.16	ND-5.77	0.17 ± 0.49	ND-2.64	0.40 ± 2.12	0.04-3.32	0.57 ± 0.96
Zn	Surface	0.50-32.62	15.63 ± 4.92	ND-44.24	5.84 ± 10.22	0.18-63.60	15.66 ± 9.26	2.64-74.87	16.38 ± 11.98
	Bottom	0.54-28.02	15.35 ± 5.48	ND-47.54	2.86 ± 7.90	0.02-42.44	8.08 ± 9.03	2.50-58.90	14.74 ± 9.84
	All	0.50-32.62	15.51 ± 5.16	ND-47.54	4.60 ± 9.44	0.02-63.60	12.56 ± 9.90	2.50-74.85	15.70 ± 11.16
Cd	Surface	0.02-0.08	0.03 ± 0.01	ND-0.10	0.03 ± 0.02	ND-0.06	0.03 ± 0.01	ND-0.26	0.03 ± 0.03
	Bottom	0.02-0.08	0.03 ± 0.01	ND-0.11	0.02 ± 0.01	ND-0.13	0.02 ± 0.02	ND-0.07	0.02 ± .0.01
	All	0.02-0.08	0.03 ± 0.01	ND-0.11	0.03 ± 0.02	ND-0.13	0.02 ± 0.01	ND ~0.26	0.03 ± 0.02
Cr	Surface	0.16-1.82	0.67 ± 0.27	0.15-2.00	0.55 ± 0.26	0.14-4.03	0.49 ± 0.56	0.11-4.86	0.88 ± 0.78
	Bottom	0.08-5.06	0.77 ± 0.63	0.21-1.09	0.51 ± 0.18	0.01-6.76	0.50 ± 0.80	ND-6.81	0.81 ± 1.00
	All	0.08-5.06	0.71 ± 0.46	0.15-2.00	0.53 ± 0.23	0.01-6.76	0.50 ± 0.67	ND-6.81	0.85 ± 0.88
As	Surface	0.33-1.18	0.67 ± 0.16	0.29-1.11	0.69 ± 0.15	0.21-1.03	0.64 ± 0.14	0.18-0.77	0.46 ± 0.15
	Bottom	0.33-0.99	0.71 ± 0.14	0.40-0.95	0.70 ± 0.12	0.28-0.87	0.64 ± 0.12	ND-0.76	0.49 ± 0.15
	All	0.33-1.18	0.68 ± 0.15	0.29-1.11	0.70 ± 0.14	0.21-1.03	0.64 ± 0.13	ND-0.77	0.48 ± 0.15
Hg	Surface	ND-0.31	0.07 ± 0.04	0.01-0.29	0.10 ± 0.05	ND-0.15	0.06 ± 0.02	ND-0.17	0.06 ± 0.02
	Bottom	ND-0.36	0.08 ± 0.05	0.01-0.33	0.12 ± 0.07	0.02-0.16	0.07 ± 0.02	0.03-0.09	0.06 ± 0.02
	All	ND-0.36	0.08 ± 0.05	0.01-0.33	0.11 ± 0.06	ND-0.16	0.07 ± 0.02	0.02-0.17	0.06 ± 0.02

nearshore of the central gulf during summer (Figures 4E, F). The higher concentrations of Zn were all observed in the offshore area during spring (*t*-test, $p < 0.01$), fall (*t*-test, $p < 0.01$) and winter (*t*-test, $p < 0.01$), while the higher concentrations were observed in the nearshore during summer (*t*-test, $p < 0.001$) (Figures 5A–D). The higher concentrations of Cd were generally observed in the nearshore areas during the four seasons (*t*-test, all $p < 0.05$) (Figures 5E–H). Significantly higher concentrations of Hg occurred in the offshore areas during summer (*t*-test, $p < 0.001$) (Figure 6B), whereas slightly higher concentrations occurred in the coastal bays during fall (*t*-test, $p < 0.01$) (Figure 6C). The higher concentrations of As during spring, summer, and fall were all observed in Tieshangang Bay and Lianzhou bay (Figure 6), whereas the higher concentrations were observed in the offshore areas during winter (*t*-test, $p < 0.001$) (Figure 6H). The concentrations of Cr were generally lower in the coastal bays during the four seasons, whereas higher concentrations occurred in the offshore areas, particularly in the fall (*t*-test, $p < 0.001$) and winter (*t*-test, $p < 0.001$) (Figure 7).

The relationship between heavy metals and other physicochemical parameters

The correlation analysis between the physicochemical parameters and heavy metals were presented in Table 3. The seven heavy metals are all related to physicochemical factors. The concentrations of Cu and Hg are positively correlated with temperature but negatively correlated with DO. In addition, the concentrations of Cu are also negatively correlated with salinity and pH. The concentrations of Cr are positively correlated with DO. The concentrations of Cd and As are negatively correlated with salinity, DO, and pH. The concentrations of Cu and As are positively correlated with TSM, but the concentrations of Hg are negatively correlated with TSM. The concentrations of Pb and Zn are positively correlated with DO but negatively correlated with temperature. In addition, the concentrations of Pb are also positively correlated with salinity.

Assessment of heavy metal contamination in the seawater

The calculated potential ERI E_r^i for each heavy metal and the ERI are presented in Table 6. During the whole year, the E_r^i values decreased in the order of Hg > Pb > Cu > Cd > Zn > As > Cr. The contribution of Hg for ERI is 94% to be the main ecological risk factor in the Beibu Gulf, and which is similar to the previous studies on the coast of the northern Beibu Gulf (Liu et al., 2020; Lao et al., 2022a). Seasonally, the highest ERI was found in summer, followed by spring, fall, and the lowest value was found in winter (Table 4). Similarly, Hg is the main ecological

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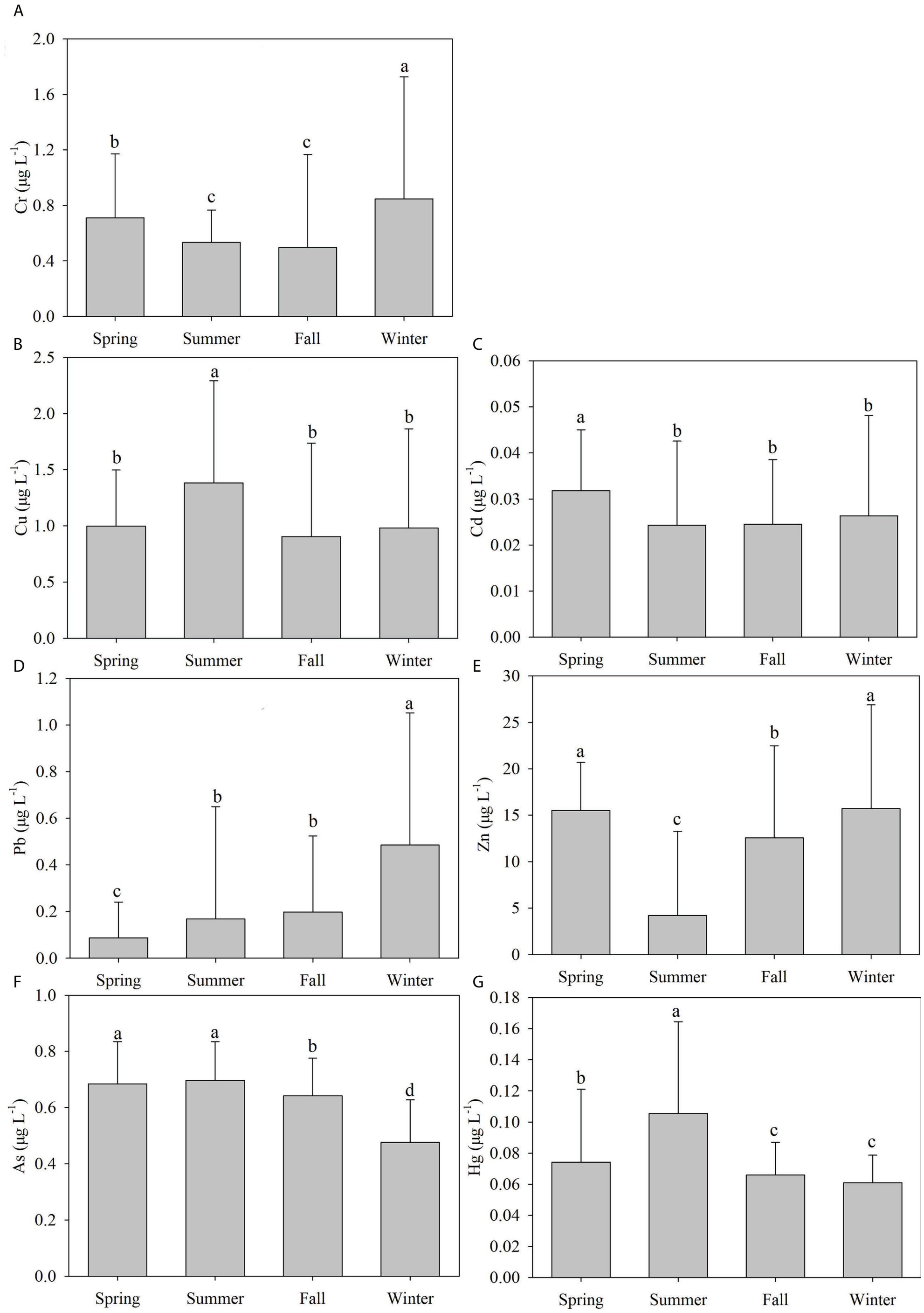

FIGURE 3
Seasonal variations of heavy metals in the seawater (including both surface and bottom) of Beibu Gulf. The same letters in the bar chart denote significant differences; different letters in the bar chart denote significant differences. **(A)** Cr; **(B)** Cu; **(C)** Cd; **(D)** Pb; **(E)** Zn; **(F)** As; **(G)** Hg.

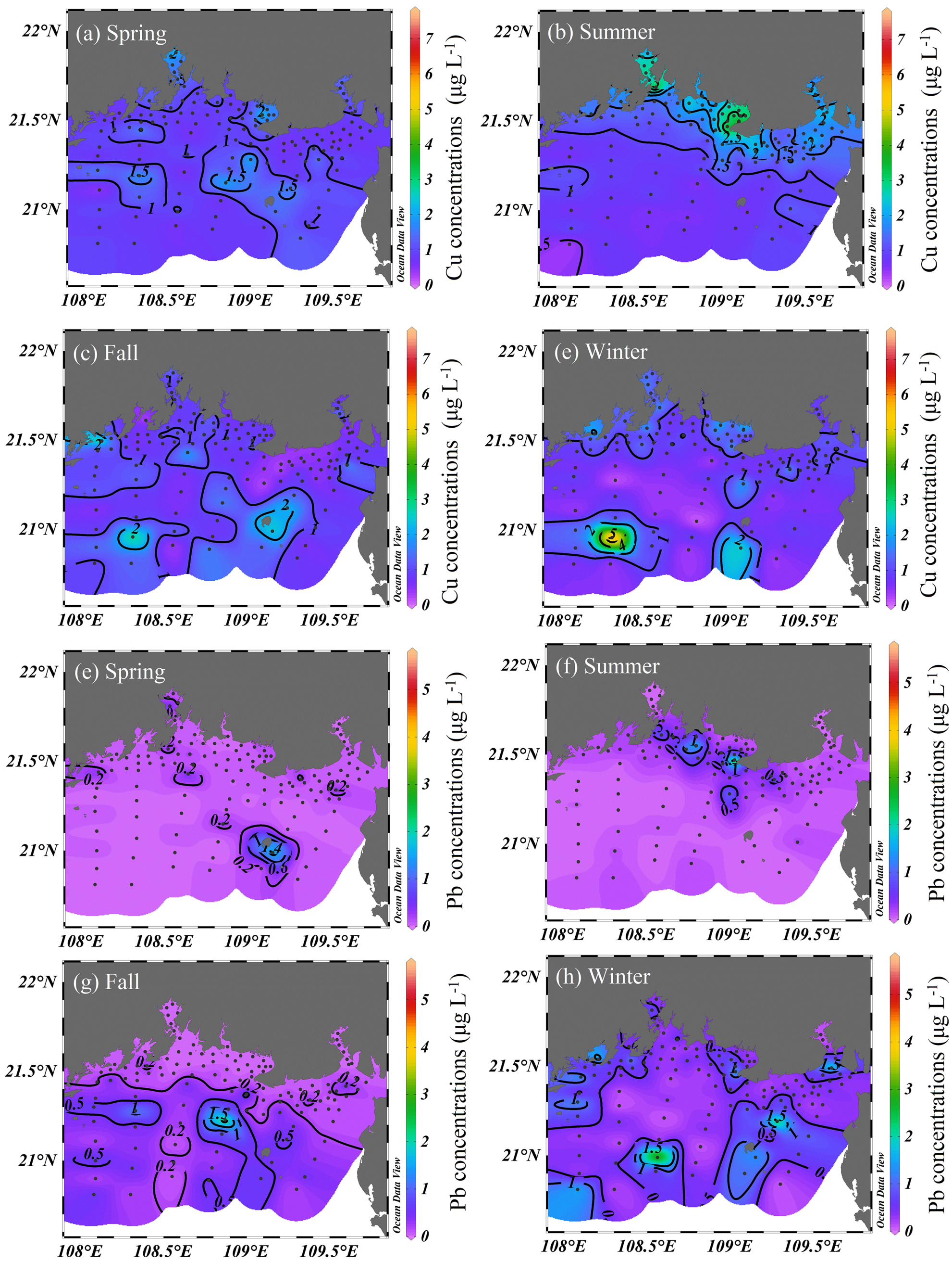

FIGURE 4
Spatial distributions of Cu and Pb in the surface seawater of Beibu Gulf during the sampling periods. **(A)** Cu-Spring; **(B)** Cu-Summer; **(C)** Cu-Fall; **(D)** Cu-Winter; **(E)** Pb-Spring; **(F)** Pb-Summer; **(G)** Pb-Fall; **(H)**-Pb-Winter.

risk factor during the four seasons. Moreover, the E_r^i values for Hg in the four seasons were all higher than 40, and the contribution for ERI in spring, summer, fall and winter were 95%, 96%, 93% and 88%, respectively. This suggests that the higher potential ecological risk from Hg occurs in the Beibu Gulf, and the heavy metal contamination of Hg in the gulf seems to be noticeable.

Discussion

Contaminated characteristics of heavy metals in seawater of Beibu Gulf

According to the National Standard of China for Seawater Quality (NSCSQ, GB 3097-1997), the concentrations of Cr, Cu,

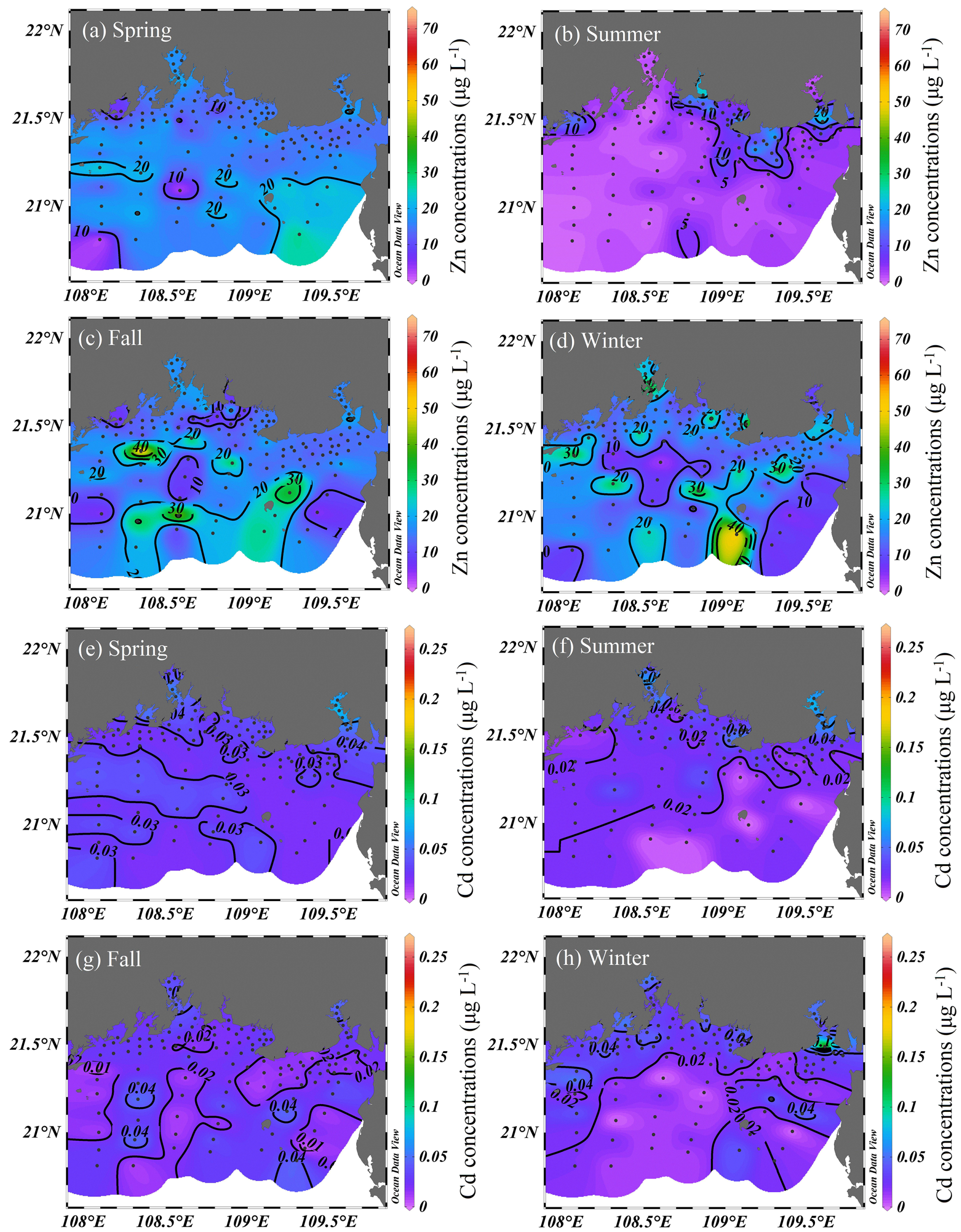

FIGURE 5
Spatial distributions of Zn and Cd in the surface seawater of Beibu Gulf during the sampling periods. **(A)** Zn-Spring; **(B)** Zn-Summer; **(C)** Zn-Fall; **(D)** Zn-Winter; **(E)** Cd-Spring; **(F)** Cd-Summer; **(G)** Cd-Fall; **(H)** Cd-Winter.

Cd, and As in the seawater of Beibu Gulf were all lower than the Grade I of NSCSQ (Table 4), suggesting that those heavy metals in the seawater of Beibu Gulf did not suffer from serious heavy metal contaminations. However, 0.5% of Pb and 18% of Zn concentrations exceed this standard, but the concentrations of those heavy metals were lower than the Grade II of NSCSQ. In addition, 84% of Hg concentrations were higher than the Grade I of NSCSQ, and there were still 4% of Hg concentrations higher than the Grade II of NSCSQ (Table 4). This indicates that Hg is the main contaminated metal in the seawater of Beibu Gulf.

Compared with other regions, the concentrations of heavy metals in the seawater of Beibu Gulf were either lower than or comparable with those of other similar regions, except for Hg

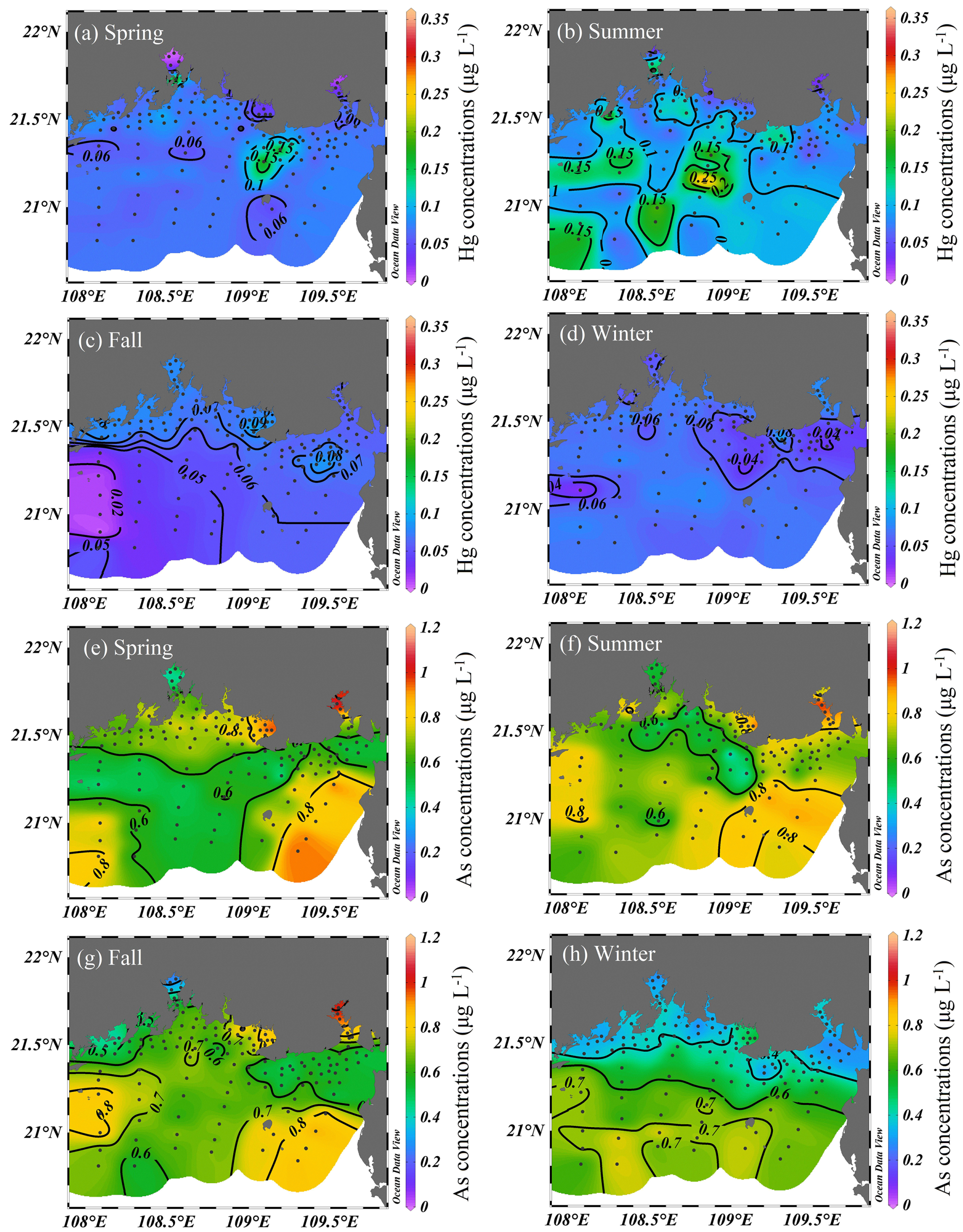

FIGURE 6
Spatial distributions of Hg and As in the surface seawater of Beibu Gulf during the sampling periods. **(A)** Hg-Spring; **(B)** Hg-Summer; **(C)** Hg-Fall; **(D)** Hg-Winter; **(E)** As-Spring; **(F)** As-Summer; **(G)** As-Fall; **(H)** As-Winter.

(Table 5). The concentrations of Hg were slightly lower than that in Liaodong Bay (Zhang et al., 2017), but higher than those other regions, such as 2.7 times higher than that in Jiaozhou Bay (Wang et al., 2012), 1.6 times higher than that in the Dingzi Bay and 1.3 times higher than that in the Xiangshan Bay (Zhao et al., 2018). This suggests that Hg is at a relatively high level in the seawater of Beibu Gulf. Similar to Liaodong Bay (Zhang et al., 2017), the rapid development of industry and intensive human activities could be responsible for the higher Hg contamination in the Beibu Gulf (Lao et al., 2019a; Liu et al., 2020). This is similar to the previous studies in the northern Beibu Gulf, which suggest that Hg is the main ecological risk factor in the gulf (Lao et al., 2019a; Liu et al., 2020; Lao et al., 2022a). The concentrations of Cu, Cd, and As in Beibu Gulf were generally lower than in other regions. The concentrations of Zn were lower than those in Liaodong Bay (Zhang et al., 2017), Dingzi

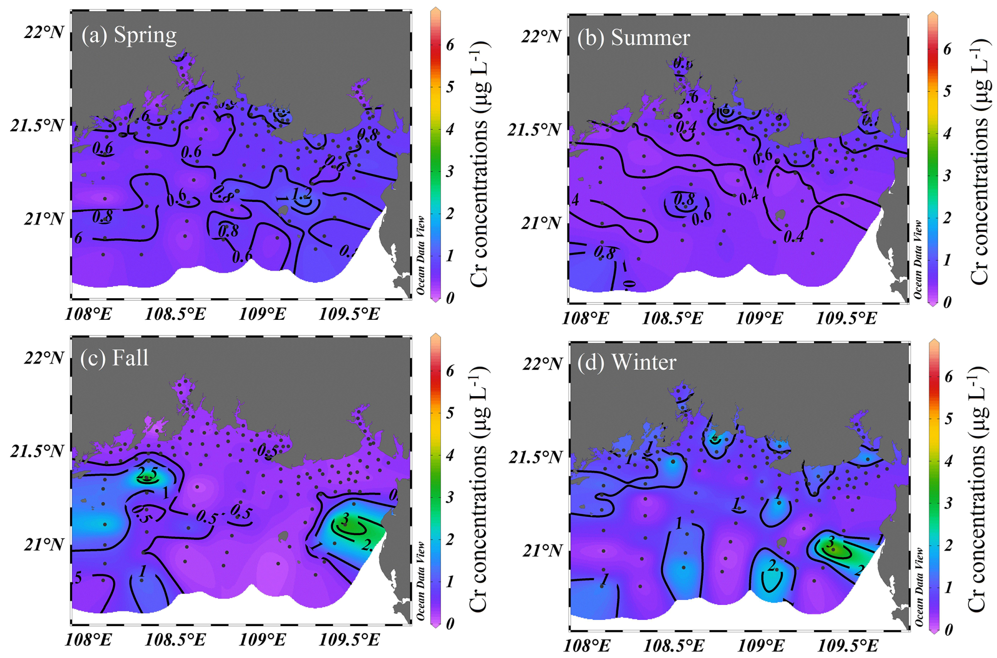

FIGURE 7
Spatial distributions of Cr in the surface seawater of Beibu Gulf during the sampling periods. **(A)** Cr-Spring; **(B)** Cr-Summer; **(C)**-Cr-Fall; (D) Cr-Winter.

Bay (Pan et al., 2014), Xiangshan Bay (Zhao et al., 2018), East Guangdong coastal area (Zhang et al., 2015) and Daya Bay (Qiu et al., 2005), but higher than those in Laoshan Bay (Wang et al., 2019) and Pearl River (Zhen et al., 2016). The concentrations of Cr were higher than that in Xiangshan Bay (Zhao et al., 2018), while the concentrations were lower than those in other regions. Although Zn, Cu and Cd in the seawater of coastal northern Beibu Gulf showed an increasing trend over the past two decades, the levels of those metals were still lower than in other relatively developed coastal bays (Lao et al., 2019a; Lao et al., 2022a). This may be related to the late beginning of the rapid development period of the coastal cities around the Beibu Gulf compared to the developed regions (Liu, 2020). The concentrations of Pb were comparable with Zhanjiang Bay (Zhang et al., 2018), but higher than the world average value (Gaillardet et al., 2005). Similar to the Zhanjiang Bay, Beibu Gulf is also a famous mariculture base in China, and the Pb concentrations showed an increasing trend over the past

TABLE 3 Correlation analysis between heavy metals and other physicochemical parameters in the Beibu Gulf.

	T	S	DO	pH	TSM	Cr	Cu	Cd	Pb	Zn	As	Hg
T	1	-0.25**	-0.34**	-0.13**	-0.01	-0.04	0.08**	-0.03	-0.12**	-0.14**	0.18**	0.20**
S		1	0.33**	0.56**	-0.06*	0.02	-0.22**	-0.29**	0.15**	0.00	-0.05	0.05
DO			1	0.40**	-0.14**	0.11**	-0.23**	-0.10**	0.25**	0.20**	-0.55**	-0.18**
pH				1	-0.08**	-0.02	-0.29**	-0.31**	0.04	0.03	-0.09**	0.03
TSM					1	0.03	0.09**	-0.05	0.03	-0.03	0.08**	-0.06*
Cr						1	0.24**	0.18**	0.24**	0.19**	-0.08**	-0.10**
Cu							1	0.32**	0.22**	0.19**	0.06*	-0.04
Cd								1	0.22**	0.19**	0.01	-0.11**
Pb									1	0.23**	-0.18**	-0.11**
Zn										1	-0.13**	-0.23**
As											1	0.11**
Hg												1

*Correlation is significant at the 0.01 level; **Correlation is significant at the 0.05 level.

TABLE 4 Potential ecological risk index of heavy metals in seawater of Beibu Gulf.

Time	E_r^i							ERI
	Cu	Pb	Zn	Cd	Cr	As	Hg	
Spring	1.00	0.45	0.78	0.9	0.03	0.34	64.00	67.5
Summer	1.36	0.85	0.23	0.9	0.02	0.35	88.00	91.71
Fall	0.91	2.00	0.63	0.6	0.02	0.32	56.00	60.48
Winter	1.56	2.85	0.79	0.9	0.03	0.24	48.00	54.37
annual	1.06	1.25	0.62	0.9	0.03	0.31	64.00	68.17

decades due to the rapid development of mariculture in the gulf (Liu et al., 2020; Lao et al., 2022a).

The biological and hydrodynamic influence on the distribution of heavy metals in the Beibu Gulf

The distribution and transport of heavy metals are greatly influenced by environmental factors and hydrological conditions (Chakraborty et al., 2016; Lao et al., 2019a; Wang et al., 2019; Lao et al., 2022a). The correlations and possible origins of heavy metals in the seawater of Beibu Gulf are further analyzed by PCA (Table 6). The values can explain 57.37% of the total heavy metals during the sampling period. In particular, PC1, PC2, PC3, and PC4 can explain 21.04%, 17.71%, 9.57%, and 9.50% of the total variance, respectively. High negative loadings for Cu, Cd, salinity, DO and pH were observed in the PC1, suggesting that those heavy metals are not only influenced by the terrestrial input but also influenced by biological activities. High positive loadings for Cr, Cu, Cd, Pb, and Zn in the PC2 indicated similar sources of those heavy metals. High positive loadings for salinity, Cr, Pb, and As were observed in the PC3, indicating that distributions of those heavy metals in the seawater of Beibu Gulf were mainly influenced by the transport of water masses with high salinity water from other areas. High negative loadings for TSM and Hg were observed in PC4, indicating the distribution of Hg was mainly influenced by the TSM in the seawater. Previous studies suggested that TSM is an important parameter that affects the distributions of dissolved heavy metals in the seawater (Feng et al., 2017; Zhang et al., 2018; Lao et al., 2019a; Lao et al., 2022a). However, the adsorption and desorption of heavy metals by particles in the seawater depend on the changes in the water environment, such as salinity, pH, and concentration of suspended particles (Lao et al., 2022a). For example, heavy metals would be more easily adsorbed onto the particles under higher salinity and TSM concentrations in the estuary areas (Feng et al., 2017), while the decrease of pH value would be more easily re-released from the particles to the seawater (Lao et al., 2022a).

Cu and Cd showed negative correlation with salinity, suggesting that those metals in the seawater of Beibu Gulf are mainly influenced by the terrestrial input. The higher concentrations of Cu and Cd were mainly observed in the

TABLE 5 Comparison of concentrations of heavy metals (µg L^{-1}) in seawater of Beibu Gulf with other regions.

Area	period	Hg	Cu	Pb	Cd	Zn	Cr	As	Reference
World average			1.68	0.079	0.08	0.6		0.62	Gaillardet et al., 2005
Jinzhou Bay, China	2009	0.03	3.06	0.61	0.92	11.87		2.19	Wang et al., 2012
Liaodong Bay, China	2009	0.14	2.86	3.98	0.66	17.76		5.46	Zhang et al., 2017
Laoshan Bay, China	2017-2018	0.015	1.50	0.81	0.12	1.81	1.23	1.16	Wang et al., 2019
Dingzi Bay, China	2010	0.05	2.02	1.07	0.36	23.83	4.10	1.33	Pan et al., 2014
Zhanjiang Bay, China	2014		4.40	0.23	0.12	12.64	2.70		Zhang et al., 2018
Xiangshan Bay, China	2011-2016	0.062	3.4	1.93	0.22	16.8	0.22	2.6	Zhao et al., 2018
Pearl River, China	2012	0.02	4.06	1.57	0.15	8.06		2.09	Zhen et al., 2016)
East Guangdong coastal, China	2007		2.24	1.94	0.11	14.05	1.20	2.48	(Zhang et al., 2015
West Guangdong coastal, China	2007		1.91	1.81	0.09	11.86	1.27	1.86	Zhang et al., 2015
Daya Bay, China	2005		3.2	2.4	0.041	42.2	2.34	2.25	Qiu et al., 2005
Beibu Gulf	2020-2021	0.08	1.06	0.23	0.03	12.12	0.65	0.62	This study
Grade I		0.05	5	1	1	20	50	20	
Grade II		0.2	10	5	5	50	100	30	

ND, not detected; Grades I-II, the National Standard of China for Seawater Quality GB 3097-1997.

TABLE 6 The results of PCA of heavy metals and other physicochemical parameters in the Beibu Gulf.

	Principal component			
	PC1	PC2	PC3	PC4
T	-0.489	-0.215	0.129	0.382
S	0.674	-0.242	**0.466**	0.000
DO	**0.816**	0.190	-0.216	0.094
pH	**0.688**	-0.309	0.330	0.045
TSM	-0.169	0.053	0.304	**-0.726**
Cr	0.083	**0.518**	**0.394**	0.127
Cu	**-0.394**	**0.569**	0.301	0.086
Cd	**-0.301**	**0.627**	-0.099	0.171
Pb	0.275	**0.571**	**0.329**	0.154
Zn	0.207	**0.570**	0.033	-0.046
As	**-0.508**	-0.283	**0.464**	-0.192
Hg	-0.184	-0.414	0.294	**0.535**
Eigenvalue	2.524	2.125	1.148	1.086
% of variance	21.037	17.712	9.569	9.502
Cumulative variance	21.037	38.749	48.318	57.370

The bold values indicate strong loadings.

coastal bays, particularly in the summer (Figures 4, 5). Previous studies have also reported that high concentrations of Cu and Cd occurred in the coastal bays and the estuary areas with low salinity in the Beibu Gulf (Lao et al., 2019a; Lao et al., 2022a). Heavy metals of Cu and Cd mainly serve as anthropogenic sources (i.e., antifouling paints, smelting and refining) (Wang et al., 2019). In the summer, fishing boats were prohibited from carrying out fishery-related activities in the SCS (about four months from 1st May). During the fishing moratorium, most of these fishing boats docked at the coastal wharf, and the fishermen began to repair and maintain the fishing boats during this period. The use of antifouling paints containing heavy metals could aggravate the contamination of those metals in the water. Moreover, the enhancement of the coastal current due to heavy rainfall during summer, the seawater of the Beibu Gulf is mainly input from the coastal current (43%) (Lao et al., 2022c), which could transport those metals from the coastal bays and the estuary areas to the offshore areas. Thus, the concentrations of Cu and Cd generally showed a decreased trend from the coastal bays to the offshore areas during summer (Figures 5F, 4B).

Similar to Cu and Cd, Cr and Zn are also mainly used in antifouling paints (Wang et al., 2019). In addition, Pb is widely used as the anti-corrosive compound for shipping and the antiknock agent in diesel fuel (Wang et al., 2018; Lao et al., 2022a). Thus, the shipping and mariculture activities mainly contributed to PC2. In addition, the distributions of Cr, Zn and Pb were similar to the Cu and Cd in summer (Figures 4B, F, 5B, F , 7B), which could also be influenced by the coastal current during this season. However, the Cu, Cd, Pb, Zn and Cr were found higher concentrations in the offshore areas during the other three seasons, suggesting that different sources and/or influent factors occurred during those periods. During the spring, fall and winter, with the decrease of the runoff in the northern gulf, the increasing intrusion of the other water masses could carry higher metals from other regions into the gulf (Lao et al., 2022c), resulting in the higher concentrations of those metals were all observed in the offshore areas. In the PC3, high positive loadings for salinity, Cr, Pb and As suggested that those metals may transport with water masses from other areas with higher salinity water. In Beibu Gulf, the higher salinity water in the west-Guangdong coastal current and SCS water are also the two dominant water masses that affect the seawater in the Beibu Gulf, and those water masses could transport a large number of materials to the gulf (Lao et al., 2022c). The proportion of SCS water to the seawater of Beibu Gulf is relatively lower in summer (30%) and fall (31%), while it changes to the dominant seawater in the gulf during winter (57%) (Lao et al., 2022c). By contrast, the contribution of the west-Guangdong coastal current is relatively stable during the whole year (24-31%) (Lao et al., 2022c). Thus, the higher concentrations of heavy metals in the offshore areas during winter may be influenced by the intrusion of SCS water and the west-Guangdong coastal current. Previous studies have reported that higher heavy metal contaminations were observed around the southern coast of Hainan Island, which likely originated from pollution discharge by intensive human activities, such as industrial discharges from port and shipping facilities, agriculture wastes, domestic sewage and frequently fishing activities (Yang et al., 2004; Li and Huang, 2012; Wang et al., 2013; Yang et al., 2019). In addition, with the rapid development of urbanization and industrialization, higher heavy metal contaminations have also been found in the Pearl

River Estuary and the coastal waters of western Guangdong Province (Li et al., 2007; Zhang et al., 2010; Zhang et al., 2015; Zhang et al., 2018; Zhang et al., 2022b; Zhou et al., 2022). The higher heavy metal contamination in those regions would enter into the Beibu Gulf with the water masses, resulting in higher concentrations of heavy metals occurring in the offshore areas of the Beibu Gulf. However, in the spring and fall, the contribution of SCS water to the heavy metals loading in the Beibu Gulf should be less due to its lower contribution to the seawater of the gulf during those seasons (Lao et al., 2022c). Thus, the higher concentrations of heavy metals in the offshore area of Beibu Gulf may mainly originate from the input of the west-Guangdong coastal current during the spring and fall.

In addition, Hg in the coastal bays of the northern Beibu Gulf mainly originated from the terrestrial input (Lao et al., 2022a). The highest concentrations of Hg were observed in summer, when the coastal current was strong due to the heavy rainfall during this period, which could erode a large number of land-based pollutants into the gulf (Lao et al., 2020; Lao et al., 2021b; Chen et al., 2022b), resulting in the high concentrations of Hg appearing in the whole water of the gulf (Figure 6B). However, although the coastal current was weaker in fall than that in summer, the current in the fall is still stronger than in other seasons (Lao et al., 2022c), resulting in the higher concentrations of Hg appearing in the coastal areas in the northern Beibu Gulf (Figure 6C). By contrast, with the weakening of the coastal current in winter and spring, the contribution of the west-Guangdong coastal current and the SCS water to the Beibu Gulf increases, and the concentrations of Hg in the offshore area are higher than that in the coastal areas (Figures 6A, D). The high contaminations of Hg were also reported on the coast of western Guangdong Province and Hainan Island (Hu et al., 2013; Li et al., 2013; Wang et al., 2013; Liu et al., 2014; Zhao et al., 2020), and the metal would input into the Beibu Gulf with the transportation of the water mass. This suggests that the transportation of water masses in Beibu Gulf is greatly influenced on the distribution of Hg in the gulf.

Generally, the seasonal changes of the water masses that affect the seawater of Beibu Gulf greatly affect the distributions of heavy metals in the gulf.

Conclusion

Spatial and seasonal variations in the concentrations of the seven heavy metals were found in the seawater of Beibu Gulf. Seasonally variations in the concentrations of heavy metals were observed in the gulf, which are mainly influenced by human activities (i.e., shipping and mariculture activities) and seasonally hydrological conditions. The higher concentrations of heavy metals generally occurred in the coastal bays or areas during the summer, whereas the higher concentrations were observed in the offshore areas during the other three seasons. This is mainly related to the seasonal changes of the water masses that affect the seawater of Beibu Gulf, such as the dominant contribution of coastal current from the northern gulf in summer, and the dominant contribution of west-Guangdong coastal current from the east and SCS water from the south during the other three seasons. This study reveals that the seasonal changes of the water masses in the Beibu Gulf greatly affect the large-scale distributions of heavy metals in the Beibu Gulf, which is different from previous studies that the coastal heavy metals in the gulf are mainly affected by the northern terrigenous input, providing new insight in the impact of water masses on the distribution of metals in the gulf.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

ZZ: conceptualization, sampling, sample analysis, and writing. HW: sampling, sample analysis, and draft preparation. YG: data management and editing. LZ, PS, and QZ: conceptualization. All authors contributed to the article and approved the submitted version.

Funding

This work was supported by the National Natural Science Foundation of China (U20A20103), Guangxi Funding Project (304024XM20N0006, 2019GXNSFBA185036, 2018AD19321) and Beihai Science & Technology Project (201995037, 202082031, 202082022).

Acknowledgments

We thank all the crews on the R/V Yueke 1, R/V Yuexiayuzhi 20028 and R/V Haike 68 for the assistance with the sampling during the cruises in 2020 and 2021, and the anonymous reviewers for the revision of the manuscript.

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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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.996202/full#supplementary-material

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frontiers | Frontiers in Marine Science

TYPE Original Research
PUBLISHED 12 October 2022
DOI 10.3389/fmars.2022.981569

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OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Marine Conservation and Sustainability, a section of the journal Frontiers in Marine Science

RECEIVED 29 June 2022
ACCEPTED 27 September 2022
PUBLISHED 12 October 2022

CITATION
Gu Y, Lyu S, Wang L, Chen Z and Wang X (2022) Assessing the carbon sink capacity of coastal mariculture shellfish resources in China from 1981–2020.
Front. Mar. Sci. 9:981569.
doi: 10.3389/fmars.2022.981569

Assessing the carbon sink capacity of coastal mariculture shellfish resources in China from 1981–2020

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The ocean has considerable potential to function as a carbon sink, absorbing anthropogenic CO_2 and buffering the effects of climate change. How the culture of shellfish can be used to increase the ocean carbon sink warrants evaluation. We analyze the production and carbon sink capacity of six important mariculture shellfish species (oyster, ark clam, mussel, scallop, clam, and razor clam) in nine coastal provinces of China from 1981–2020 using quality assessment and logarithmic mean Divisia index (LMDI) decomposition methods. Over this time period both cultured shellfish production and its contribution to the carbon sink generally increase, averaging approximately 600,000 t annually over the last four decades. Both the annual production and carbon sink capacity of China's mariculture shellfish industry vary geographically. The total annual tonnage (scale) of cultured shellfish, and to a lesser extent, coastal shellfish species composition (structure) influence carbon sink capacity, and affect China's plans to achieve "dual carbon goals." Combining historical analysis and the LMDI method, we propose a scheme that optimally and more sustainably manages China's culture of shellfish.

KEYWORDS

mariculture shellfish, China, ocean carbon sink, logarithmic mean divisia index, mariculture management

1 Introduction

Climate change can adversely affect species ecology, ecosystems, economic development, and human lifestyles. This change is widely attributed to increased CO_2, which contributes up to 70% to the cause of global temperature rises (Jackson et al., 2017). Because greenhouse gas emissions are of global concern, governments now pay more regard to both reducing them, and to developing low-carbon economies and forms of carbon sink storage (Liu and Tang, 2013; Zhang et al., 2020; Cavan and Hill, 2022). Continued industrialization and urbanization in China has led to the unit-energy consumption of energy-intensive products being higher than that of other developed countries (Jiang and Fang, 2021). China imported 540 × 10^6 t of crude oil and 102 × 10^6 t of natural gas in 2020, which have considerable potential to contribute to further CO_2 emissions (General Administration of Customs, January 2021).

In 2021 the Chinese government issued a document referred to as the "Opinions on making good carbon peaking and carbon-neutral work" (hereinafter referred to as "dual carbon goals") that identified the capacity of ecosystems to sequester carbon (Huang et al., 2020; Huang, 2021). This requires an evaluation of the ecological carbon sink and other carbon assets to drive the carbon market toward neutrality. Many issues that require detailed study remain in the development of the national carbon emissions trading market (Lin and Ge, 2019; Yu et al., 2020a).

Compared with the "classical carbon sink" (CO_2 absorption through afforestation and vegetation restoration) (Lin and Ge, 2019), the "ecological carbon sink" is more broadly defined to include ecological carbon sequestration in oceans, grasslands, wetlands, soils, permafrost, and karst habitats. As we know, terrestrial ecosystems play a significant role in carbon absorption and storage. However, the effect of forests and vegetation in terrestrial ecosystems on the carbon cycle is short-term, since the carbon will later be released into the atmosphere by decomposition (Fodrie et al., 2017; Chu et al., 2019). Additionally, the rapid expansion of human society places increasing demands on land, reducing the amount available for future large-scale afforestation for the purposes of increasing the carbon sink. Because the ocean covers 77% of the Earth's surface and is the world's largest carbon storage area, it has enormous ecological significance and potential as a carbon sink (Meentemeyer et al., 2015; Kondrik et al., 2018). Oceans absorb about 2 × 10^9 t of atmospheric greenhouse gases annually, almost 30% of annual global greenhouse gas emissions (Houghton, 2007; Raven, 2018).

Filter-feeding shellfish cultured in marine environments, hereinafter referred to as "mariculture shellfish," are promising "marine filterers" because they require no artificial feeding and are sustained by natural resources. These shellfish have a high carbon sequestration capacity (Tang et al., 2018) because their feeding activities remove considerable particulate organic carbon from seawater; they sequester this carbon as $CaCO_3$ in their shells and soft tissues (Zhang et al., 2021). Considerable carbon is also removed from saltwater during harvest (Tang et al., 2018). Understanding just how mariculture of these shellfish sequesters carbon will improve understanding of how shallow marine ecosystems can absorb atmospheric CO_2, how they regulate the global carbon cycle, and how this can be exploited to promote development of the carbon trading market based on marine fisheries. The ecological and economic benefits of mariculture shellfish and algal species in carbon sink fisheries in Liaoning Province were described by Yu et al. (2020b); the carbon-sink capacity of mariculture shellfish in coastal South China Sea waters was described by Shao et al. (2019); and logarithmic mean Divisia index (LMDI) decomposition methods confirmed the importance of scale in the carbon sink capacity of mariculture shellfish in China (Ren, 2021).

The chemical composition and scale (total annual tonnage) of net organic matter at harvest of bivalves and algae and the ratio of dry weight to total wet weight (dry weight ratio) of these shellfish and algae have traditionally been used to estimate their carbon sink capacity (Zhou et al., 2002). Existing studies have also focused on measuring the carbon sequestration capacity of cultured species, factors that influence this, and development countermeasures. However, long-term, large-scale research on the carbon-sink contribution of mariculture shellfish in coastal waters of China is lacking. Accordingly, our understanding of the ecological contribution of mariculture shellfish to carbon sequestration, and how the shellfish culture industry can be developed to further contribute to carbon sequestration, is limited. We analyze the carbon sink capacity of six major mariculture shellfish species in nine coastal provinces in China over a 40-year period, and based on this provide a theoretical basis for optimizing shellfish mariculture management to better integrate their ecological function as a carbon sink with associated economic and social benefits.

2 Materials and methods

2.1 Data sources

Production data for major mariculture shellfish species (oyster, ark clam, mussel, scallop, clam and razor clam) for nine coastal provinces of China (Liaoning, Hebei, Shandong, Jiangsu, Zhejiang, Fujian, Guangdong, Guangxi, Hainan) over 40 years from 1981–2020 were sourced from Chinese Fishery Statistical Yearbooks [Fishery Bureau of Ministry of Agriculture and Rural Affairs of China (1982–2021)].

2.2 Data processing

2.2.1 Carbon sink measurement

Because carbon in mariculture shellfish exists in both shells and soft tissues, their carbon sink is represented by the sum of individual carbon contents, determined following Tang et al. (2011):

$$C_B = C_{ST} + C_S \quad (1)$$

$$C_{ST} = P \times R_{ST} \times W_C \quad (2)$$

$$C_S = P \times R_S \times W_{CS} \quad (3)$$

where C_B, C_{ST}, and C_S denote carbon fixed by shellfish (g), carbon fixed by tissue (g), and carbon fixed by shellfish (g), respectively; P, R_{ST}, and W_C denote shellfish scale (g), the proportion of dry mass of molluscan tissue (%), and carbon content of molluscan tissue (%), respectively; and R_S and W_{CS} indicate the proportion of shellfish dry mass (%), and the carbon content of shellfish (%), respectively.

Dry mass ratios of soft tissues, shells, and carbon contents for different species of shellfish are summarized in Table 1 (Zhou et al., 2002; Qi et al., 2012; Lv et al., 2014; Ye et al., 2021a).

2.2.2 Influencing factor analysis method

Based on the LMDI decomposition method of Ang (2015), we deem the following to be representative factors influencing the carbon sink capacity of shellfish: carbon sink coefficient (*CSC*), shellfish structure factor (*SSF*) (i.e.), and shellfish scale factor (*SQ*) (i.e.),. Relationships among them are as follows (Ji and Wang, 2016; Zhang et al., 2017):

$$CS = \sum_{i=1} n \frac{CS_i}{SQ_i} \times \frac{SQ_i}{SQ} \times SQ \quad (4)$$

Where n represents the each mariculture shellfish species (n = 6), CS is the total carbon sink, CS_i is the carbon sink of shellfish species i, SQ_i is the production of shellfish species i, and SQ is total shellfish production.

$$CS = \sum_{i=1} nCSC_i \times SSF_i \times SQ \quad (5)$$

Using a one-year time spacing, the base period for calculating the results in year t was year $t{-}1$, and base data were brought into the *LMDI* index decomposition method formula. The change in the carbon sink in period t relative to the base period can be expressed as:

$$\begin{aligned} \Delta CS &= CS^t - CS^0 \\ &= \sum_{i=1}^{n} CSC_i^t \times SSF_i^t \times SQ^t - \sum_{i=1}^{n} CSC_i^0 \times SSF_i^0 \times SQ^0 \\ &= \Delta CS_{CSC} + \Delta CS_{SSF} + \Delta CS_{SQ} \end{aligned} \quad (6)$$

$$R = \frac{cs^t}{cs^0} = R_{CSC} \times R_{SSF} \times R_{SQ} \quad (7)$$

Basic equations for the contribution values of different decomposition factors are:

$$\Delta CS_{CSC} = \sum W \times \ln \frac{CSC^t}{CSC^0}$$

$$\Delta CS_{SSF} = \sum W \times \ln \frac{SSF^t}{SSF^0}$$

$$\Delta CS_{SQ} = \sum W \times \ln \frac{SQ^t}{SQ^0}$$

Where $W = \frac{CS^t - CS^0}{\ln(CS^t/CS^0)}$. The contribution rates (R) of different decomposition factors are:

$$R_{CSC} = exp(\theta \times \Delta CS_{CSC})$$

$$R_{SSF} = exp(\theta \times \Delta CS_{SSF})$$

$$R_{SQ} = exp\left(\theta \times \Delta CS_{SQ}\right)$$

Let $\theta = \frac{\ln CS^t - \ln CS^0}{CS^t - CS^0}$

We assume that no interannual variation in the carbon sink coefficient of mariculture shellfish exists, the contribution value of carbon sink coefficient variation is 0, and the contribution rate is 1. Based on these assumptions, we

TABLE 1 Tissues and shell dry mass ratios and carbon contents of six mariculture shellfish species in China.

Species	R_{ST}/%	R_S/%	W_C/%	W_{CS}/%	References
Oyster	1.30	63.80	44.90	11.50	(Ren, 2021)
Mussel	4.63	70.64	46.00	12.70	(Ren, 2021)
Scallop	7.32	56.58	43.90	11.40	(Ren, 2021)
Clam	7.67	44.65	42.80	11.40	(Ren, 2021)
Razor clam	6.62	64.78	44.99	13.24	(Ye et al., 2021a; Zhang et al., 2021)
Ark clam	3.66	34.33	45.86	11.29	(Tang et al., 2018)

R_{ST}, proportion of dry mass of shellfish tissue (%); W_C, shellfish tissue carbon content (%); R_S, proportion of dry mass of shell (%); W_{CS}, shell carbon content (%).

evaluate the influences of species composition and tonnage on the carbon sink of mariculture shellfish.

3 Results

3.1 Interannual variation in mariculture shellfish production and carbon sink

Production of mariculture shellfish in China, and the carbon sink represented by these species has risen consistently over time (Figure 1). From 1981–2006, production increased from 9.8 × 10^4 t to 9.8 × 10^6 t. The first dip in production over the 40-year period occurred in 2007, after which production again trended upward to 1.35 × 10^7 t in 2020. The carbon sink increased from 1× 10^4 t to 1.17 × 10^6 t from 1981–2020.

3.2 Spatial and temporal patterns in mariculture shellfish carbon sink tonnage

The carbon sink in nine coastal provinces trended upward from 1981–2020 (Table 2), and was higher in Shandong, Fujian, and Liaoning provinces (Figure 2). From 2001, the carbon sink in Guangdong Province exceeded that of Zhejiang Province; sink values in other provinces were relatively similar.

From 1981–2000, sink values in Shandong (1.25 × 10^6 t), Fujian (8.4 × 10^5 t), and Liaoning (7 × 10^5 t) provinces were high. These were followed by Zhejiang (3.4 × 10^5 t), Guangdong (2.5 × 10^5 t), Guangxi (2 × 10^5 t), Jiangsu (7 × 10^4 t), Hebei (4 × 10^4 t), and Hainan (0.5 × 10^4 t) provinces. From 2001 to 2020, Shandong, Fujian, and Liaoning provinces had high carbon sinks (5.96 × 10^6 t (up 4.71 × 10^6 t), 4.07 × 10^6 t (up 2.32 × 10^6 t), and 2.9 × 10^6 t (up 2.2 × 10^6 t), respectively), followed by

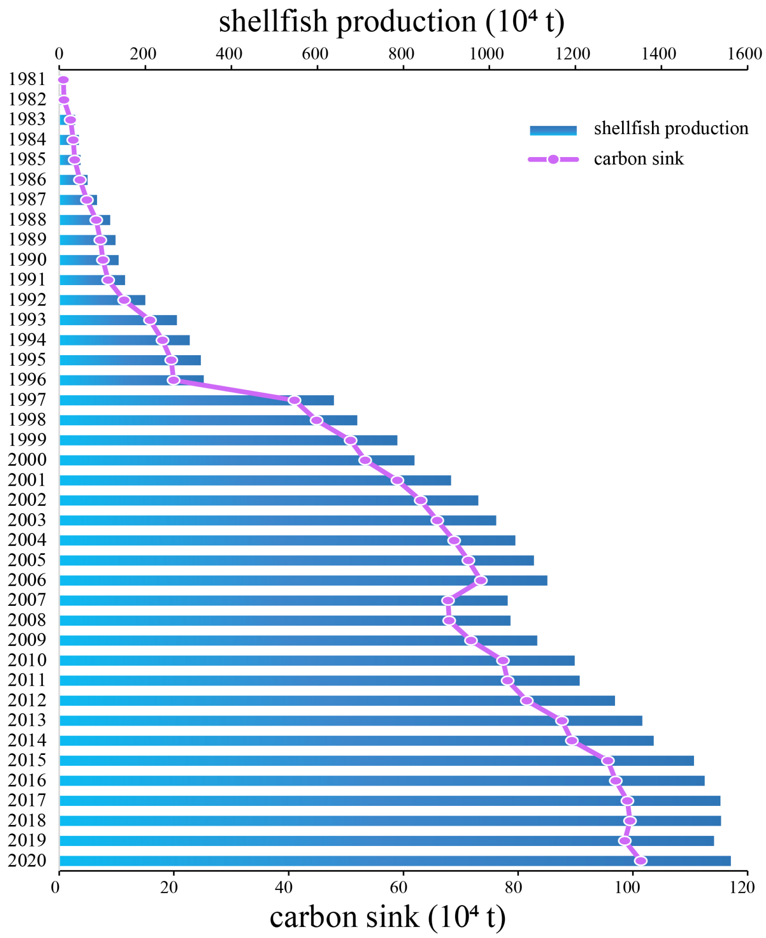

FIGURE 1
Annual mariculture shellfish production and carbon sink tonnage (x 10^4) in China, 1981–2020.

TABLE 2 Mariculture shellfish carbon sink capacities in nine coastal provinces, China, 1981–2000 and 2001–2020.

Zone	Year	Oyster(t)	Ark-clam(t)	Mussel(t)	Scallop(t)	Clam(t)	Razor-clam(t)
Liaoning	1981-2000	66745	865	384418	120336	124494	2742
	2001-2020	314603	51844	150400	646512	1517072	65109
	Overall	381347	52710	534818	766847	1641566	67851
Shandong	1981-2000	160091	6012	250467	524416	270490	40506
	2001-2020	1095275	12100	783879	1452812	2014822	330736
	Overall	1255366	18112	1034346	1977228	2285312	371242
Heibei	1981-2000	238	3089	2248	14877	19271	46
	2001-2020	5565	12905	5408	465143	82440	613
	Overall	5803	15994	7656	480020	101712	659
Jiangsu	1981-2000	1656	2046	0	0	58740	7593
	2001-2020	67752	22852	66549	73	541880	149345
	Overall	69407	24898	66549	73	600620	156939
Zhejiang	1981-2000	31893	36467	16962	605	14291	238587
	2001-2020	239193	144362	212127	1661	122025	620986
	Overall	271086	180829	229089	2265	136316	859572
Fujian	1981-2000	486321	4482	67455	6600	104536	170529
	2001-2020	2610521	51333	182467	17214	532086	506753
	Overall	3096842	55815	249922	23814	636623	677283
Hainan	1981-2000	1676	313	32	95	2460	0
	2001-2020	5643	2179	163	1522	14502	0
	Overall	7319	2493	195	1617	16961	0
Guangdong	1981-2000	602360	22301	122994	36176	238843	18848
	2001-2020	1210682	33533	102295	102317	427009	19264
	Overall	1813042	55834	225290	138494	665852	38113
Guangxi	1981-2000	119892	2487	2212	867	74902	18
	2001-2020	654659	4378	19137	8974	324485	4489
	Overall	774551	6865	21349	9841	399387	4508

Guangdong (2.52×10^6 t (up 2.27×10^6 t)), Zhejiang (1.4×10^6 t (up 1.06×10^6 t)), and Guangxi (1.24×10^6 t (up 1.04×10^6 t)) provinces. Jiangsu (8.9×10^5 t, up 8.2×10^5 t), Hebei (6×10^5 t, up 5.6×10^5 t), and Hainan (2.5×10^4 t, up 2×10^4 t) provinces had low carbon sinks, with the total carbon sink in Hebei and Jiangsu provinces rising significantly (14% and 12%, respectively). Zhejiang Province has the lowest growth rate of 3.12%.

The distributions of oyster, ark clam, mussel, scallop, clam, and razor clam have varied considerably over time, particularly from 2001, and for each were generally higher than the preceding 20 years (Table 2). In northern China (Liaoning, Shandong, Hebei), scallops and clams were significantly higher than those in the other four species. However, oysters and clams were generally higher than those of the other four species in southern China (Zhejiang, Fujian, Hainan, Guangdong, Guangxi).

3.3 Factors affecting mariculture shellfish carbon sink tonnage

Contributions of individual shellfish species to carbon sink tonnage in China from 1985–2020 are presented in Table 3. Ranked by scale factor, the value for 1997 (2.0568) was the highest among years, differing by 0.6559 from the second highest value (1.4009) in 1993, third in 1988 (1.3442), fourth in 1987 (1.3344), and fifth in 1986 (1.3298); for remaining years the contributions were more consistent, from ~1.1 (2007) to < 1.0 (2019). The top two species (and mean values) ranked by structure factor from 1985–1993 were scallops (1.5153) and clams (1.1445); from 1994–2002, oysters (1.3078) and Arcidae (1.0411); from 2003–2011, clams (1.1162) and scallops (1.0055); from 2012–2020, oysters (1.0122) and scallops (1.0052); and from 2012–2020, again, oysters (1.0122) and scallops (1.0052).

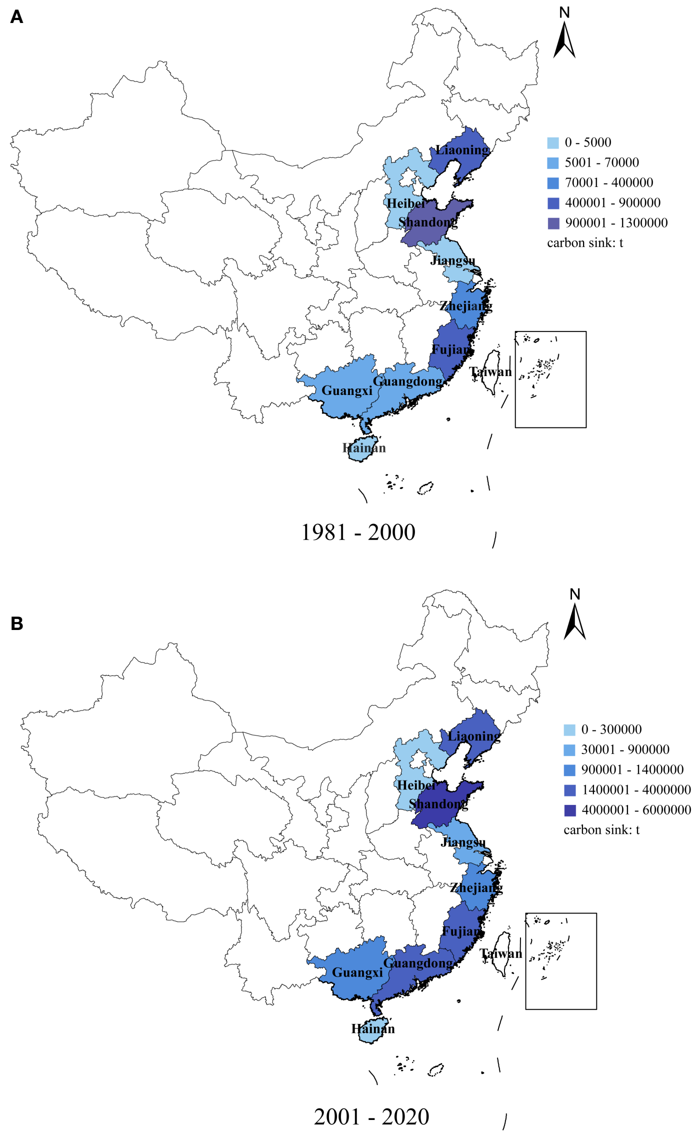

FIGURE 2
Total carbon sequestration tonnage of mariculture shellfish in nine coastal provinces, China: **(A)** 1981–2000, **(B)** 2001–2020.

Scale generally dominated the influence of the mariculture carbon sink in China, with species composition (structure) playing a lesser role. From 1985–2020, the overall contribution of scale factor to China's mariculture carbon sink has exceeded that of structure and been greater than 1.0, with highest values of ~1.4. Overall levels were relatively stable, but fluctuated in 2007 and 2019. The structure factor also fluctuated, with significant differences between the lowest and highest values, but the contribution to the carbon sink has remained positive, mostly ~1.0. Oysters, clams, and scallops had a greater structure factor, while differences between remaining shellfish products were lower.

4 Discussion

4.1 Coastal shellfish culture

China is the largest global producer of mariculture shellfish (Yu et al., 2020a) in an industry gaining importance for providing high-protein food, increasing coastal resident employment, and promoting regional economic development (Engle et al., 2022). We report China's mariculture shellfish production to trend upward from 9.8×10^4 t in 1981 to 1.35×10^7 t in 2020. Until 2018, China's contribution to global shellfish production was 75.9%, and consumption 75.7%, with oysters,

TABLE 3 Contribution rates of factors influencing the carbon sink tonnage of individual mariculture shellfish species in China, 1985–2020.

	structure factor(*SSF*)						scale factor(*SQ*)
year	**oyster**	**ark clam**	**mussel**	**scallop**	**clam**	**razor clam**	
1985	1.1313	1.0129	0.8537	1.9726	1.3242	1.0341	1.1051
1986	0.8130	1.0894	1.2293	2.1429	0.9937	0.7547	1.3298
1987	0.8931	1.0350	1.1123	1.3807	0.9617	0.7935	1.3344
1988	0.8394	0.7573	1.0223	2.0795	0.8784	0.7833	1.3442
1989	0.8910	1.0153	1.0300	0.9575	1.2466	0.8881	1.1083
1990	1.0614	1.0169	0.9515	1.0687	1.1855	0.9538	1.0625
1991	0.9505	0.9108	0.8995	1.1481	1.2571	1.0543	1.1169
1992	1.0589	0.7102	0.8141	1.3496	1.3216	0.9046	1.3288
1993	0.9774	1.0001	0.6750	1.5381	1.1315	0.8009	1.4009
1994	1.6400	1.1408	0.7180	0.9988	1.0676	1.0000	1.1349
1995	1.0957	1.1802	0.9204	1.0218	0.8895	1.1166	1.0864
1996	0.9818	1.0380	0.8606	1.0686	0.9442	1.0857	1.0205
1997	3.0286	0.6444	0.5309	0.4872	1.2639	0.5067	2.0568
1998	1.1127	1.1123	1.2423	0.5747	1.0214	1.0718	1.0934
1999	0.9313	1.0557	0.9926	0.9992	1.1298	1.0195	1.1327
2000	1.0488	1.0068	0.8369	1.2292	0.8563	1.0983	1.0503
2001	0.9594	1.0549	0.9619	0.9448	1.1275	0.9777	1.1053
2002	0.9724	0.9576	1.0937	0.9122	1.0694	0.9960	1.0681
2003	1.0035	1.3273	1.0208	0.9520	1.0975	1.0495	1.0461
2004	0.9435	0.9383	0.9688	0.9355	1.0144	0.9282	1.0446
2005	0.9845	0.9069	1.0388	1.0981	0.9852	1.0185	1.0362
2006	0.9869	1.0093	0.9375	1.0761	1.0251	0.9229	1.0306
2007	0.9778	0.9594	0.6522	1.1001	1.0624	1.0814	0.9221
2008	0.9461	1.0412	1.0779	0.9688	2.3740	1.1089	1.0027
2009	0.9878	0.8935	1.2873	1.0698	0.4494	0.8603	1.0562
2010	0.9663	1.0384	1.0209	1.0216	1.0270	0.9708	1.0779
2011	1.0208	0.9351	0.9973	0.9186	1.0107	1.0320	1.0102
2012	1.0077	0.9139	1.0343	1.0403	0.9918	0.9312	1.0428
2013	0.9939	1.1200	0.9133	1.1742	0.9614	0.9338	1.0753
2014	1.0118	1.0289	1.0576	0.8946	1.0096	1.0707	1.0196
2015	0.9817	0.9631	0.9800	1.0112	0.9442	0.9423	1.0704
2016	1.0421	0.9936	1.0251	1.0273	1.0260	1.0222	1.0144
2017	0.9886	0.9406	1.0340	1.0569	0.9806	1.0266	1.0209
2018	1.0486	1.0511	0.9695	0.9511	0.9724	0.9844	1.0045
2019	1.0258	1.0507	0.9725	0.9618	0.9810	1.0283	0.9911
2020	1.0095	0.9660	0.9906	0.9289	1.0338	0.9624	1.0283

clams, and scallops being the most important species affecting China's carbon sink capacity between 1981 and 2020 (Food and Agriculture Organization (FAO), 2020). Oysters (*Ostrea gigas*), clam (*Ruditapes philippinarum*), and scallops accounted for 29.5%, 23.6%, and 11% of projected global mollusk production, respectively (Food and Agriculture Organization (FAO), 2020). The huge potential of shellfish farming in coastal waters of China will directly influence the biological carbon capability, future studies should focus on selecting dominant shellfish species, developing integrated multi-trophic level aquaculture models, and expanding aquaculture areas (Ye et al., 2021b).

China has 3×10^6 km^2 of sea area under its jurisdiction, which in cludes more than 4.7×10^6 km^2 of marginal sea area, and nearly 217.04×10^6 hectares of coastal mudflats potentially available for shellfish farming (Zhang et al., 2017). However, mariculture in China mainly occurs in bays and near-shore areas. However, most areas suitable for near-shore mariculture have been exploited. High coastal aquaculture density, limited space, and reduced shellfish product quality and unit production, all constrain further development of coastal mariculture (Teng et al., 2021). Planning for coastal and coastal marine areas is a relatively new responsibility of China's government policymakers.

Management approaches to develop sustainable coastal shellfish farming combined with other coastal activities in Dutch coastal North Sea waters were examined by Jansen et al. (2016). The growing demand for proteins derived from aquatic sources suggests that bivalve shellfish mariculture will become increasingly important. It is imperative that development of environmentally and economically sustainable coastal aquaculture is based on science (Cheney et al., 2010).

4.2 Climate change and shellfish carbon sink potential

China is committed to achieving "peak carbon and carbon neutrality" to address global climate change. Global warming affects many aspects of nature and humanity, and many of these changes may be irreversible. Rising temperatures and sea levels, and frequent extreme weather events pose significant long-term threats and challenges to global food supply, ecology, energy, and human survival and development (Eastwood, 2021). For the Chinese government to achieve carbon neutrality within 40 years, it must explore low-carbon strategies and ecological carbon sink technologies. In fact, global development of ecological carbon sink technology is of the utmost importance in the 21st century.

In addition to forest and grassland ecosystems, the importance of carbon sequestration by marine organisms as an ecological carbon sink is becoming increasingly recognized (McKay et al., 2021). Remote islands and seamounts of the United Kingdom's Tristan da Cunha archipelago Marine Protected Zone support substantial biogenic carbon stocks, the conservation of which (and other such carbon-rich natural habitats) can significantly mitigate against climate change (Barnes et al., 2021). Macrophytic algae also sequester more carbon than seagrasses, salt marshes, and mangroves, and play an essential role in marine organic carbon storage (Raven, 2018). Previous studies on the roles of shellfish mariculture in carbon sequestration have mainly used shellfish wet and dry weight ratios in calculations, and their roles as sinks or sources of CO_2 is controversial. Bartolini et al. (2021) developed a bioenergetic model of the carbon sequestration potential of mariculture shellfish to calculate CO_2 fluxes, taking into consideration respiration (CO_2 emissions) and shell ($CaCO_3$) calcification, and demonstrated seasonal variability in the shellfish carbon sink and carbon source conversion. This study mainly considers the role of shellfish as a carbon sink and reports the development of carbon sink fisheries, especially shellfish farming, to have far-reaching implications for improving watershed environments, mitigating against global greenhouse effects, and for the economy and social functioning (Mcleod et al., 2011). Bivalve shellfish farming benefits society beyond its traditional market value (Houghton, 2007). We report the average annual removable carbon sink of mariculture shellfish in China to exceed 1×10^6 t, and for 2020, to have reached 1.17×10^6 t. As of September 2021, the cumulative volume of carbon emission allowances traded on the Chinese carbon market was ~17.65×10^6 t, with a cumulative transaction value of ~US\$$126 \times 10^6$ (Yi et al., 2018). Based on estimated expenditure of US\$150–600 t^{-1} for CO_2(C) reduction in industrialized countries according to the 1997 Kyoto Protocol (Filgueira et al., 2015), the economic value of mariculture shellfish in China for reducing atmospheric CO_2 from 1981–2020 is equivalent to US\$$80–330 \times 10^6$ annually.

4.3 Developing shellfish aquaculture in China

Justification for expanding shellfish aquaculture in China should take the ecological benefits of this industry as a carbon sink, and the environmental role it plays in controlling algae into consideration. Development plans should incorporate regional characteristics of natural marine areas, also take shellfish biological characteristics and habitat suitability into consideration, and be guided by market demand to more effectively promote realization of energy conservation, emission reduction, and the dual carbon goals in China. Shellfish farming technology and ecological enrichment, shellfish and nearshore mudflat farming waters combined with the construction of shellfish reef symbiotic ecological pasture will usher in new research opportunities.

In recent years, conservation of coastal resources has involved the closure of many areas to farming, and pollution from aquaculture to have been otherwise regulated. However, from an economic perspective, and for carbon sequestration, the downside of these conservation efforts is that the amount of coast suitable for shellfish aquaculture has reduced. Currently, coastal beach farming licenses are issued by the Bureau of Agriculture and Rural Affairs (in charge of fisheries and aquaculture). Additionally, the use of coastal resources for aquaculture requires the approval of the Bureau of Natural Resources, in the form of a 'sea area use permit,' which requires an environmental impact assessment be undertaken for the aquaculture project. Approval of the environmental impact assessment is the responsibility of the Bureau of Ecology and Environment. A revised organizational and administrative model would streamline this process. Accordingly, we propose that a working body be established to coordinate the integrated management of coastal aquaculture waters, and a conceptual framework (Figure 3) to rationalize the shellfish industry's structural layout under the dual carbon goal. Because the Ministry of Agriculture prohibits the use of raking

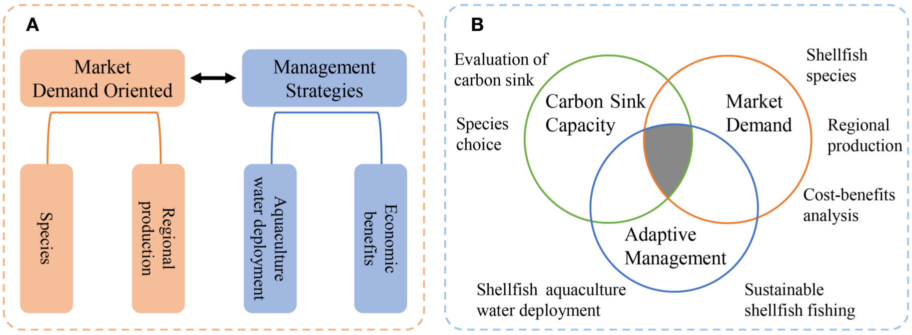

FIGURE 3
Shellfish aquaculture development models: **(A)** Traditional; **(B)** Ecology-oriented.

gear for shellfish collection, development of ecologically friendly fishing technologies is also necessary for efficient harvest and habitat protection.

5 Conclusion

This study analyzed the spatial and temporal distribution characteristics and main influencing factors of the carbon sink capacity of mariculture shellfish in China. We found that the average annual removable carbon sink of mariculture shellfish in China exceeded 1×10^6 t, and it climbed to 1.17×10^6 t in 2020 with an upward overall trend. Among them, Oysters, clams, and scallops were the main source of removable carbon sinks in China's mariculture. Furthermore, the shellfish in China's mariculture is very extensive and has been widely cultivated in coastal regions of China. With the deepening of technology in China's mariculture, the scale and production of shellfish will be updated, which will contribute substantially to China's fishery carbon sink. However, evaluation for the carbon sink of mariculture shellfish has not yet a unified standard and needs to be further studied.

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

YG: methodology and initial draft preparation. SL and ZC: revision and data collection; LW: conceptualization and data analysis. XW: experiment design, reviewing and editing, supervision, and funding acquisition. All authors contributed to the article and approved the submitted version.

Funding

This study was supported by the fund of Sino-Indonesian technical cooperation in coastal marine ranching (125001012 00021002) and the National Key Research and Development Program of China (2020YFD0901103).

Acknowledgments

We thank Dr. Liqiang Zhao for his valuable comments and Mr. Bingnan Li for assisting with figure drawing. We thank Steve O'Shea, PhD, from Liwen Bianji (Edanz) (www.liwenbianji.cn/), for his editing of the English text of a draft of this manuscript.

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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frontiers | Frontiers in Marine Science

TYPE Original Research
PUBLISHED 07 February 2023
DOI 10.3389/fmars.2023.1130547

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OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Marine Conservation and Sustainability, a section of the journal Frontiers in Marine Science

RECEIVED 23 December 2022
ACCEPTED 23 January 2023
PUBLISHED 07 February 2023

CITATION
Lyu S, Lauden HN, Wang L, Chen G, Wang Z, Lin K and Wang X (2023) Acoustic telemetry system as a novel approach for evaluating the effective attraction of fish to artificial reefs.
Front. Mar. Sci. 10:1130547.
doi: 10.3389/fmars.2023.1130547

Acoustic telemetry system as a novel approach for evaluating the effective attraction of fish to artificial reefs

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Due to there being a lack of suitable approaches for evaluating the effectiveness of artificial reefs, two experiments were designed to examine the feasibility of acoustic telemetry, a rapidly developing method for tracking aquatic animals. The first experiment was conducted to understand the deployment procedures of an acoustic telemetry system and determine the appropriate deployment of receivers' spacing, while the second experiment was conducted to quantify the site fidelity and habitat use of 11 reef fish in the Fangchenggang artificial reef area in the northern South China Sea, China. The results indicated that the logistic regression model was an effective way to balance the detection probability at different distances between the range test transmitter and receiver, with above 50% detection probability within 240 m and 80% detection probability within 110 m. The residency index, as a quantification of site fidelity, was 0.85 ± 0.24. The 100% minimum convex polygon, 95% kernel utilization distribution, and 50% kernel utilization distribution, which are the indicators of habitat use, were 34,522.94 ± 35,548.95, 1,467.52 ± 1,619.05, and 236.01 ± 294.59 m^2, respectively. High site fidelity and the small spatial scale of habitat use for reef fish demonstrated that artificial reefs were an effective man-made structure to attract fish. Overall, this study supports the feasibility of the acoustic telemetry system, indicating that it provides a good approach for quantifying the associations between artificial reefs and fish.

KEYWORDS

acoustic telemetry, artificial reefs, fish attraction, site fidelity, habitat use

1 Introduction

Global marine biodiversity and fishery resources have continuously decreased under the constant pressure of overfishing, water pollution, and climate change in recent years (Jackson et al., 2001; Worm et al., 2006; O'Hara et al., 2021). According to statistics from the Food and Agriculture Organization (FAO), the proportion of fish stocks within biologically sustainable levels decreased from 90% in 1974 to 64.6% in 2019 (Food and Agriculture Organization (FAO), 2020; FAO, 2022). Some active strategic management measures have been implemented worldwide to create more sustainable fisheries, including input-oriented control measures (such as fishing permits, closed fishing areas, and seasonal fishing restrictions) (FAO, 2003; Morison, 2004; Tang, 2011), output-oriented control measures (such as total allowable catches and fishing quotas) (Pope, 2009; Lyu et al., 2022), and technological control measures (such as marine conservation areas, marine life stocks enhancement, and artificial reefs construction) (FAO, 2011; Shen and Heino, 2014; Zhang et al., 2021). Among these measures, artificial reefs (ARs), man-made submarine structures, have the main purpose of increasing the diversity and biomass of fishery resources by providing additional favorable habitats for the organisms living in coastal waters (Sreekanth et al., 2017). Historically, Japan is the first country to research the ecological applications of ARs (OKA, 1962). Over the years, ARs have been widely deployed in coastal waters all over the world and have been studied in 56 countries (Lima et al., 2019). In China, the government invested a total of 5 billion RMB (approximately 0.75 billion USD) in marine ranching and AR construction from 2000 to 2016. As a result, more than 200 marine ranches in an area of 852.6 km^2 had been built, where they had placed ARs of 60 million m^3 in volume (Zhou et al., 2019). With the continuous investment in AR construction, there are increasing concerns about whether ARs can achieve the desired goals of enhancing stocks.

Evaluating the effectiveness of ARs is a challenge due to the complexity of topography in ARs. To our knowledge, methods for the effective evaluation of ARs can be divided into two categories: laboratory simulation and field monitoring. Laboratory simulation evaluates the effectiveness of ARs by observing the behavioral responses of reef fishes to the scaled-down AR models in experimental troughs (Zhou et al., 2011; Zhang et al., 2022). However, there are limitations of this *ex situ* approach in reflecting the actual situation of natural waters. In contrast, field monitoring includes traditional fishing gear, diving visual census, underwater video, and hydroacoustic detection (Lam, 2003; Liu et al., 2015; Yuan et al., 2021). However, these methods also have limitations. For instance, fishing gear (such as bottom trawl nets, gill nets, hooks and lines, and cage traps) have selectivity constraints for fishery targets. Bottom trawling, in particular, can only be used on the edge of an AR area and can easily cause habitat damage (Sun et al., 2020). Diving visual census and underwater video are limited due to factors such as light intensity, water depth, and turbidity (Zeng et al., 2021). Meanwhile, hydroacoustic detection may not detect benthic animals when they are in the acoustic blind zone, and it is difficult to separate the signal of animals from that of ARs (Ona and Mitson, 1996). Thus, other techniques need to be developed while implementing the approaches described above to fully understand the effectiveness of ARs.

Acoustic telemetry, also called ultrasonic telemetry, has become a popular *in situ* approach to studying the movement and habitat use of aquatic animals (Cooke et al., 2004; Hedger et al., 2009; Alós et al., 2012). The acoustic telemetry system is mainly composed of receivers and transmitters (Lyu et al., 2021). To obtain accurate information, the scientific deployment of the acoustic telemetry system (i.e., the receiver placement and transmitter attachment) is essential. Animals need to be individually tagged with transmitters that emit unique signals with position and environmental data (such as water temperature and depth), which are detected by the receivers placed underwater (i.e., the receiver array) (Brownscombe et al., 2020). Although numerous studies have quantified the movement of different species from migratory fishes (such as tunas and salmons) to sedentary fishes (such as rockfish and snappers) in the estuaries, bays, coral reef habitats, and open sea areas by acoustic telemetry (Welsh et al., 2012; Smith et al., 2015; Biggs and Nemeth, 2016; Block et al., 2019; Keller et al., 2020), few studies did that in AR area. Furthermore, for the AR effectiveness evaluation, most of the previous studies focused on species variation, quantity, and weight of fish assemblage in the AR area (Charbonnel et al., 2002; Cenci et al., 2011; Zeng et al., 2018). However, few studies have evaluated the effectiveness of ARs from the perspective of fish utilization in AR habitats by acoustic telemetry, meaning information regarding site fidelity and habitat use of reef fish in AR areas is limited.

The overall goal of the present study was to examine the feasibility of using acoustic telemetry to evaluate the fish attraction effectiveness of ARs. The specific objectives were to 1) understand the deployment procedures of acoustic equipment, 2) determine the appropriate receiver spacing, and 3) quantify the site fidelity and habitat use of reef fish in the Fangchenggang AR area, Beibu Gulf, northern South China Sea. The research results may enrich approaches to evaluating the effectiveness of ARs and contribute to the decision-making process of sustainable fisheries.

2 Materials and methods

2.1 Experiment I: deployment test of the acoustic telemetry system

2.2.1 Experimental design

To optimize the deployment of acoustic equipment and test the appropriate receiver spacing, a total of eight VR2Tx receivers and one range test transmitter with a 10-s fixed delay transmission interval (Vemco Ltd., Halifax, Nova Scotia, Canada) were used to deploy the acoustic telemetry system in the coastal waters with a depth averaging 12 m. The range test transmitter was moored in the front, followed by the receiver mooring every 50 m in a straight line. All of them were suspended at a depth of 7 m above the seabed (Figure 1).

2.2.2 Experimental procedure

Firstly, the position (longitude and latitude) of the transmitter and receiver were determined by Google Earth software (Google Inc., Mountain View, California, USA). Prior to placement, the transmitter and receiver were singly tied at a depth of 7 m from the bottom of the nylon rope using cable ties. An anchor and a buoy were tied to the two ends of the nylon rope, respectively (Figure 1). Some parameters such as the battery remaining capacity of the receiver were set in a computer installed with Vemco user environment (VUE) software (www.innovasea.com). Then, the transmitter and receiver were placed in the predetermined position with the help of a high-accuracy differential GPS instrument (Trimble Inc., Sunnyvale, California,

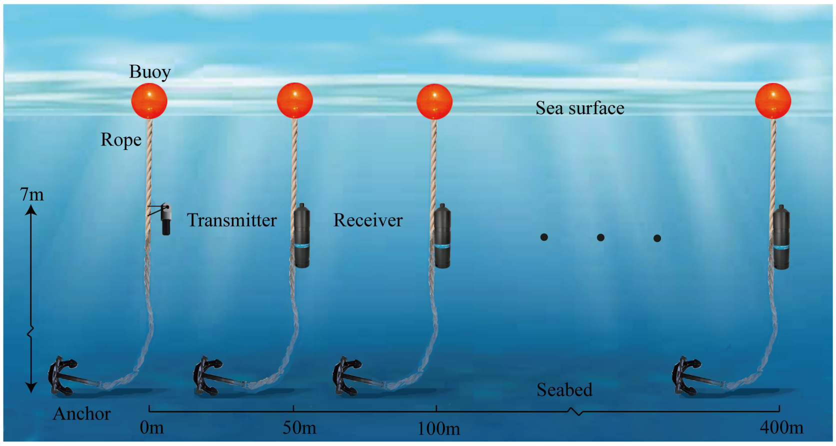

FIGURE 1
Schematic of range test experiment showing the deployment of the moored transmitter and receiver. The range test transmitter (not attached directly to the rope) was moored in the front (0 m), and eight receivers were moored at fixed distances from the transmitter (50, 100, 150, 200, 250, 300, 350, and 400 m).

USA). After 1 h, they were retrieved from the sea, and the experimental data in the receivers were downloaded by the VUE software.

2.2 Experiment II: fish tracking in the Fangchenggang AR area

2.2.1 Study area

The fish tracking experiment was conducted in the Fangchenggang AR area (21°25.278′–21°25.697′N, 108°12.924′–108° 14.039′E) with a water depth averaging 16 m between July and September 2017. Since the first ARs were placed in 1979, about 2,190 ARs (3–6 m in height) with 123,760 m^3 in volume have been placed here to date (Figure 2) (Jia et al., 2021).

2.2.2 Receiver placement

Prior to receiver placement, a range test was performed in accordance with the procedures in Experiment I to know the appropriate receiver spacing in the study area; the only difference is that receivers were moored upside down. The results of the range test showed that hourly detection probability was above 80% within 150 m, so the receiver spacing was set as 150 m to guarantee high detection proportion. To cover the AR concentration zone, 11 Vemco VR2Tx receivers were moored upside down at a depth of 7 m above the seabed given the height of ARs and the bottom swimming of reef fish. The receivers were placed in polygons to increase the probability that transmissions could be detected by multiple receivers simultaneously (Figure 2). Given that biofouling might occlude signals, all the receivers were coated with an antifouling paint in advance (Heupel et al., 2008). In addition, a transmitter as the

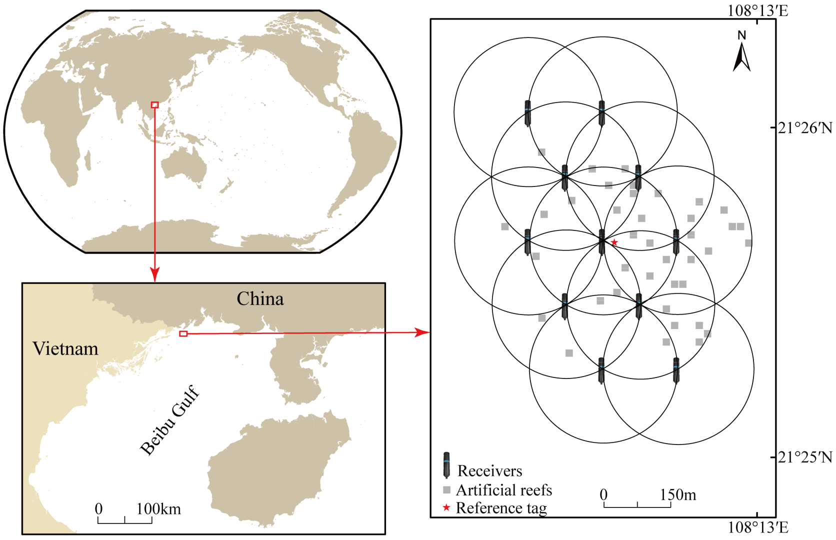

FIGURE 2
Map of the study area located in Beibu Gulf, northern South China Sea. The 11-receiver array was placed in polygons between July and September 2017. A reference tag was placed at the center of the array.

reference tag was moored at the center of the receiver array to validate the accuracy of positioning results presented by the acoustic telemetry system (Muñoz et al., 2020).

2.2.3 Fish capture, tagging, and release

The animal study was approved by the Animal Experimental Ethics Committee of Guangdong Ocean University, China. A previous study found that the released seabreams have homing behavior, as they tend to return to the site where they were captured (Mitamura et al., 2005). To test this, a total of 11 individuals of reef fish from six species, with total lengths ranging from 185 to 270 mm and weights ranging from 195 to 500 g, were captured in Fangchenggang coastal waters (not in the study AR area) using line angling by local fishermen. These fish were reared for 48 h at a conventional cage net to guarantee that they are in a normal state.

Prior to tagging, the nylon line was looped at the middle of the transmitter (Vemco V9, 69 kHz, 47 mm in length, 9 mm in diameter, 2.7 g in water, 60–120-s random delay transmission interval) and fixed by cyanoacrylate glue; then, the processed transmitters and a curved needle were immersed in a 75% ethanol solution for 5 min. After that, each individual was anesthetized by immersion in the seawater containing a dose of 100 mg/L of tricaine methane-sulfonate (MS 222) until loss of fish body equilibrium was observed (Neves et al., 2018). All the individuals were measured to the nearest millimeter in total length and weighed to the nearest gram. One end of the nylon line on the processed transmitter was threaded through the fish dorsal muscle using the curved needle and tied with another end of the line; 0.5% povidone-iodine solution was then sprayed around the wound to prevent infection. For tagging, the fish out of the water process was completed within 5 min. Then, the tagged fish were placed in a tank with fresh seawater to recover their normal behavior (Figure 3). Finally, they were held at the ballast tank of a fishing vessel and released at the center of the receiver array in the study area. The biological information and release date of 11 tagged fish are summarized in Table 1.

2.3 Statistical analysis

2.3.1 Experiment I

The detection proportion (DP_i, %) for each receiver is calculated as follows (Mathies et al., 2014):

$$DP_i = \frac{OD_i}{ED_i} \times 100$$

where OD_i is the number of observed detections for a receiver i and ED_i is the number of expected detections. One-way ANOVA was conducted to test for significant differences in the detection proportion at different distances between the range test transmitter and receiver; the data were checked for normality using the Shapiro–Wilk test and for homogeneity of variances with Levene's test, which were performed in the SPSS 22.0 software (IBM Inc., Armonk, New York, USA). $p < 0.05$ was considered statistically significant.

Considering that the transmission detected or not detected was the binary response variable, a logistic regression model was fitted to the data to predict the detection probability at different distances (i.e., the appropriate receiver spacing) by using the "glm" function in the R version 4.2.0 (Kessel et al., 2014; Swadling et al., 2020). The model significance was examined by the Hosmer and Lemeshow goodness-of-fit test, and $p > 0.05$ means it provides a satisfactory fit to the data (Hosmer and Lemeshow, 2000).

2.3.2 Experiment II

The presence and absence of fish in the study area could be detected by an individual receiver, while the fish position was detected by three or more receivers simultaneously and calculated based on the time difference of transmission arrival at the receivers (Williams-Grove and Szedlmayer, 2017). We had originally intended to download the data at the end of the experiment. However, due to the typhoon, receivers were retrieved twice during the experiment, and tracking dates were 7 to 14 July, 21 July to 1 August, and 2 August to 8 September 2017. A residency index (RI_j) was used to quantify the site fidelity of the reef fish to the AR area, which was defined as follows (March et al., 2010; Alós et al., 2011):

$$RI_j = \frac{DD_j}{TD_j}$$

where DD_j is the number of detected days for a tagged fish j and TD_j is the tracking days between the released date and the last detected date within the receiver array. RI_j varies from 0 (lowest, completely absent) to 1 (highest, completely present) (Moxham et al., 2019).

The home range was used to characterize the habitat use. Hence, three measures of the home range were estimated for the tagged fish: 100% minimum convex polygon (100% MCP, i.e., based on 100% of the observed fish positions), 95% kernel utilization distribution (95% KUD, i.e., general activity area), and 50% KUD (i.e., core activity area)

FIGURE 3
Digital images of fish tagging process: **(A)** *Acanthopagrus latus* tagged with a Vemco V9 acoustic transmitter, **(B)** a curved needle used for tagging, and **(C)** some tagged fish placed in the fresh seawater.

TABLE 1 Summary of the data for 11 reef fish tagged with acoustic transmitters between July and September 2017, including fish ID, species name, total length (TL), weight, released date, last detected date, detected days (*DD*), tracking days (*TD*), residency index (*RI*), number of (Num.) detections, and number of (Num.) positions.

ID	Scientific name	TL (mm)	Weight (g)	Released date	Last detected date	*DD* (d)	*TD* (d)	*RI*	Num. detections	Num. positions
#1	*Lutjanus johnii*	185	215	7 Jul.	8 Sept.	38	38	1.00	33,130	7,593
#2	*L. johnii*	200	225	7 Jul.	8 Sept.	23	38	0.61	2,906	2,641
#3	*Epinephelus bleekeri*	205	250	7 Jul.	8 Sept.	27	38	0.71	2,578	2,376
#4	*E. bleekeri*	204	250	21 Jul.	8 Sept.	30	30	1.00	7,260	2,592
#5	*Acanthopagrus latus*	213	200	21 Jul.	8 Sept.	27	30	0.90	8,212	1,278
#6	*A. latus*	205	195	21 Jul.	8 Sept.	6	30	0.20	101	63
#7	*Acanthopagrus schlegelii*	255	305	21 Jul.	8 Sept.	28	30	0.93	4,221	2,881
#8	*Lutjanus erythropterus*	240	280	21 Jul.	8 Sept.	30	30	1.00	7,168	2,458
#9	*L. erythropterus*	270	500	22 Aug.	8 Sept.	18	18	1.00	18,478	1,748
#10	*L. johnii*	203	250	22 Aug.	8 Sept.	18	18	1.00	52,383	9,590
#11	*Lethrinus nebulosus*	195	200	22 Aug.	8 Sept.	18	18	1.00	5,816	2,743

(Alós et al., 2012), which were performed using the Arctoolbox in Arcgis 10.8 software (ESRI Inc., Redlands, California, USA).

3 Results

3.1 Receiver detection range

The detection proportion declined significantly with increasing distance between the range test transmitter and receiver (one-way ANOVA, $p < 0.05$). The mean detection proportion per 20 min (mean ± SD) varied from a high of 81.1% ± 0.7% at 50 m to a low of 19.2% ± 4.2% at 400 m. The largest incremental decrease in detection proportion was observed between 250 and 300 m. The logistic regression model provides a satisfactory fit to the data (Hosmer and Lemeshow test, $p > 0.05$), which indicated that 50% detection probability was achieved at approximately 240 m and 80% detection probability was achieved at approximately 110 m (Figure 4).

3.2 Site fidelity

During the tracking experiment, a total of 142,253 detections for 11 tagged fish were observed within the receiver array, ranging from 101 for fish #6 to 52,383 for #10 (Table 1). Fish showed a high site fidelity to the AR area, and the mean *RI* was 0.85 ± 0.24. Three out of 11 tagged fish expressed moving behaviors. Three individuals (#2, #6, and #7) left the study area but returned and stayed until the end of the experiment. Two individuals (#3 and #5) left and returned to the study area multiple times but ultimately stayed until the end of the experiment (Table 1). The remaining individuals stayed in the study area throughout the experiment (Figure 5).

3.3 Habitat use range

A total of 35,963 positions were obtained for 11 tagged fish during the tracking experiment. Fish #10 had the maximum number of positions (9,590), but the positioning result of fish #6 was poor with the minimum number of positions (63) (Table 1). Each fish occupied a small range in the AR area (Figure 6). Habitat use range estimated using the 100% MCP was between 337.45 m^2 for fish #6 and 133,527.08 m^2 for fish #1, with a mean value of 34,522.94 ± 35,548.95 m^2; the 95% KUD was between 50.54 m^2 for fish #6 and 4,925.45 m^2 for fish #9, with a mean value of 1,467.52 ± 1,619.05 m^2; the 50% KUD was between 10.92 m^2 for fish #7 and 1,009.64 m^2 for fish #9, with a mean value of 236.01 ± 294.59 m^2.

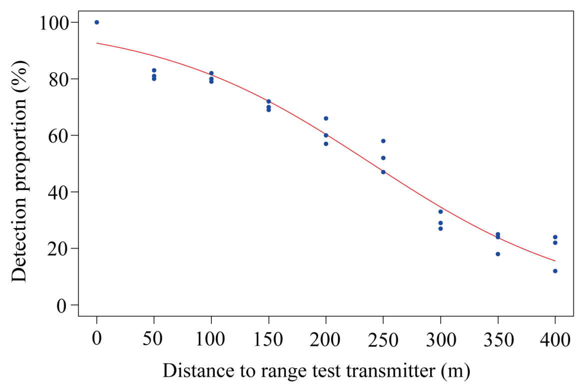

FIGURE 4
Detection proportion profiles of the 1-h range test in experiment I. Blue dots represent the observed detection proportion per 20 min (n = 3). Red line represents the logistic curve.

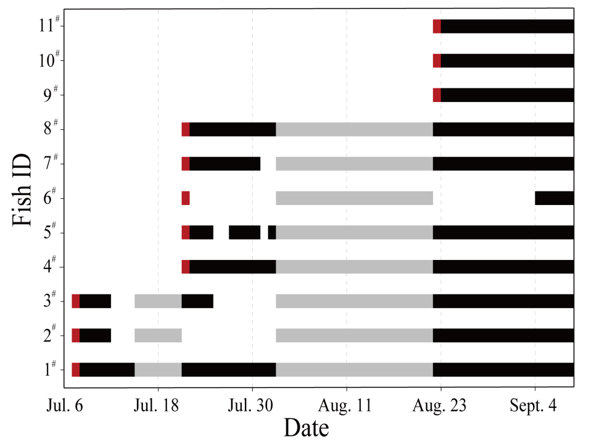

FIGURE 5
Plot of the daily presence–absence of 11 tagged reef fish between July and September 2017. Red represents the released date, black represents the detected date after the release, and gray represents the date without deploying the receiver array.

4 Discussion

This was the first study to conduct a range test and fish tracking using an acoustic telemetry system in the AR area of the northern South China Sea. Through two experiments, we mastered the usage of acoustic equipment and quantified the site fidelity and habitat use of fish. Our results showed the high site fidelity and small spatial scale of habitat use for reef fish, which demonstrated that ARs were an effective man-made structure for attracting fish. The present study finally proved that acoustic telemetry can be successfully used to evaluate the fish attraction effectiveness of ARs.

The key to the deployment of the acoustic telemetry system was the receiver placement and transmitter attachment. Before the receiver is placed, two common methods can be chosen for receiver mooring. One is the concrete mooring (i.e., a concrete block base with an embedded metal bar or polyvinyl chloride pipe), and another is what the present study did. The receiver is moored at a depth of about 1 m from the bottom and needs to be retrieved by diving using the first method (Whoriskey et al., 2019), whereas physical barriers can obstruct the transmission of signals (Welsh et al., 2012; Mathies et al., 2014). Given the height of ARs and the convenience of retrieval, our study chose the second method. In addition, determining appropriate receiver spacing by range test is essential prior to receiver placement. Previous publications have highlighted that the receiver's detection range varies significantly over space and time and recommend that acoustic telemetry studies need to perform *in situ* range tests (Kessel et al., 2014). In our study, the range test results were different in Experiment I (80% detection probability within 110 m) and Experiment II (80% detection probability within 150 m), which supports the above recommendation. This is likely due to the bottom topography like ARs, but long-term range test with different environmental factors (such as water depth, tied, and ambient noise)

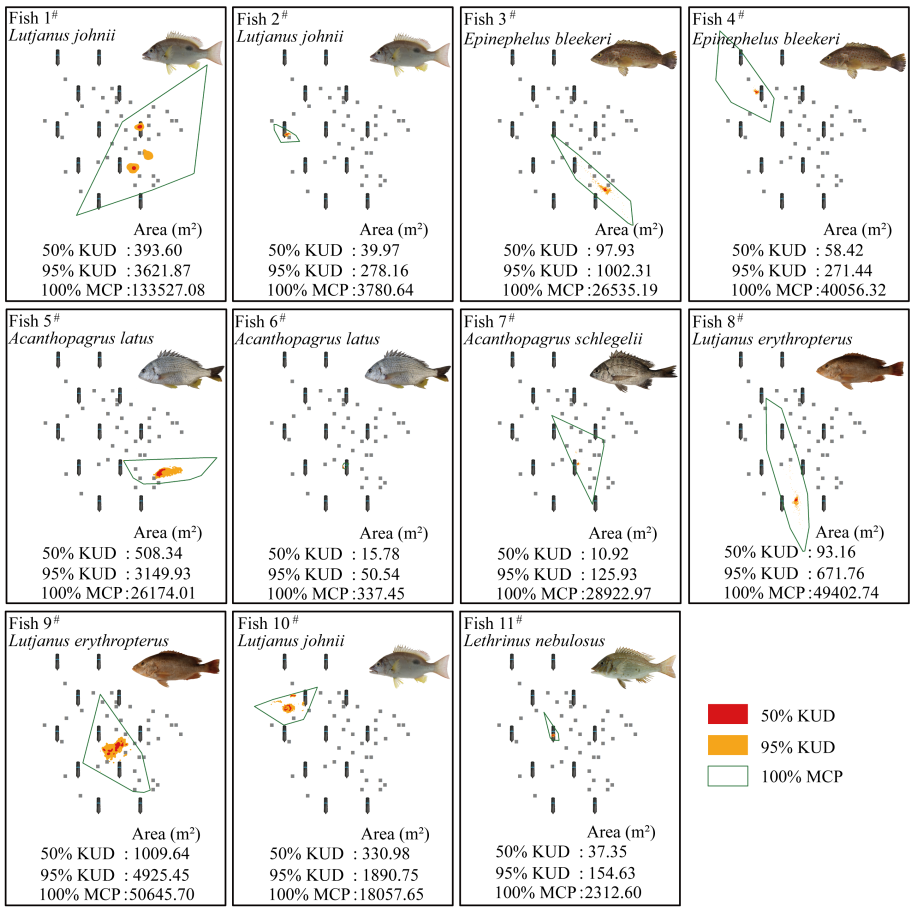

FIGURE 6
Spatial plot of the habitat use range with the minimum convex polygon (100% MCP) and kernel utilization distribution (95% and 50% KUD) for 11 tagged fish in the Fangchenggang artificial reef sea area. MCP, minimum convex polygon; KUD, kernel utilization distribution.

needs to be further studied for obtaining optimal receiver spacing. For transmitter attachment, three main methods for tagging fish with transmitters have been reported. Transmitters can be secured externally, inserted into the stomach, and surgically implanted in fish (Hussey et al., 2015). The study results from Dance et al. (2016) indicated that external attachment of transmitters in fish was detected significantly more than doing so for internal attachment and pointed out that internal attachments may weaken the detection range. In contrast, external attachments are easily performed and minimize handling time. Therefore, our study used external attachment. The result with no transmitter loss and no fish death in our study suggested that external attachment of transmitters may be a successful method for reef fish.

Fish site fidelity and habitat use range are two important indicators to characterize the effectiveness of ARs. In this study, most of the fish showed strong fidelity to the ARs with the mean *RI* of 0.85 ± 0.24, except that of fish #6 (with *RI* of 0.2) was not observed until 5 days before the end of the tracking experiment. Although some fish left and returned to the study area during the experiment (it is possible that they were exploring the surroundings and searching for a place to live in), 11 fish (not captured from the study area) stayed in the AR area at the end of the experiment. However, on the contrary, Mitamura et al. (2005) found that the released seabreams have homing behavior, as they tend to return to the site where they were captured. The reason for this difference is that it is possible that the AR area in this study provides a favorable habitat for fish feeding and hiding. For habitat use range, our results indicated that each fish occupied a range in the AR area for living, but in general, it was a small spatial range. This is similar to the findings in an army tank reef from Topping and Szedlmayer (2011). Moreover, to avoid the effect of a typhoon, the receivers were retrieved and connected to the computer to obtain data. It is also advisable to download the data regularly throughout the study to prevent data loss due to boat traffic or bad weather.

The current approaches for evaluating the effectiveness of ARs have limitations and represent only a snapshot of the complex AR ecosystem (Brownscombe et al., 2022). Luckily, the acoustic telemetry system can provide more continuous tracking for the organisms in the AR area. Furthermore, the current approaches require the contrast area for evaluating the effectiveness of ARs. However, it is a challenge to identify a suitable contrast area; so, to date, there is no scientific way to determine the spacing between the AR area and the contrast area (Roni et al., 2018). The MCP in the present study includes all the observed activity positions for each fish in the AR area; the longest distance between the MCP points may be the spacing between the AR area and contrast area, which needs more kinds of reef fish to verify due to the significant MCP differences. In fact, it is still a debate whether the ARs enhance fish population or simply temporally attract fish aggregation (Pickering and Whitmarsh, 1997; Brickhill et al., 2005). Even though the capability of ARs in enhancing fish populations requires long-term study, our study demonstrated that ARs can play a role in attracting fish, including fish that did not originate from the ARs. This information provides valuable contributions to stock enhancement projects in selecting fish species and releasing sites; i.e., priority should be given to the reef fish and AR area.

5 Conclusions

AR construction is expected to become more widely used for maintaining sustainable coastal fisheries. However, it will be challenging to evaluate the effectiveness of ARs, especially with current evaluation approaches. Our study demonstrates that acoustic telemetry can be used as a supplemental approach for evaluating the fish attraction effectiveness of ARs. Meanwhile, this approach is also applicable to studies of other organisms such as shrimp and crabs in the AR area. To better guide AR construction and management, further research is needed to understand the preferences of different reef fish for different AR types (concrete reefs or boat reefs), shapes (cubic or cylindrical), sizes, and depths in the future.

Data availability statement

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

Ethics statement

The animal study was reviewed and approved by the Animal Experimental Ethics Committee of Guangdong Ocean University, China.

Author contributions

SL, GC, and XW conceptualized and designed the study. SL, LW, ZW, and KL conducted the fieldwork and participated in the data analysis. SL drafted the manuscript. HL, LW, GC, and XW wrote sections of the manuscript and revised the manuscript. All authors contributed to the article and approved the submitted version.

Funding

This study was supported by the special funds for Sino-Indonesian Technical Cooperation in Coastal Marine Ranching (12500101200021002), the Science and Technology Infrastructure Project of the Department of Science and Technology of Guangdong Province (2021B1212110005), and the Postgraduate Education Innovation Project of Guangdong Ocean University (202245).

Acknowledgments

We thank Bingnan Li and Xiaowen Chen for assisting with figure drawing and Lei Zeng for assisting with the deployment of equipment in the field.

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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TYPE Original Research
PUBLISHED 09 February 2023
DOI 10.3389/fmars.2023.1133462

OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Marine Conservation and Sustainability, a section of the journal Frontiers in Marine Science

RECEIVED 29 December 2022
ACCEPTED 31 January 2023
PUBLISHED 09 February 2023

CITATION
Xu L, Du F, Tang Q, Wang L, Ning J, Huang D, Li Y, Liu S and Wang X (2023) Seasonal variability of nektonic community structure and phylogenetic diversity in Weizhou Island, the Beibu Gulf. *Front. Mar. Sci.* 10:1133462. doi: 10.3389/fmars.2023.1133462

Seasonal variability of nektonic community structure and phylogenetic diversity in Weizhou Island, the Beibu Gulf

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The favorable natural conditions and variety of habitats in the Beibu Gulf provide a basis for harboring a high diversity of marine organisms. Sustainable coastal ecosystem management can be benefited from a comprehensive assessment of species diversity. In this study, we analyzed the seasonal changes in nektonic phylogenetic and community structures in the waters of Weizhou Island in the northern Beibu Gulf. The results showed that both the nektonic phylogenetic diversity and community structure in the northern Beibu Gulf exhibited strong seasonal differences between spring and autumn. The catch density was 291.9 kg per km^2 in spring and 1081.1 kg per km^2 in autumn. Phylogenetic diversity of nektonic communities obviously increased from spring to autumn, while phylogenetic patterns changed from clustering to overdispersion. The seasonal patterns of nektonic communities were mainly related to the different fishing intensities in spring and autumn. Summer fishing intensity in the Beibu Gulf was effectively controlled by a mid-summer fishing moratorium, during which nektonic diversity and fish stocks rapidly recovered from the larval pool. Our study revealed that fishing intensity had a greater impact on nektonic communities at smaller spatial scales, and even exceeded the effects of environmental factors.

KEYWORDS

phylogenetic diversity, nekton community, the Beibu Gulf, Weizhou Island, community structure

Introduction

Studying species composition dynamics is key to understanding community ecology. Clarifying the causes of temporal and spatial variation in species composition has long been a major issue for ecologists (Palmer, 1994; Vellend and Agrawal, 2010). In the last 30 years, there have been two main theories regarding the formation of species composition and biodiversity of a local community. One is the niche-based theory, which emphasizes environmental filtration as a main driving force of community structuring. Environmental filtration includes the effects of the abiotic environment on organisms and the interactions between organisms; that is, environmental selection (Chase and Leibold, 2003). The other theory is the community neutral theory (Hubbell, 2001), which is a generalization of neutral theory of molecular evolution at the macro level (Kimura, 1968). The community neutral theory ignores interspecific difference or assumes that interspecific difference has little effect on species coexistence, and instead emphasizes the influence of stochastic processes on the formation of community composition (Hubbell, 2005). The balance between assembly and dispersal of ecological communities is caused by ecological drift; this is the core of the community neutral theory, similar to genetic drift in population genetics (Bell, 2001).

Ecologists have recognized that niche-based theory and community neutral theory are not diametrically opposed, and a community is likely determined by the interplay of the two processes (Tilman, 2004; Gewin, 2006; Adler et al., 2007). However, the species composition of a community does not sufficiently reflect the pattern of diversity and assembly process of the community. For example, although two communities may have the same number of species, their evolutionary origins and community construction processes may be completely different.

Since 2000, it has become increasingly common to use phylogenetic relatedness to investigate the origin and history of species within a community and to understand the influence of ecological and historical factors on assembly process of the community (Webb, 2000; Cavender-Bares et al., 2009; Mouquet et al., 2012). Given known phylogenetic relatedness and rates of evolution of functional traits, different patterns of phylogenetic community structure are expected depending on whether competitive exclusion or environmental filtering was the primary driver that influenced community historical assembly (Webb et al., 2002). If competitive exclusion drives community assembly, we expect phylogenetic overdispersion because closely related species tend to compete more intensely for the same resources than distantly related species. Conversely, if environmental filtering plays a driving role in community assembly, selection caused by environmental filtration often results in a higher degree of co-occurrence of closely related species, leading to phylogenetic clustering (Weiher and Keddy, 1999; Cavender-Bares et al., 2009).

Recently, several examples from different ecosystems worldwide have extended the use of phylogenetic approaches to investigate patterns in community structure. D'agata et al. (2014) reported that anthropogenic activities have significantly reduced the functional and phylogenetic diversity of a crucial fish family (Scaridae and Chaetodontidae) in the coral reefs of Pacific. Winter et al. (2009) analyzed the large-scale effects of native species extinctions and the introduction of alien species on taxonomic and phylogenetic diversity of floras across Europe; their findings revealed that plant invasions exceeded extinctions in the last 500 years. Jiang et al. (2019) revealed that the influences of human activities since 1960 were sufficient to obscure the phylogenetic distinctiveness in the nearly 5 million years of evolutionary history of freshwater fish from isolated plateau lakes in southwestern China. Xu et al. (2021a) studied the nektonic communities of two bays in the South China Sea; they demonstrated that differentiation of spatial and temporal patterns in both phylogenetic and community structure was primarily related to stochastic processes in structuring nektonic communities and fishing intensity differences between the two bays.

The Beibu Gulf (17°–21°45′N, 105°–110°10′E) (as known as the Gulf of Tonkin) is in the northwest of the South China Sea and has a long coastline that belongs to both Vietnam and China. As a natural semi-closed gulf, the Beibu Gulf covers a water area of approximately 128,000 km^2 with an average water depth approximately 39 m and a maximum of 100 m. It extends from the Hainan Island and Leizhou Peninsula in the east to the coast of northern Vietnam in the west, and reaches the coast of Guangxi Zhuang Autonomous Region in the north (Xu et al., 2021b). The climate around the Beibu Gulf is tropical subtropical monsoon climate, moving northeast in spring and southwest in autumn; this transports warm sea water through ocean currents and circulation throughout the year. Moreover, the Beibu Gulf has a flat seabed and diverse habitats, including coral reefs, mangrove forests, and numerous estuaries, such as Nanliu River in China and Red River in Vietnam, from which rivers discharge sufficient nutrients (Ma et al., 2010). These favorable natural conditions and variety of habitats provide a basis for harboring a high diversity of marine organisms, and this gulf attracts thousands of species of fish to feed, breed, and spawn.

According to a previous report, more than 900 fish species that belong to 475 genera and 162 families inhabit the Beibu Gulf (Ma et al., 2008; Zhang et al., 2022). The Beibu Gulf is one of the most diverse and productive water-based ecosystems in the South China Sea. More than 60 commercially important fish, squid, and shrimp taxa support substantial fishing efforts, such as conger pike (*Muraenesox cinereus*), round scad (*Decapterus maruadsi*), hairtail (*Trichiurus lepturus*), blood snapper (*Lutjanus sanguineus*), Japanese horse mackerel (*Trachurus japonicus*), and longtail tuna (*Thunnus tonggol*) (Qiu et al., 2010; Wang et al., 2012). Consequently, the Beibu Gulf is one of the four famous fishing grounds in China, and it is important for the livelihoods of millions of fishermen along the coasts of China and Vietnam, and plays an increasingly important role in employment, food security, and the local economy (Chen et al., 2009). However, with the rapid increase in the number of marine fishing vessels in the Beibu Gulf since the 1970s, catch rates and fishing efforts have rapidly increased.

Fish community structure has been transformed from high-value species to lower-value species; for example, large yellow croaker (*Larimichthys crocea*) and crimson snapper (*Lutjanus erythropterus*) were replaced by finespot goby (*Chaeturichthys stigmatias*)(Wang et al., 2012; Zhang et al., 2022). Abrupt decreases in fish density occurred in 1993 and 1998, and overexploitation eventually depleted fisheries stocks in the late 1990s, especially those of demersal species. In addition to overexploitation, various other anthropogenic activities, such as coastal mangrove damage, illegal fishing, mariculture pollution, and habitat degradation, also pose substantial threats to the fish stocks and marine ecosystem of the Beibu Gulf (Qiu et al., 2010; Shen and Heino, 2014; Wang et al., 2019). Previous studies on the fishery resources and coastal environment of the Beibu Gulf mainly focused on the species diversity, quantity, population dynamic change, and spatiotemporal distribution of fishery resources (Chen et al., 2009; Wang et al., 2012; Wang et al., 2019; Hou et al., 2022; Tian et al., 2022).

A comprehensive assessment of species diversity is urgently needed to avoid permanent damage to ecosystems and the loss of valuable marine resources. Very little is known about the phylogenetic relationships among nektonic species of the Beibu Gulf, and the temporal distribution of phylogenetic diversity remains unclear. Therefore, the specific purposes of this study were to investigate nektonic community seasonal variation and factors affecting their phylogenetic diversity in the Beibu Gulf. We hypothesized that there would be obvious temporal variation of nektonic community phylogenetic diversity and composition in the Beibu Gulf.

Materials and methods

Study area

Weizhou Island (21°–21°5′N, 109°–109°10′E) is in the northern part of the Beibu Gulf, approximately 36 miles from the mainland. Weizhou Island is the youngest and biggest island in the Beibu Gulf. It is an inhabited volcanic island that covers an area of approximately 25 km^2. The annual average water surface temperature is about 24°C, and ranges from 19°C to 30°C. The annual average seawater salinity is 32‰, pH of seawater ranges from 8.0 to 8.23, and seawater transparency ranges from 3 m to 10 m (Yu et al., 2019). Weizhou Island is the northernmost coral reef ecosystem in the South China Sea. It is also a popular tourist destination, attracting approximately 600,000 visitors annually in recent years, and it is heavily influenced by anthropogenic activities (Yu, 2012; Chen et al., 2013).

Sample collection

Two fishery surveys were conducted in the waters of Weizhou Island in the northern Beibu Gulf by the South China Sea Fisheries Research Institute in the spring (April 8–10) and autumn (September 22–24) of 2022. Nektonic communities were collected by the 135 kW commercial fishing vessel “*Haiyu60087*” using bottom trawl nets and pair trawl nets from five sampling sites in this area. At each sampling site, the trawl was towed for 30 min at an average speed of 3 kn (Figure 1).

The following data were recorded for each trawl: speed, GPS position, towing distance, depth and duration time. All collected samples were first identified to species by morphology, and then weighed and counted. Species identification and nomenclature follow the previous taxonomic literature and available documented diagnostic morphological characters for marine species from FishBase (http://www.fishbase.org). Conductivity, water temperature, pH, and dissolved oxygen were determined during the surveys using a handheld multiparameter meter (YSI Pro Plus). Water samples were taken with a 5-L plexiglass deep-water sampler from the bottom layer at each site for analysis of chlorophyll a.

Phylogenetic tree

For each identified species, we downloaded the sequences of cytochrome c oxidase subunit 1 gene from public database (GenBank or BOLD, see Table S1). All downloaded sequences were assembled and examined in BioEdit, and aligned under default options (Hall, 1999). Bayesian inference was used to reconstruct the phylogenetic tree with the COI dataset in BEAST 1.8 (Drummond et al., 2012). The BEAST parameters were set in BEAUti 1.8, and the sequences were further manually edited. A generalized time reversible substitution model with gamma distribution was set for the entire aligned sequence dataset. An uncorrelated relaxed molecular clock and a coalescent model with a constant population size were selected. Markov chain Monte Carlo (MCMC) chains were run for 200,000,000 iterations. The maximum clade credibility consensus tree was constructed in TreeAnnotator 1.8, with the first million generations discarded as burn-in. FigTree 1.4.0 was used to display the final consensus tree.

Statistical analysis

Catch density (kg·km^{-2}) of each site was expressed as catch rate (catch per unit effort), according to Sparre and Venema (1998). Seasonal changes in the nekton species composition and community structure were analyzed by principal coordination analysis (PCoA) based on Bray–Curtis distance (Legendre and

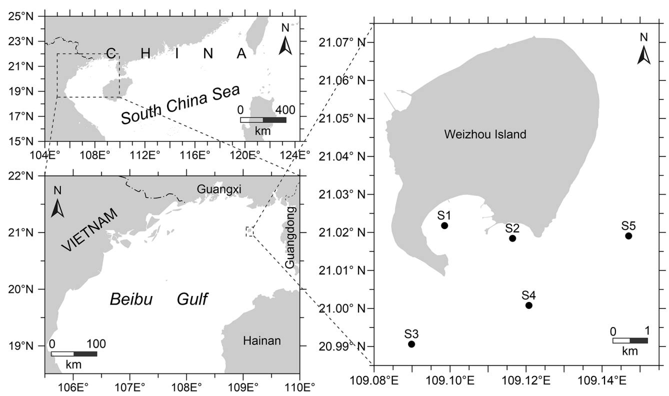

FIGURE 1
Map showing study area and sampling locations in the Beibu Gulf of the South China Sea.

Anderson, 1999). We used the abundance data to analyze species composition and community structure. The differences of species composition and community structure between autumn and spring were assessed by permutational multivariate analysis of variance (Per-MANOVA) also based on Bray–Curtis distance (Anderson, 2017). The level of statistical significance was set to $P<0.05$. PCoA and Per-MANOVA were performed with R statistical software R 4.0 (R Development Core Team, 2021) using the cmdscale and adonis functions in the package of vegan (Oksanen et al., 2019).

Phylogenetic structures of the nektonic communities in the waters of Weizhou Island were separately analyzed for spring and autumn dataset. First, we calculated the phylogenetic diversity of nektonic communities in the waters of Weizhou Island and examined the differences between the two seasons. Then, the net relatedness index (NRI) was used as a standardized index to evaluate the average phylogenetic distance between pairs of taxa in the sample. This index was used to estimate the overall phylogenetic relatedness of a nektonic community, and quantify the total clustering of taxa in a phylogenetic tree. Positive NRI values indicate phylogenetic relatedness exhibiting clustering, whereas negative values indicate phylogenetic relatedness exhibiting overdispersion (Faith, 1992; Webb, 2000; Webb et al., 2002).

Two indices were used to evaluate the variation of phylogenetic diversity at different phylogenetic levels. Mean pairwise distance (MPD) and mean nearest taxon distance (MNTD) represented the average pairwise distances of all taxa in the phylogenetic tree and the average distance between each taxon and its most closely related terminal taxon in the phylogenetic tree, respectively. Then, we used nonmetric multidimensional scaling ordination (nMDS) to reveal the differences in phylogenetic diversity among the sampling sites. For phylogenetic beta diversity (phylobeta diversity), we used mean phylogenetic dissimilarity between species (D_{pw}) in pairs of sampling sites and mean nearest taxon distance (D_{nn}) between the two sampling sites to capture deep and shallow phylogenetic variation, respectively (Webb et al., 2002; Swenson, 2011). Multiple regression on distance matrices (MRM) was used to reveal the effects of each environmental variable on both phylogenetic beta diversity indices (D_{pw} and D_{nn}) of the nektonic communities in the waters of Weizhou Island (Lichstein, 2007). All of the above analyses were carried out in R 4.0 with the packages splits, vegan, ape, picante, nlme, and ecodist (Goslee and Urban, 2007; Ezard et al., 2009; Kembel et al., 2010; Oksanen et al., 2019; R Development Core Team, 2021).

Results

Species composition and community structure

A total of 102 nektonic species were identified in our samples from the waters of Weizhou Island in the northern Beibu Gulf, including 8 cephalopods, 31 crustaceans, and 63 fish species, respectively. In the spring survey, we identified 6, 17, and 31 species associated with cephalopods, crustaceans, and fish, respectively; in the autumn survey, we identified 7, 21, and 31 species associated with cephalopods, crustaceans, and fish, respectively.

Fish, crustacean, and cephalopod catch densities of each sampling site in the waters of Weizhou Island are shown in Table S2. Maximum total catch density of Weizhou Island was found at S5 in the autumn survey (2346.81 $kg{\cdot}km^{-2}$), whereas minimum total catch density was found at S2 in the spring survey (169.75 $kg{\cdot}km^{-2}$). The total catch density as well as densities of fish and invertebrates in the autumn survey were significantly higher than those in the spring survey (Figure 2). The PCoA showed that all the samples in autumn were well separated from those in spring (Figure 3). The Per-MANOVA test showed that species composition and community structure were both significantly different between autumn and spring (p <0.05) (Table 1).

Phylogenetic diversity

The phylogenetic tree represented by all sample species collected in this study is shown in Supplementary Figures S1, S2. The average phylogenetic diversity of spring nektonic communities was 2.1, but reached 2.9 in autumn nektonic communities. There were clear significant differences in phylogenetic diversity between spring and autumn nektonic communities ($p < 0.001$); (Figure 4A). Positive NRI

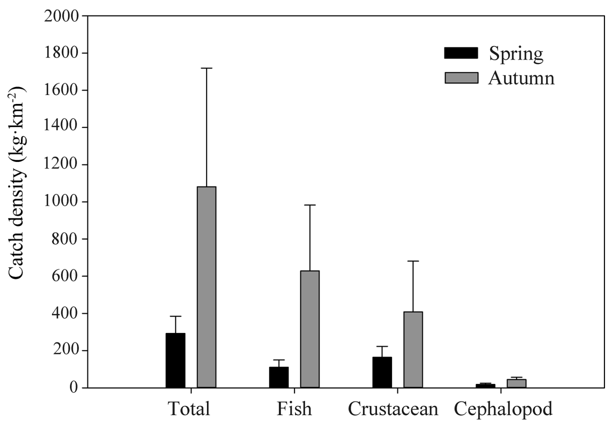

FIGURE 2
Comparison of catch density of fish and benthic invertebrates in Weizhou Island of Beibu Gulf in spring and autumn.

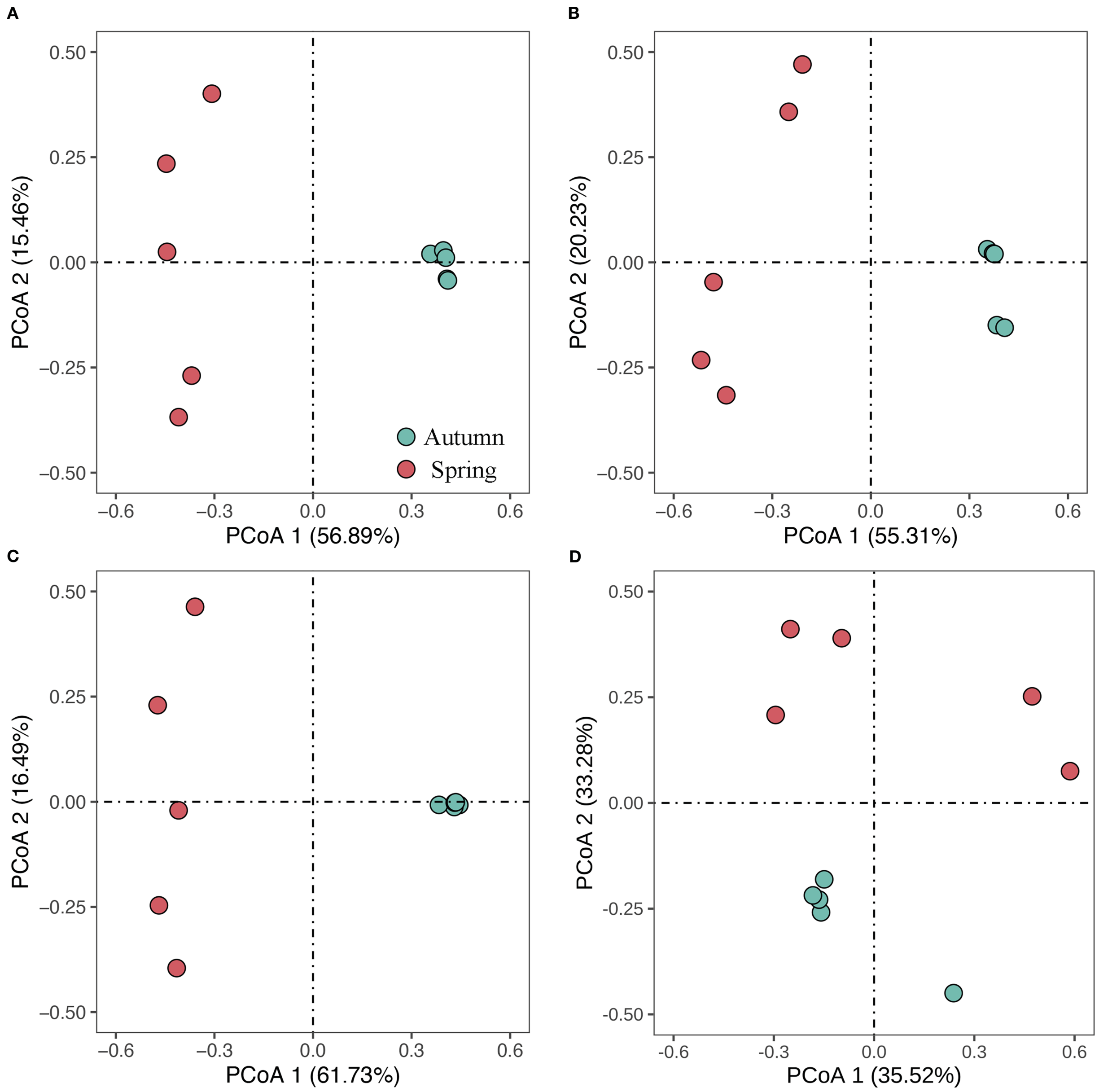

FIGURE 3
Biplot of principle coordination analysis showing the Bray-Curtis distance of community structure of **(A)** all species, **(B)** fish, **(C)** crustacean and **(D)** cephalopod between spring and autumn.

values in spring nektonic communities indicated phylogenetic clustering, whereas negative NRI values in autumn nektonic communities indicated phylogenetic overdispersion (Figure 4B). Nonmetric multidimensional scaling detected obvious ordination differentiations of phylogenetic alpha diversity at deep and shallow phylogenetic levels (MPD and MNTD) in the nektonic communities of Weizhou Island (Figure 5), showing a clear trend of seasonal separation.

The multiple regression on distance matrices significantly predicted the influence of environmental variables on the phylobeta diversity at both the deep and shallow phylogenetic levels for nekton community. The MRM models total explained 68.7% (p = 0.006) and 80.5% (p = 0.006) of environmental variance in phylobeta diversity at both deep (D_{pw}) and shallow (D_{nn}) phylogenetic levels, respectively. Salinity (p = 0.014), water temperature (p = 0.027), and transparency (p = 0.022) significantly explained the variation in phylobeta diversity at deep phylogenetic levels for nekton community, whereas salinity (p = 0.011), water temperature (p = 0.006) and depth (p = 0.043) were significantly related to the variation in phylobeta diversity at shallow phylogenetic levels (Table 2).

Discussion

Our results showed significant seasonal patterns in average catch density, community structure and phylogenetic diversity. The total catch density in spring was only 1/3 of that in autumn, which is approximately 1/7 of the fishery resource density in the 1960s and approximately 1/4 of that surveyed at the end of the 1970s. Phylogenetic diversity of nekton community increased appreciably

TABLE 1 The statistics of the Per-MANOVA test based on the Bray-Curtis distances of community structure between autumn and spring.

All species	Season	df	Sums of Squares	Mean Squares	F	R^2	p
		1	1.57	1.57	10.36	0.56	0.009
	residual	8	1.21	0.15		0.44	
	total	9	2.78				
Fish	season	1	1.45	1.45	9.11	0.53	0.008
	residual	8	1.27	0.16		0.47	
	total	9	2.72				
Crustacean	season	1	1.15	1.15	17.11	0.68	0.013
	residual	8	0.54	0.067		0.32	
	total	9	1.69				
Cephalopod	season	1	0.79	0.80	3.7	0.32	0.012
	residual	8	1.71	0.21		0.68	
	total	9	2.51				

df, degree of freedom.

from spring to autumn, while phylogenetic patterns changed from clustering to overdispersion. As a highly productive area with rich fish diversity and fertile fishery resources, fisheries, marine ecosystem dynamics, oceanography, and marine policy have been intensively studied in the Beibu Gulf (Yu and Mu, 2006; Wang et al., 2012; Gao et al., 2015; Wang et al., 2019; Xu et al., 2019). Detailed investigation of fishery resources in the Beibu Gulf can be traced back to the China and Vietnam comprehensive oceanographic survey of the Beibu Gulf in the late 1950s and early 1960s. A total of 1519 fish species have been recorded in the Beibu Gulf since the first comprehensive oceanographic survey, of which 107 are currently listed as endangered by the IUCN.

Previous studies have shown that the total fishing density in the Beibu Gulf has decreased by more than 60% in recent years, and the catch density of 12 traditional commercial demersal fishes has decreased by an even greater 85%. Indeed, the average stock density of many important fishes is only 10% of what it was in the 1960s (Zhang et al., 2021; Su et al., 2022). According to Yuan (1995), fishery resource density along the coast of Beibu Gulf was approximately 5 tons per km^2 in the 1960s, but was 3 ton per km^2 by the end of the 1970s. In our investigation, the average catch density in Weizhou Island in the northeast part of the Beibu Gulf was 686 kg per km^2, indicates that the fishery resources in the northeast of the Beibu Gulf are in serious decline.

Furthermore, the traditional commercial fish and dominant species changed from larger, higher value, and higher trophic level species to smaller species with a shorter life span, lower value, and lower trophic level. For example, golden threadfin bream (*Nemipterus virgatus*), lizardfish (*Trachinocephalus myops*), and humphead snapper (*Lutjanus sanguineus*) were replaced by round scad

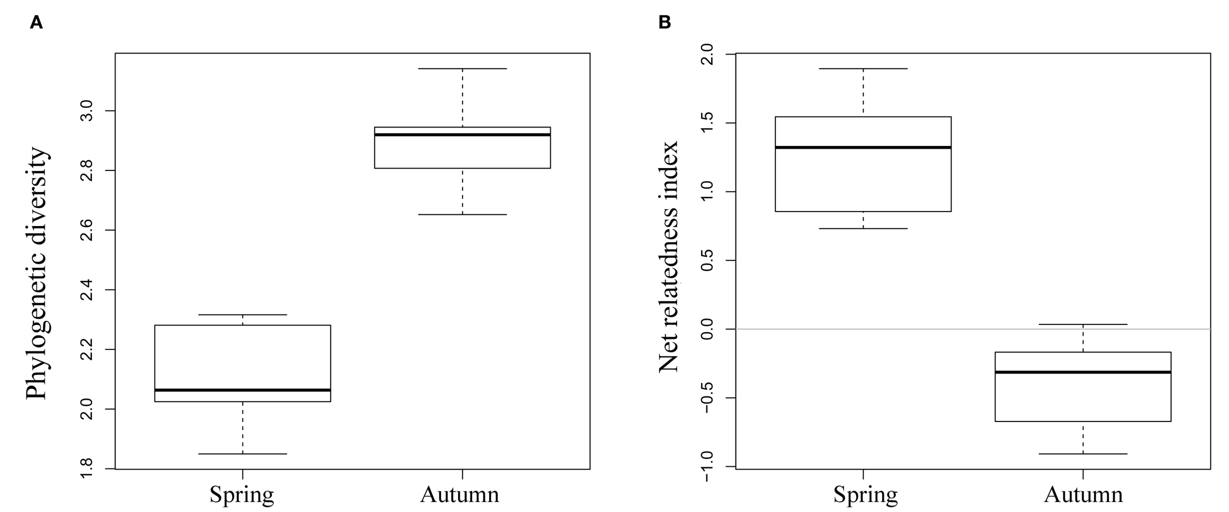

FIGURE 4
Variance analysis with permutation tests for values of phylogenetic diversity **(A)** and net relatedness index **(B)** in nektonic communities of Weizhou Island in spring and autumn.

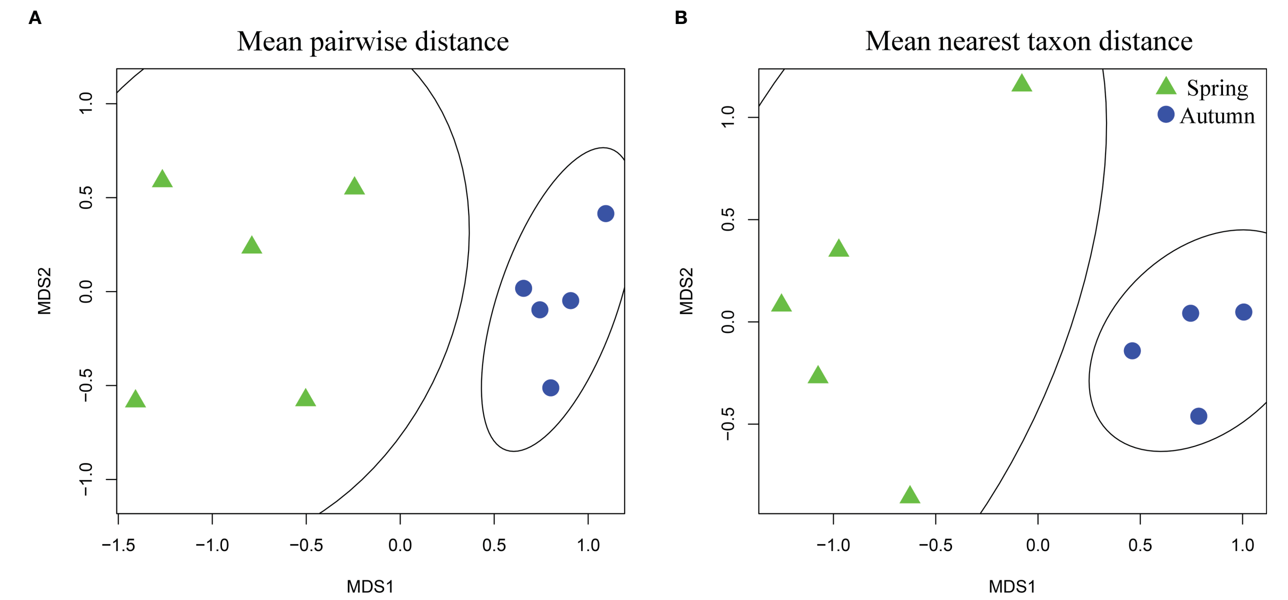

FIGURE 5
Nonmetric multidimensional scaling ordination plots of phylogenetic alpha diversity of nektonic communities occurring in spring and autumn based on mean pairwise distance **(A)** and mean nearest taxon distance **(B)**.

TABLE 2 Results of multiple regression on distance matrices (MRM) analyses for the effect of environmental variables in phylogenetic beta diversity both at deep (D_{pw}) and shallow (D_{nn}) phylogenetic levels from spring and autumn nektonic communities in the waters of Weizhou Island.

Predictor	D_{pw}		D_{nn}	
	Coefficient	*p*	Coefficient	
Intercept	0.204	0.007	0.201	0.851
Chl-a	-0.005	0.216	-0.016	0.058
pH	0.065	0.145	0.071	0.406
Salinity	0.025	0.014	0.055	0.011
Dissolved oxygen	0.003	0.454	0.008	0.413
Temperature	0.002	0.027	0.008	0.006
Transparency	0.001	0.022	0.001	0.225
Depth	-0.001	0.051	-0.002	0.043
R^2	0.687	0.006	0.805	0.006

(*Decapterus maruadsi*), cardinalfish (*Apogonichthys ellioti*), and horse mackerel (*Trachurus japonicus*) (Wang et al., 2012; Wang et al., 2019; Su et al., 2022). At the end of the 1960s, the number of fishing boats and their horsepower increased with the introduction and promotion of motorboats, and fishing techniques (fish-finders and navigators) continuously improved; this dramatically increased the fishing efforts and catches. Overfishing is one of the main reasons for the decline of fish biodiversity and fishery resources in the Beibu Gulf even the South China Sea (Chen et al., 2011; Zhang et al., 2021; Su et al., 2022).

Numerous studies have revealed the importance of seasonal variations in explaining the structure and distribution of coastal nektonic communities (Hoff and Ibara, 1977; Lazzari et al., 1999; Raposa et al., 2003; Pattrick and Strydom, 2008; Ramos-Miranda et al., 2008). The results of our study further support that the environmental heterogeneity caused by seasonal variation contributes to the coastal nekton community assembly and phylogenetic diversity in the Beibu Gulf. There was distinct seasonal differentiation in both community structure and phylogenetic diversity of coastal nekton communities. A total of 64 nekton species were caught in spring, including 31, 6, and 17 species associated with fish, cephalopods, and crustaceans, respectively. Alternatively, a total of 76 nekton species were found in autumn, including 48, 7, and 31 species associated with fish, cephalopods, and crustaceans, respectively.

The fishes in the middle and northern part of the Beibu Gulf were mainly tropical and carnivorous. The changes of fish community structure in this area were mainly related to the seasonal variation of the bottom water temperature (Wang et al., 2020; Feng et al., 2021). Water temperature is a key factor that affects the distribution of fish communities because it directly affects the growth and development of fish and their traits, such as feeding, reproduction, and winter migration. Therefore, seasonal changes of water temperature resulted in seasonal differences in fish community composition. When the water temperature was low in winter, the tropical seasonal migratory fish left the coastal area of the Beibu Gulf and migrated to the deep-water area of the open sea, which resulted in the presence of mainly sedentary fish species in the Beibu Gulf in winter. In spring, the water temperature gradually warmed up, and the coastal current turned from weak to strong; this brought abundant nutrients to the coastal area, and the migratory fish began to swim to the coastal area for spawning and breeding, thus enriching the composition of fish species in the northern waters of the Beibu Gulf (Yuan, 1995; Hou et al., 2008; Wang et al., 2012; Zhang et al., 2014; Xu et al., 2021b).

In addition, the seasonal variation of fish communities in the northern part of the Beibu Gulf may also be related to the monsoon, tidal flow, coastal current, and the habitats. Upwelling along the coast of the Beibu Gulf can transport nutrient-rich bottom seawater to the middle and upper layers; this provides sufficient nutrients for the growth and reproduction of bait organisms, and thus affects the seasonal changes of fish community structure. Under the influence of the summer monsoon, there was obvious cyclonic circulation in the northern waters of the Beibu Gulf, which formed in June and reached maturity for one month. This drove the migration of fish community to the southeast (Gao et al., 2017). In spring, the coastal water force was relatively weak, which created favorable conditions for the propagation of plankton, thus driving fish to migrate to the shore. In autumn, the fish community migrated to the southeastern sea area under the influence of the anticyclonic circulation in the southern Beibu Gulf (Gao et al., 2015). In winter, when the water temperature drops, the seasonal migratory fish migrated to the open sea, and fish richness decreased. The inshore sea area was dominated by sedentary fish.

In general, the large-scale distribution patterns of fish or nektonic communities are primarily influenced by oceanographic factors, such as circulation, tidal flow, and coastal currents, which can greatly affect on larval dispersal distance and bait organism distribution (Norcross and Shaw, 1984; McClanahan and Arthur, 2001). However, at small spatial or regional scales, such as coastal, coral reef, or estuarine ecosystems, the distribution and composition of nektonic communities are also associated with stochasticity in nektonic community structuring (Letourneur et al., 2003; La Mesa et al., 2011; Xu et al., 2021a). Our results showed that the average phylogenetic diversity of autumn nektonic communities was significantly higher than that of spring nektonic communities. Positive NRI values in spring nektonic communities indicated phylogenetic clustering, whereas negative NRI values in autumn nektonic communities indicated phylogenetic overdispersion. These results indicated that stochastic processes play a strong role in structuring nektonic communities of the northern waters of the Beibu Gulf.

In late spring, fishing intensity becomes stronger in the northern waters of the gulf as fishermen from both China and Vietnam try to catch as many fish as possible, especially some commercial species, in a shorter period of time using more efficient equipment and methods (such as a lot of artisanal shrimp trawlers) (Yu and Mu, 2006; Vu, 2013; Tian et al., 2022). In our case, the total catch density declined to 291.9 kg per km^2 in spring, which was only approximately 1/3 of the fishery resource density in autumn. Fishing intensity acted as an environmental filter, leading to coexistence of closely related species, and remarkable phylogenetic clustering was found in nektonic communities of this area. Therefore, fishing intensity had a greater impact on nektonic community, and even exceeded the effect of environmental factors.

The northern Beibu Gulf, like other coastal areas of China, faces overexploitation and depletion of fishery resources. Because of the combined effects of marine and coastal resource overexploitation and marine pollution, many highly productive coastal and offshore fisheries have disappeared or relocated far from the country's coastlines (Zhong and Power, 1997). To improve this situation, the Chinese government implemented a series of corresponding management regulations and protection policies. First, they introduced the fishing license system. The Chinese government recognized that depletion of coastal and offshore fishery resources was due to a lack of effective management and overcapacity in fishing vessels. Since 1979, the government has controlled the national fishing capacity through the fishing license system. All fishing vessels were required to obtain licenses from the government before fishing. Second, the government introduced a mid-summer fishing moratorium. China's Ministry of Agriculture has instituted a fishing ban from May to August every year since 1998 across a large area of the South China Sea north of latitude 12°N. The annual fishing ban covers the spawning season for most fish and invertebrates, mainly in the summer, and is therefore known as the "mid-summer fishing moratorium" (Yu and Yu, 2008). Third, they signed agreements for fisheries management with neighboring countries. For the Beibu Gulf, China and Vietnam signed a fishing agreement to peacefully settle their fishing disputes and maintain lasting stability of the fishing communities (Yu and Mu, 2006). Under comprehensive management, the summer fishing intensity in the Beibu Gulf was controlled to the maximum extent possible, and nektonic diversity and fish stocks were effectively recovered and recruited from the larval pool. However, we still have a long way to go to restore the fishery to levels of 1970s even 1960s. This can be achieved through demonstrated management and restoration methods and experiences from others cases around the world (Moland et al., 2021; Kemp et al., 2023).

Conclusion

The nektonic communities in the waters of Weizhou Island in the northern Beibu Gulf showed significant seasonal patterns in average catch density, community structure and phylogenetic diversity. Phylogenetic diversity of nekton community obviously increased from spring to autumn, while phylogenetic patterns changed from clustering to overdispersion. The seasonal patterns of nektonic communities were mainly related to the different fishing intensities in the two seasons. Nektonic communities benefited from the mid-summer fishing moratorium, when the fish stocks rapidly recovered. We propose that fishing intensity had a greater impact on nektonic community at small spatial scales, even exceeding the effect of environmental factors. Our research also provided insights into effective future fishery management practices in the Beibu Gulf.

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.

Ethics statement

The animal study was reviewed and approved by South China Sea Fisheries Research Institute, Chinese Academy of Fishery Sciences.

Author contributions

LX: Conceptualization, Methodology, Formal analysis, Data curation, Writing - original draft, Writing - review and editing. QT, LW, JN, DH, YL, and SL: Methodology, Formal analysis. XW and FD: Funding acquisition, Project administration, Resources. All authors contributed to the article and approved the submitted version.

Funding

This study was funded by Hainan Provincial Natural Science Foundation of China (422MS156), Science and Technology Basic Resources Investigation Program of China (2018FY100105, 2017FY201405).

Acknowledgments

We thank all colleagues and students for their help with sampling. We thank Mallory Eckstut, PhD, from Liwen Bianji (Edanz) (www.liwenbianji.cn) for editing the English text of a draft of this manuscript.

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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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2023.1133462/full#supplementary-material

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frontiers | Frontiers in Marine Science

TYPE Original Research
PUBLISHED 10 February 2023
DOI 10.3389/fmars.2023.1112487

Check for updates

OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Marine Conservation and Sustainability, a section of the journal Frontiers in Marine Science

RECEIVED 30 November 2022
ACCEPTED 30 January 2023
PUBLISHED 10 February 2023

CITATION
Lu J, Zhang Y, Shi H and Lv X (2023) Spatio-temporal changes and driving forces of reclamation based on remote sensing: A case study of the Guangxi Beibu Gulf. *Front. Mar. Sci.* 10:1112487.
doi: 10.3389/fmars.2023.1112487

Spatio-temporal changes and driving forces of reclamation based on remote sensing: A case study of the Guangxi Beibu Gulf

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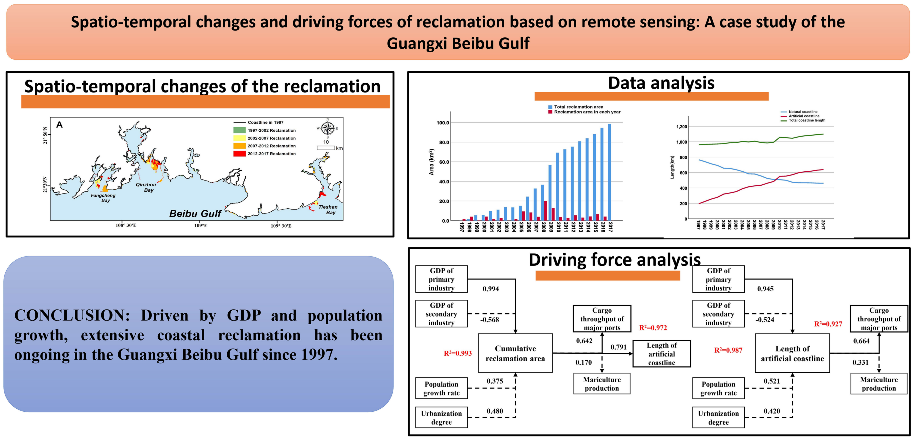
Since 2000, coastal reclamation projects have been implemented in the Guangxi Beibu Gulf to alleviate the shortage of coastal land resources. As a result, the reclamation area has increased significantly. In this study, based on the Landsat program, we tracked coastal reclamation in the coastal waters of Guangxi in the 21st century. An indicator system was proposed to assess the driving forces of reclamation synthetically. Our results showed that 98.6 km^2 of coastal waters of the Guangxi Beibu Gulf was reclaimed from 1997 to 2017, in which three regions underwent great changes: Fangcheng Bay, Tieshan Bay, and Qiznhou Bay. Furthermore, spatio-temporal changes of reclamation were affected by the combination of population growth, economic development, and marine industry development in coastal cities. These results provide an important historical reference for tracking the human development processes of the Guangxi Beibu Gulf, and also offer some suggestions for the rational allocation of reclamation resources.

KEYWORDS

coastline changes, reclamation, driving factor, linear regression, path analysis



GRAPHIC ABSTRACT

1 Introduction

Coastal reclamation, one of humankind's most radical modifications of the ocean, is motivated by a growing demand for land resources. Multiple driving factors, including coastal and foreshore defenses (Herbeck and Flitner, 2019), residential and commercial developments (Chee et al., 2023), and growing coastal populations and infrastructure needs (Bisaro et al., 2020), such as airports or ports (Suzuki, 2003; Wang et al., 2014), have resulted in large scales of land reclamation. For example, Chee et al., 2023, demonstrated that the need to develop and modernize was the main driver cited as reasons to reclaim Malaysian coastlines. Suzuki, 2003, showed that in Japan the topography and the requirement for residential, commercial, and industrial development contributed to the need to expand into the sea. Further, port expansions are also a driver for coastal reclamation (Muller et al., 2020; Lin et al., 2021), In addition, the rapid expansion of the coastal economy and accelerated coastal population growth in the Bohai Sea have caused a sharp increase in land reclamation (Temmerman et al., 2013). Moreover, many coastal countries, including America (Kennish, 2001), China (Ma et al., 2014), Singapore (Powell, 2021), and Malaysia (Chee et al., 2023), have conducted coastal reclamation for urban development. Therefore, the drivers of land reclamation are often multitudinous, so accurate evaluation of these factors is important for marine management.

According to the world's first map of the physical footprint of marine construction, Bugnot et al. (2020) noted that coastal reclamation was continuing to spread and taking up more and more of the global ocean area in 2020; China is the economic zone with the most oceanic construction (accounting for 40% of the global ocean construction) since its reform and opening up in the early 1980s. Studies showed that the majority of China's reclamation was concentrated in the Bohai Sea, Yangtze Estuary Delta, and Pearl River Delta (Tian et al., 2016). However, reclamation activities also increased significantly in the Guangxi Beibu Gulf, where a large amount of land was needed for urban construction, further harbors, farmlands, and aquaculture ponds within the development of the Beibu Gulf Economic Zone (Sun et al., 2020; Zhao et al., 2021; Lyu et al., 2022). The drivers of land reclamation are often multitudinous, so accurate evaluation of these factors is important for marine management.

The Guangxi Beibu Gulf is located in the northwestern part of the South China Sea. It is bounded by the Leizhou Peninsula and Hainan Island to the east, the Guangxi Zhuang Autonomous Region to the north, and Vietnam to the west. It is connected to the South China Sea *via* the Qiongzhou Strait. (Lao et al., 2021). Compared with other coastal areas in China, the development and exploitation of marine resources in the Beibu Gulf started relatively later due to the particularities of its geographical location. However, after years of development and construction, the Guangxi Beibu Gulf Economic Zone has become a multi-regional cooperation center and the leader of Guangxi's opening-up policies, and been incorporated into China's national development strategy (Han et al., 2018). For the past two decades, the Guangxi Beibu Gulf has experienced extreme coastal reclamation, which has resulted in the significant loss of coastal wetlands and degradation of the natural shoreline; this poses significant challenges to its ecological environment and the ecosystem service functions, especially the widely distributed and typical coastal wetlands with mangroves and seagrass beds within the coastal waters of Guangxi in the Beibu Gulf (Sun et al., 2020).

Previous studies on the reclamation of the Guangxi Beibu Gulf have mainly focused on coastline changes (Yu et al., 2021), hydrodynamic changes (Wang et al., 2021), and pollutant discharge (Lyu et al., 2022). At present, there have been no attempts to derive a consecutive-yearly estimate of the extent of reclamation and its driving factors. Some studies have already discussed the relationship between reclamation and socio-economic factors. For example, Tian et al. (2016) analyzed and quantified the spatio-temporal variation of reclamation in China, and found that high-intensity coastal reclamation was mainly driven by the booming economy, especially after 2000, which was associated with urbanization and industrial development in China's coastal region. Meng et al. (2017) found that marine industrial development and industrial wastewater discharge had a positive correlation with sea reclamation. Hence, the most complete assessments of driving factors on the reclamation should consider multiple statistical data, such as gross economic product, human population density, and marine industry development.

More recent remote sensing images have provided a unique opportunity to investigate the distribution of reclamation activities in the Guangxi Beibu Gulf coast from 1997 to 2017. We accurately measured the position of reclamations derived from two remote sensing images (Path/Row: 125/045,124/045), a composite ground truth that ideally aggregates images from the same month taken by Landsat (Figure 1A). Subsequently we provide a new evaluation indicator system for the assessment of the driving force factors of reclamation. The hypothesis that GDP and population growth have significant effects on reclamation in coastal cities was supported in our study. The general objective of this paper was to comprehensively evaluate the impacts of driving forces on reclamation in near-coastal waters of the Guangxi Beibu Gulf. The specific objectives were: 1) to draw a diagram of the spatio-temporal changes of near-coastal reclamation in coastal waters; 2) to explain the initiation mechanisms of reclamation intensity and its changes from the factors of population, economy, urbanization, and industrialization. The results of this study will provide some references for the development and protection of the Guangxi Beibu Gulf coast.

2 Materials and methods

2.1 Studied area

The Guangxi Beibu Gulf is located in the northwestern part of the South China Sea and bounded by the Leizhou Peninsula and Hainan Island on the east (Figure 1). The Beibu Gulf is an important newly developing industry and port area. It has some bays, including Fangcheng Bay, Qinzhou Bay, Lianzhou Bay, and Tieshan Bay (Zhu et al., 2022). The main types of natural coastlines include coral reefs, intertidal silt, and mangrove swamps, which are mostly found on the west coast of the Guangxi Beibu Gulf, and about 80% of rock coasts are on the east coast; the rest are sand and silt coasts (Sun et al., 2020). With the increase in development intensity, the natural coasts of the Beibu Gulf are being damaged at an alarming rate (Zhao et al., 2021).

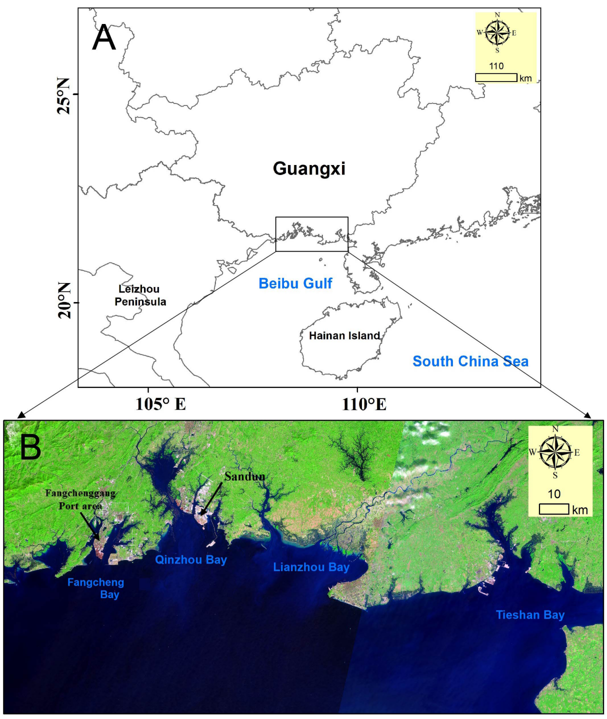


FIGURE 1
Map showing the location of the study area **(A)**. The main bays and two reclamation projects **(B)** are noted on Landsat images (captured on 22 Oct 2017).

In recent years, reclamation activities have increased in the Beibu Gulf due to its special location and unique natural resources. Consequently, the land-use types have been remarkably changed. For example, the Nanliu River estuary delta has been used for aquaculture activities, and Qinzhou Harbor (32.5 km^2) was reclaimed for residential and commercial developments in Qinzhou City (Lyu et al., 2022). This study involved three cities, including Fangchenggang City, Qinzhou City, and Beihai City in Guangxi Province, China, with a total regional GDP of 103.5 billion RMB and a total population of 24.6 million (Guangxi Statistical Yearbook, 1995–2015).

2.2 Data resource

The data used in this study were mainly from the following four resources: remote sensing image data from the geospatial data cloud (http://www.gscloud.cn) (Table 1); vector data (including the length of artificial coastlines, natural coastlines, reclamation areas, and their utilization types) extracted from the Geographic Information System (Versions: ArcGIS. 10.1); statistical data from the China Marine Statistical Yearbook (1997-2018) and the Statistical Yearbooks of Guangxi Zhuang Autonomous Region (1997-2018); Google Earth Pro 7.3 data as a geographical reference for identifying and correcting marine constructions such as ports, wharves, and dams.

In this study, we present new interpretation signs of reclamation based on remote sensing images and the knowledge of the morphological features, vegetation, and coastal engineering characteristics (shape, size, color, and texture). Herein, the technological framework is shown in Figure 2. The goals are: 1) to identify the extent of existing coastal reclamation by establishing interpretation signs in the Guangxi Beibu Gulf; 2) to reveal the characteristics of the spatio-temporal changes of the coastline and reclamation; and 3) to identify the driving forces of reclamation.

2.3 Remote sensing image processing

Twenty-one remote sensing images of the Guangxi Beibu Gulf reclamation area were used in this study. Table 1 shows detailed information on the land satellite image data. The radiometric calibration, geometric correction, band fusion (including bands 3, 4, and 5), image mosaic, and image cutting of the land satellite image data were conducted according to ENVI 5.3.

Coastline: the coastline data of the Guangxi Beibu Gulf from 1997 to 2017 were processed using ArcGIS10.1 software. According to the method from Sun et al. (2020), the coastlines were divided into natural coastlines and artificial coastlines. Natural coastlines mainly include bedrock coastline, sandy coastline, muddy coastline, estuary coastline, and biological coastline, and artificial coastlines mainly include port coastline, mariculture pond coastline, and transportation coastline; the interpretation rules used in this study were the same as

TABLE 1 List of land satellite image data of the Guangxi Beibu Gulf.

Region	Year	Image sensor	Path/Row	Spatial Resolution
Beibu Gulf	1997-2017	Landsat5 TM, Landsat7 ETM, Landsat8 OLI.	125/045, 124/045	30 m

Sun et al. (2020). Additionally, the extracted coastline was the instantaneous boundary between water and land, and the impact of tides on coastlines was not considered.

Reclamation: based on the knowledge of the morphological features, vegetation types, and development and utilization status, we established the relationship between the remote sensing image shape, size, color or tone, shadow, location, structure, texture, and other features and corresponding interpretation types. Then, the reclamation types were classified through visual interpretation of the remote sensing images as: ponds, industrial and urban land, ports, breakwaters, and cross-sea bridges. The details are shown in Table 2.

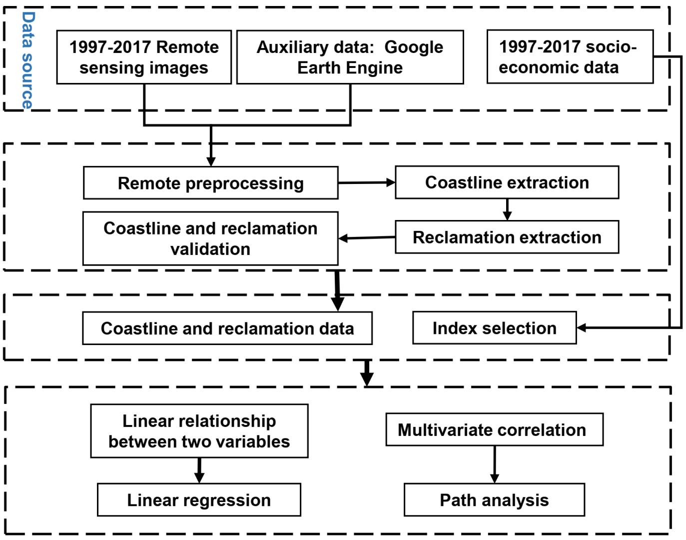
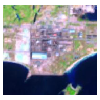


FIGURE 2
Method flow chart of the study.

TABLE 2 Interpretation signs for different types of reclamation and utilization.

Reclamation Types	Sign	Description of interpretation sign (band 543)
Pond		Dark blue or bluish-white, uniform tone, clear texture, flaky or striped distribution
Industrial and urban land		Pink, blue-gray, uneven tone, rough texture, irregular shape, flaky distribution, covered by vegetation
Port		Clear gray texture, generally small in width, distributed in places where water and land meet directly
Cross-sea bridge		Cross-sea bridges with clear gray texture, coherent water waves on both sides, and projections on the sea surface
Breakwater		The textures of breakwaters are blurred, gray, mostly in strips, and perpendicular to the land.

Validation: The extraction accuracy of reclamation was assessed by comparing the outputs with Google Earth imagery. A total of 100 control coordinate sites that covered all reclamation types were collected from Google Earth images to verify the accuracy of the visual interpretation of the reclamation. The overall accuracy was 97%, which indicated good performance.

2.4 Driving force analysis

2.4.1 Index selection

In China, economic development, population growth, agricultural requirements, and other industries contribute to the need to expand into the sea (Chee et al., 2023; Tian et al., 2016). On the basis of the preceding description, a hierarchical assessment indicator system was established (Table 3), and the definition of indicators was presented using Statistical Bulletins.

2.4.2 Statistical analysis

Linear regression refers to the dependent variable as a linear function of one or more independent variables, subject to a random “disturbance” or “error” term (Ruivo et al., 2022). This method has been a widely used technique in finance and environment research with its advantages of simplicity in application, efficiency in computation, and ease of interpretation (Thompson et al., 2006; Gilli et al., 2019). In this study, linear regressions were applied to assess reclamation using continuous yearly variables, such as gross domestic product, population growth rate, urbanization degree, mariculture production, and cargo throughput. In this study, linear regression analysis was performed using SPSS 19.0 software.

Path analysis is an extension of multiple regression that can be used for investigating direct and indirect relationships between variables and latent variables (Wood and Brodie, 2016; Bello et al., 2020). Model fit is measured using the coefficient of determination (R^2), and a high R^2 indicates the goodness of fit of model equations. In this study, path analysis was performed to determine the overall effect of socioeconomic factors on reclamation, and the expected model of causal factors upfront was proposed as shown in Figure 3.

3 Result

3.1 Reclamation expansion

The development process of reclamation in the Guangxi Beibu Gulf is shown in Figure 4A. The increase in the cumulative reclamation area in the Guangxi Beibu Gulf was 98.6 km^2 from 1997 to 2017, and the accumulated area of reclamation from 2007 to 2017 accounted for 82.3% of its total reclamation since 1987. This illustrated that large-scale reclamation activities in the coastal waters of Guangxi in the Beibu Gulf began after 2007, and happened mainly in three regions that have undergone great changes, particularly in Qinzhou Bay (42.5%) and Fangcheng Bay (20.7%) (Figure 4A). In Fangcheng Bay, the natural coastline was used for urban development and port land after 2001. In Qinzhou Bay, two nearly 7 km-long

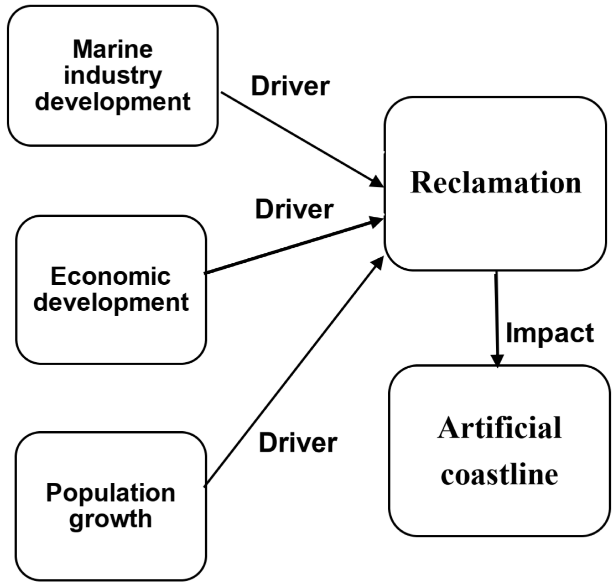


FIGURE 3
A path analysis model of the reclamation.

TABLE 3 Evaluation index system of the driving force factors of the reclamation.

First-grade indicators	Second-grade indicators	Definition
1.Economic development	1. GDP of primary industry	the end result of agricultural economic activities (including farming, forestry, animal husbandry, and fishery).
	2. GDP of secondary industry	the end result of industrial economic activities (including mining and quarrying, manufacturing, and electricity, gas, and water production and supply).
2.Population growth	3. Population growth rate	the rate of population growth caused by natural and migration changes over a given time period (usually within a year).
	4. Urbanization degree	the urban population as a percentage of the total population.
3.Marine industry development	5. Mariculture production	the output of aquatic products whose young are artificially released or naturally collected, raised, and managed artificially, and which are caught from the waters of mariculture.
	6. Cargo throughput	the weight of the cargo being loaded and unloaded.

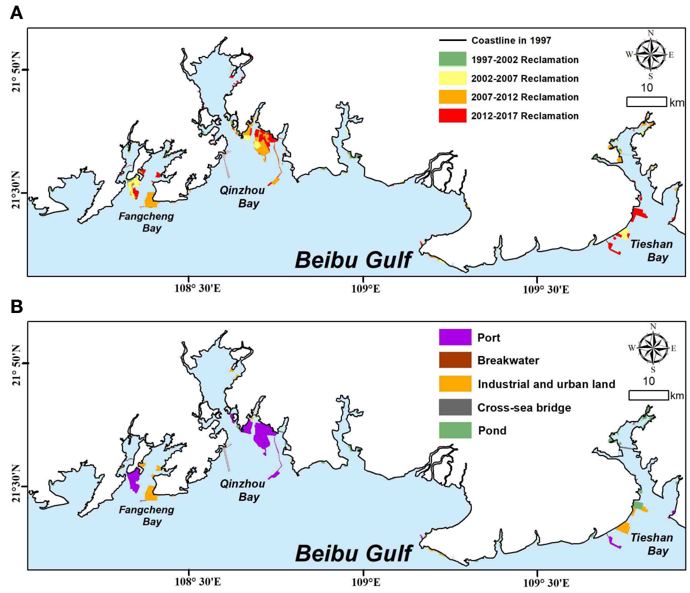


FIGURE 4
Spatio-temporal change of reclamation and its use types.

breakwaters were located on the western coast, which connect to the land and aim to protect the coast; additionally, a large reclamation project in Qinzhou Bay for urban and industrial use named Sandun covered an area of approximately 30 km^2. The third region is located in Tieshan Bay, where three reclamation projects have been completed since 2001.

Figure 4B presents the areas of each coastal reclamation type along the Guangxi coast. Of all the reclamation projects, 44.8% could be attributed to ports. The ports, industrial and urban areas, ponds, cross-sea bridges, and breakwaters accounted for 30.9%, 20.3%, 2.4%, and 1.6% of the total reclaimed area within the Guangxi Beibu Gulf, respectively.

Figure 5 illustrates the cumulative areas of coastal reclamation in the Guangxi Beibu Gulf over the previous 20 years. It could clearly be seen that the rate of increase in reclamation in Guangxi first increased and then decreased from 1997 to 2017, reaching a peak of 54.1 km^2 and with an average of 10.8 km^2 per year over 2006-2010. After 2010, the rate of growth slowed significantly, with an average of 3.7 km^2 per year from 2010-2017.

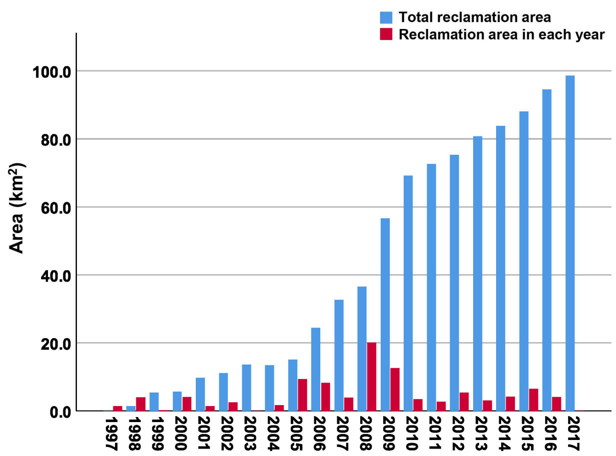


FIGURE 5
Changes in reclamation area from 1997 to 2017.

3.2 Reclamation-induced coastline change

As shown in Figure 6, in 1997 the coastline was mainly natural coastline, such as mangrove, beach, and estuary coastlines, accounting for 79.7% of the total coastline length of the Guangxi Beibu Gulf. After 2007, the length and proportion of the urban and industrial coastline and port coastline increased significantly, making the artificial shoreline jump from 20.3% (1997) to 58.1% (2017). In the past 20 years, natural coast has been reclaimed throughout the gulf, with three areas of particular concern: one in Fangcheng Bay (Figures 6A, E), another in Qinzhou Bay (Figures 6B, F), and the third is a large-scale breeding pond constructed after 2000 in the Nanliu River estuary, which was converted from unused land (Figures 6C, G). In terms of spatial distribution, the natural coastline was mainly distributed in the western parts of Fangcheng Bay and western parts of Qinzhou Bay, and the artificial coastline mostly distributed in Tieshan Bay, the eastern parts of Fangcheng Bay, and the coastal waters of the Nanliu River.

It is obvious that reclamation can greatly change the coastline length and type. For example, Landsat satellite data enabled us to obtain the coastline changes for large areas, i.e., bays like Qinzhou and Fangcheng, in a relatively short period of time. In addition, reclamation can also reshape the geometrical morphology of coastlines, such as the Nanliu River estuary where the natural coastline was converted to a pond coastline. This showed that the artificial coastline length and total coastline length had increased during the 20-year period (Figure 7), while the natural coastline showed a slow but steady decrease from 1997 to 2017. We further analyzed the trend of the artificial coastline increase and noted a sharp

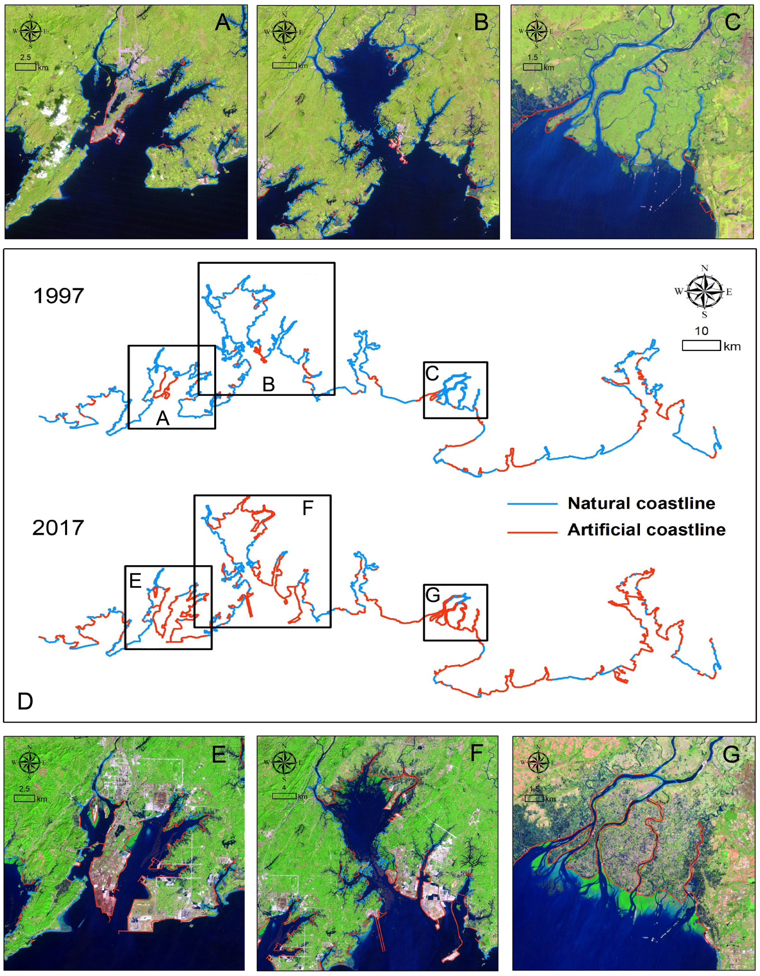


FIGURE 6
Spatio-temporal changes of the coastline in the Guangxi Beibu Gulf in 1997 and 2017 **(D)**. The natural coast has been reclaimed throughout the entire gulf, where three regions have undergone great changes that were recorded by remote sensing observation, including: remote sensing images of Fangcheng Bay in 1997 **(A)** and 2017 **(E)**; remote sensing images of Qinzhou Bay in 1997 **(B)** and 2017 **(F)**; and remote sensing images of Nanliu River estuary in 1997 **(C)** and 2017 **(G)**.

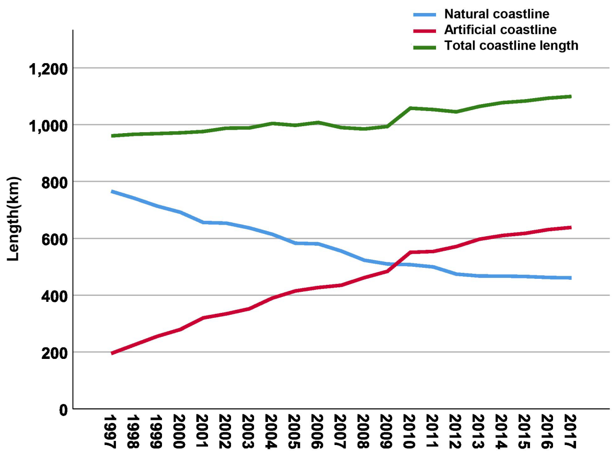


FIGURE 7
Changes in coastline length from 1997 to 2017.

increase before 2010. It increased by 2.8 times from 195.1 km in 1997 to 550.6 km in 2010.

3.3 Driver forces of reclamation

In the linear regression model of reclamation (Figures 8A–C), the high R^2 for both GDP of primary industry (R^2 = 0.952) and degree of urbanization (R^2 = 0.907) indicated these factors have promoted reclamation. It was clear that the growth of the GDP of the primary industry and the degree of urbanization was positively correlated with the area of reclamation, which significantly increased. In the linear regression model of artificial coastlines (Figures 8D–F), the high R^2 for both GDP of the secondary industry (R^2 = 0.919) and the degree of urbanization (R^2 = 0.977) indicated these factors have promoted artificial coastlines.

In the path analysis of the Guangxi Beibu Gulf reclamation model (Figure 9A), the GDP of the primary industry had the largest

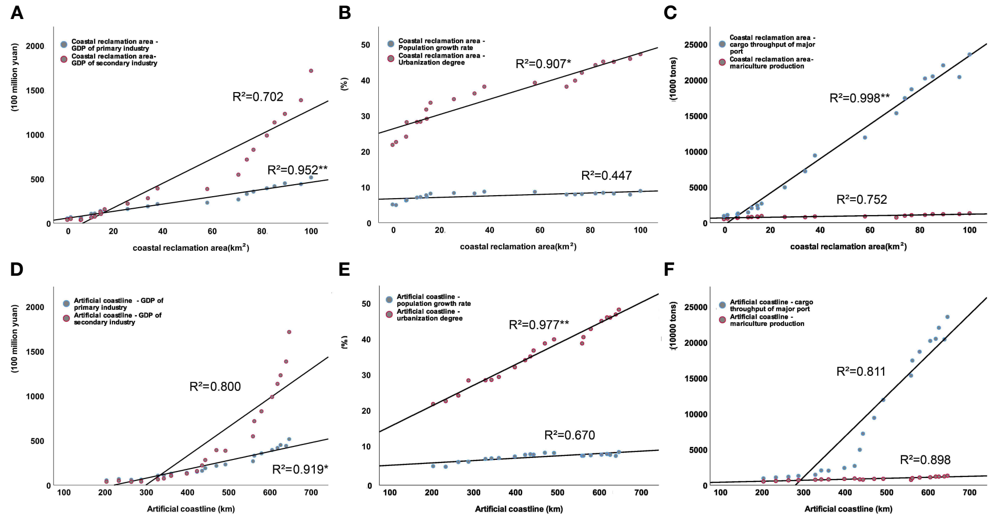


FIGURE 8
Linear regression between coastal reclamation and socio-economic factors, including economic development **(A)**, population growth **(B)**, and marine industry development **(C)** in coastal cities. **(D–F)** denotes the linear regression between coastline change and socio-economic indicators.

influence on the cumulative reclamation area (standardized betas of the regression equations: 0.994). The population growth rate and degree of urbanization both had a positive influence relationship with the cumulative reclamation area, the standardized betas of which being 0.480 and 0.375, respectively. However, our hypothesis concerning economic contribution was inconsistent with secondary industry GDP. In this model, the GDP of secondary industry had a weakly negative relationship with cumulative reclamation area (standardized beta: −0.356) and the length of artificial coastlines (standardized beta: −0.524); this was because the expanded reclamation that gradually moved toward industrialization had a low population, GDP, and urban development area before any infrastructure-related to industry was built. Moreover, the cumulative reclamation areas showed positive effects on the length of artificial coastlines and the cargo throughput of major ports, with standardized betas of 0.791 and 0.642, respectively. In the path analysis of the Guangxi Beibu Gulf coastline models (Figure 9B), the GDP of primary industry also had the largest influence on the length of artificial coastlines (standardized betas: 0.945). Artificial coastlines were found to have a positive direct effect on the cargo throughput of major ports (standardized betas: 0.664).

4 Discussion

4.1 Verification of reclamation and its driving forces

This study encompassed a 21-year record and 42 remote sensing images of the Guangxi Beibu Gulf. Importantly, these remote sensing images provided insights into the changes in coastline at different temporal and spatial scales, especially in bays where artificial reclamation was significant. Throughout the entire 21-year record, approximately 36.1% of the coastline exhibited statistically significant man-made reclamation, which occurred in river estuaries and bay mouths (Figure 6). Furthermore, the percentage of artificial coasts rose rapidly from 42.5% in 1997 to 72.7% in 2017, as a result of high-intensity human activities including reclaiming land from the sea. We compared results over the same period and found that the overall error was 4.1-9.8% (Sun et al., 2020). The causes of the conversion of natural shorelines to artificial shorelines included reclamation and land-use changes. Based on the result for the area, reclamation was the dominant factor leading to the change of coastline, and its contribution rate reached 62.9% (Figure 6).

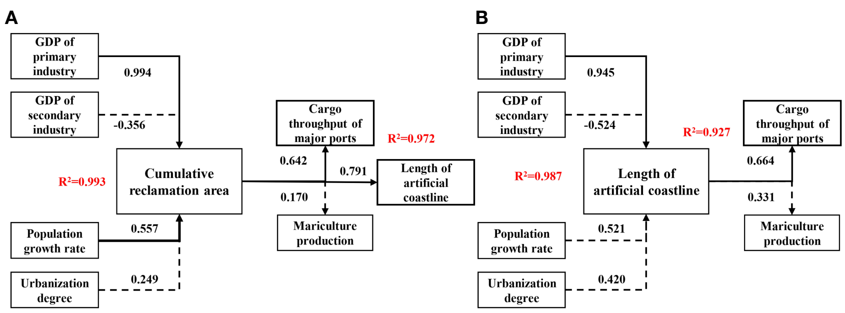


FIGURE 9
Path analysis to estimate the reclamation **(A)** and artificial coastline **(B)** and relationships between socio-economic factors. Numbers show the standardized betas of the regression equations. Solid lines indicate that the effect is significant; dotted lines indicate that the effect is insignificant. The R^2 for all the equations was high and ranged between 0.927 and 0.993, indicating good performance.

According to the results of the linear regression modeling, GDP development was the main reason for the change of coastal reclamation in the Guangxi Beibu Gulf, which was consistent with previous studies in other coastal regions of China (Wang et al., 2014; Chen et al., 2017). However, the driving mechanism of coastal reclamation is complicated (Meng et al., 2017). Meng et al., 2017 confirmed that the employees in marine industries and areas of mariculture had a positive effect on the change of coastal reclamation in China. Jiang et al., 2021 further found that policy implementation controlled and limited the scale of coastal reclamation. In addition, the driving forces of reclamation in the world have already been studied by other scholars. The study by Chee et al. (2023) showed that the rise in human populations, urbanization, and reduction in construction costs led to a large amount of reclamation in Malaysia. In the United Kingdom, approximately 6,500 ha of the Shannon estuary lowlands have been reclaimed for agricultural development (Healy and Hickey, 2002). As a result, a variety of socioeconomic factors influence land reclamation. We aimed to provide a new index system that evaluated the socioeconomic factors driving land reclamation. The path analysis is capable of exploring the driving forces of reclamation projects using varying regression equations, and the findings showed that population growth, economic development, and marine industry development all influenced the spatio-temporal changes in reclamation in the Guangxi Beibu Gulf.

4.2 Economic benefits of reclamation

The Guangxi Beibu Gulf is one of the most important economic zones in China. However, its limited land supply has led to insufficient space for its urban expansion, especially on the west coast of Qinzhou Bay and the south coast of Fangcheng Bay which both contain mangrove, muddy, sandy shoals, and low-level terrain. In order to obtain expanded space for further developments in ports and ponds, intensive reclamation projects have taken place in these regions (Figure 4B). Since 1997, two large-scale reclamation activities have also occurred and led to the industrial development of cities around the Beibu Gulf. There has been a stark increase in the number of coastal reclamation projects for aquaculture ponds, breakwaters, port terminals, cross-sea bridges, and industrial developments in the coastal cities. According to statistics, from 1997 to 2017, the cargo throughput of the main ports of Guangxi increased by 11.6 times, and the aquaculture production increased by 3.3 times (China Marine Statistical Yearbook). With the exploitation of reclamation, the growth of the marine industry has gradually taken the lead in coastal cities' overall economic expansion.

4.3 Other driving force

The reclamation in Guangxi has grown rapidly since 2006, at an average of 10.8 km^2 per year from 2006-2010. After 2010, the rate of growth slowed significantly, with an average of 3.7 km^2 per year from 2010-2017. This decreasing trend was highlighted as the reason the Beibu Gulf has vigorously developed ports and tourism to drive economic benefits in the past seven years. Although the extension of Qinzhou and Fangcheng ports to the sea area is limited, more emphasis has been placed on port expansion after 2010 than on reclaiming coastal land for ponds and construction land in the Guangxi Beibu Gulf. This was the major reason for the declining trend in the yearly reclamation area in the Beibu Gulf region. In addition, the spread of land reclamation also became relatively sluggish to safeguard the environment and ecology (Zhao et al., 2021).

From the path analysis between the reclamation area and indicators (Figure 9), it was found that socio-economic factors had significant effects on reclamation which, in turn, promoted marine industrial development and increased revenue. However, the evaluation index system of the driving force factors of the reclamation may have some limitations that need to be improved in future studies: economic development, population growth, and marine industry development were focused on without the consideration of the unquantifiable indicators, such as institutional policies and technical measures (Chee et al., 2023). For example, the implementation of the '2006 Beibu Gulf Development Plan' provides a good opportunity and platform for the development of ports, logistics, and coastal industry; the reduction in construction costs brought about by technological advancements has also made land reclamation more appealing to investors (Miao and Xue, 2021).

4.4 Suggestions for coastal reclamation

Although coastal reclamation projects conducted along the Guangxi coast have boosted economic development, they have also inevitably brought potential impacts on coastal zones, such as reshaping the coastline (Ma et al., 2014; Md et al., 2019), altering land-use types (Zhao et al., 2021), and changing the ecology and environment (Zhang et al., 2020; Lu et al., 2022). Management of the Guangxi Beibu Gulf is currently focused on the social and economic benefits of reclaimed land while ignoring the ecological and environmental influence. As a result, environmental pollution in reclaimed areas is becoming increasingly severe, and biodiversity is being harmed, especially in oil production areas and mariculture ponds (Chen et al., 2018; Lin et al., 2021), which are gradually becoming the primary constraint affecting the sustainable utilization of reclaimed land and the sustainable development of the coastal economy. On the basis of the Guangxi Beibu Gulf reclamation conditions, we suggest strengthening the scientific control and efficient use of coastal reclaimed land and paying attention to the combination of environmental protection and management based on adequate knowledge of the coastal and marine ecosystems. In addition, in areas of intensive reclamation, such as Fangcheng Bay and Qinzhou Bay, reclamation activities should be timely regulated and properly reduced according to regular monitoring and assessment (Shen et al., 2016).

At present, coastal reclamation is in transition from a high-intensity development stage to a more conservative and prudent stage in Guangxi. However, when it comes to resolving the conflict between the economy and land resources, coastal reclamation remains the first option. To keep regional economic development sustainable, we must weigh the benefits and drawbacks of reclamation and economic growth, and then we must implement suitable coastline reclamation measures.

5 Conclusions

The reclamation evaluation of the Guangxi Beibu Gulf indicated the following: 1) since 1997, large-scale coastal reclamation has been conducted in the Guangxi Beibu Gulf, with a total area of 98.6 km^2, of which three regions, Fangcheng Bay, Tieshan Bay, and Qiznhou Bay, have undergone great changes; 2) spatio-temporal changes of reclamation were affected by the combination of population growth, economic development, urbanization, and marine industry development in coastal cities.

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 authors.

Author contributions

JL: conceptualization, data curation, formal analysis, investigation, methodology, software, validation, visualization, writing - original draft, and writing - review and editing. YZ: data curation, formal analysis, methodology, supervision, and visualization. HS: conceptualization, funding acquisition, methodology, project administration, and resources. XL: formal analysis, methodology, writing - review and editing, project administration, and resources. All authors contributed to the article and approved the submitted version.

Funding

This study was supported by the National Natural Science Foundation of China (No.U1806214 & No.51779048) and the National Key Research and Development Program of China (No. 2018YFD0900806).

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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frontiers | Frontiers in Marine Science

TYPE Original Research
PUBLISHED 14 March 2023
DOI 10.3389/fmars.2023.1159602

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OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Marine Conservation and Sustainability, a section of the journal Frontiers in Marine Science

RECEIVED 06 February 2023
ACCEPTED 28 February 2023
PUBLISHED 14 March 2023

CITATION
Peng S, Wang X, Du F, Sun D, Wang Y, Chen P and Qiu Y (2023) Variations in fish community composition and trophic structure under multiple drivers in the Beibu Gulf.
Front. Mar. Sci. 10:1159602.
doi: 10.3389/fmars.2023.1159602

Variations in fish community composition and trophic structure under multiple drivers in the Beibu Gulf

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Introduction: Beibu Gulf is a semi-enclosed bay with important ecological and economic value of the northwestern South China Sea (SCS). It proved to be a stressed ecosystem and therefore clearly vulnerable to further external disturbances.

Methods: Data from 26 fishery bottom trawl surveys in the Beibu Gulf from 2006 to 2018 are analyzed to reveal changes in the fish abundance, dominant species composition, diversity, mean trophic level (MTL), and fishing-in-balance (FiB) index.

Results: Fish abundance decreased significantly ($p< 0.05$) with increased anthropogenic disturbance (e.g., fishing intensity and land-derived pollutants), with catch per unit effort (CPUE) decreasing from 40.69 $kg{\cdot}h^{-1}$ in 2006 to 15.84 $kg{\cdot}h^{-1}$ in 2018. Dominant species composition has changed dramatically from 2006 to 2018, with fish communities shifting from demersal to pelagic species, and from large and high-trophic-level species to small and low-trophic-level species. Meanwhile, Margalef's richness and Shannon–Wiener diversity indexes trend downward. The MTL declines from 3.82 in 2006 to 3.71 in 2018 (at 0.08 trophic level per decade), and decreasing with the decrease of the proportion of high-trophic fish and demersal fish in total catch ($p< 0.05$). A FiB index tends to be less than 0, this index declines with decreasing MTL and fish abundance ($p< 0.05$).

Discussion: Overall, fish stocks in the Beibu Gulf continue to decline and are currently overexploited. Multiple external disturbances, such as fishing (including overfishing, dominance of trawl fishery, and 'skipper effect'), habitat disturbance, pollution, and temperature changes, may have contributed to significant changes in fish communities and trophic structure in the Beibu Gulf.

KEYWORDS
fish community, diversity, trophic level, human activities, Beibu Gulf, South China Sea

1 Introduction

Coastal ecosystems are highly productive, rich in biodiversity, have sustained coastal fisheries for centuries, and support the livelihoods of millions of people globally (Barbier et al., 2011; Lau et al., 2019; Zhang et al., 2020b). In China, since the 1950s, more than 90% of the total marine catch has come from coastal waters (Shan et al., 2016). Unfortunately these waters are also becoming increasingly degraded by fishing (including overfishing, dominance of trawl fishery, and ‘skipper effect’), aquaculture, pollution, industrialization, and the effects of climate change (Crain et al., 2008; Bland et al., 2018; Han et al., 2018; Liang and Pauly, 2019), especially in semi-enclosed shallow bays (Chen et al., 2015; Shan et al., 2016; Zhang et al., 2020b).

Beibu Gulf is a natural semi-enclosed shallow bay in the northwestern SCS. Its unique geomorphology and climate render the area highly productive, and its fishery resources rich (Chen et al., 2009; Wang et al., 2012a). For instance, there are 960 fish species belonging to 475 genera and 162 families reported from the Beibu Gulf, approximately 80% of them are demersal and 20% of them are pelagic (Nguyen et al., 2013). The gulf waters is also one of four traditional fishing grounds in China, and this region is important for food security, the economy, and for employment (Chen et al., 2009; Su et al., 2021).

However, growing demand for fish products has led to increased fishing intensity within the SCS, where the total power of motorized fishing vessels has increased almost 8-fold since the 1980s (Wei et al., 2019). Among them, trawlers were dominant, and their proportion of fishery production remained stable at 40%-50% from 2006-2018 (Wei et al., 2019). At the same time, the skippers tend to target species with high-trophic-level and high value (‘skipper effect’), even though their biomass may be low (Liang and Pauly, 2019). Overfished has led to a decrease in fish abundance and diversity (Pauly et al., 1998; Zhang et al., 2020b). In addition to marine fishing, Beibu Gulf is also affected by increased regional aquaculture and pollution from land (e.g., nitrogen and phosphorus), causing significant eutrophication and red tides (Liu et al., 2019; Leng et al., 2020; Ning and Chen, 2021; Wen et al., 2022), thereby reducing fish growth rates and abundance (Cao et al., 2012; Shan et al., 2016). Meanwhile, nuclear power plants in Guangxi and Hainan province coastal areas also contribute to environmental problems, such as increased water temperature (Yu et al., 2010). Climate change may further degrade critical fish habitat, increase natural fish mortality and reduce fish stocks (Hoegh-Guldberg and Bruno, 2010; Wang et al., 2022).

Furthermore, in addition to reducing fish stocks and biodiversity, overfished affects mean trophic levels (Pauly and Liang, 2019; Su et al., 2021)—one of eight diversity metrics indicating levels of biodiversity reported by Pauly and Watson (2005). MTL has been widely used to evaluate the effects of fishing on fish communities and fisheries resource sustainability (Cury et al., 2005), and many national and international accounts have since identified it to be decreasing. For instance, the MTL in the Quanzhou Bay declined at a rate of 0.10 trophic-level per decade (Du et al., 2010), in the Persian Gulf by 0.11 trophic-level per decade (Razzaghi et al., 2017), and in the Beibu Gulf by 0.04 trophic-level per decade (Su et al., 2021).

In recent decades, studies on the Beibu Gulf fish stocks have focused on fisheries stocks (Sun and Lin, 2004; Wang and Yuan, 2008; Zou et al., 2013; Fu et al., 2019), fish community structure (Chen et al., 2006; Qiao et al., 2008), species diversity (Wang et al., 2011; Wang et al., 2012b), and biological characteristics (Wang et al., 2012a; Wang et al., 2020; Zhang et al., 2020a; Wang et al., 2021). However, few studies have examined how fish communities and trophic structure have changed in response to external stressors. We analyze fish communities and MTL in the Beibu Gulf using data from 26 bottom trawl fishery resource surveys conducted twice annually from 2006–2018. We describe successional characteristics of these communities, and provide a reference for more sustainable development of these fishery resources.

2 Materials and methods

2.1 Data sources

2.1.1 Catch data

Catch data were obtained from bottom-trawl fishery resource surveys in the Beibu Gulf (17°00’–21°45’N, 105°40’–110°10’E) in January (dry season) and July (wet season) from 2006–2018. During each survey, 52 stations were trawled (Figure 1) using a single vessel, the *Beiyu 60011* (441 kW power) and gear of 60.5-m length, 37.7-m headrope length, 40-mm codend mesh sizes, towed for ~1 h, and hauled at 3.0–4.0 kn.

2.1.2 Correlation analysis

Data for total motorized fishing vessel power in the SCS were obtained from Wei et al. (2019) and Chinese Fishery Statistical Yearbooks (Fishery Bureau of Ministry of Agriculture and Rural Affairs of China, 2006-2018). Data for total land-derived pollutants into the Beibu Gulf were retrieved from Ning and Chen (2021) and Zhu et al. (2022), and sea surface temperature (SST) for the region (105–110°E and 17–21°N) from NOAA

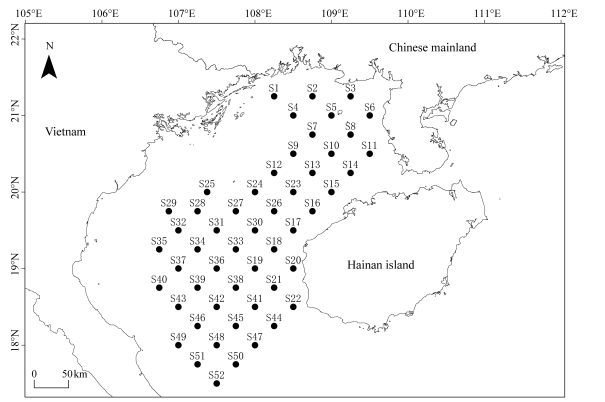

FIGURE 1
Map of Beibu Gulf survey stations (black dots) from 2006–2018, surrounded by Guangxi, Guangdong and Hainan provinces of China, and Vietnam.

(https://coastwatch.pfeg.noaa.gov/erddap/griddap/erdMH1sstdmdayR20190SQ.html). Total motorized fishing vessel power in the SCS and total land-derived pollutants and SST in the Beibu Gulf did not correlate significantly (Pearson correlation analysis, $p > 0.05$).

2.2 Data processing

2.2.1 Fish abundance

Because the survey vessel and gear were consistent from 2006–2018, we analyze CPUE normalized to a hauling speed of 3.5 kn. CPUE for each year is calculated as follows (Nishida and Chen, 2004):

$$\mathrm{CPUE}_{ik} = Y_{ik}/T_{ik}$$

where CPUE_{ik} is stock abundance at station i in year k (kg·h^{-1}), Y_{ik} is the catch at station i in year k (kg), T_{ik} is the hauling time at station i in year k (h).

2.2.2 Dominant species composition

We regard the top 10 species with the greatest proportional (%) contribution to total catch as being dominant for each year (Su et al., 2021). Interannual variation in these dominant species is assessed using dominant species replacement rate (R), calculated as follows (Yang et al., 2000):

$$R = [(a + \mathrm{b} - 2c)/(a + \mathrm{b} - c)] \cdot 100$$

where a and b are the number of dominant species in consecutive years, and c is the number of common dominant species in consecutive years.

2.2.3 Diversity indexes

We appraise diversity using the Shannon–Wiener diversity (H') and Margalef's richness (D') indexes (Young and Young, 1998). Because of considerable variation in catch existed both within species and among species, diversity expressed using catch was closer to energy distribution among species (Wilhm, 1968). Accordingly, for each index we calculate diversity using catch data as follows:

$$D' = (S - 1)/\mathrm{In}W$$

$$H' = \sum_{i-1}^{S} P_i \mathrm{In} P_i$$

where S is number of species, W is total catch (g), and P_i is the proportion of species i to the total catch.

2.2.4 Mean trophic level

We apply a trophic level of 3.5 to differentiate high from low-trophic-level species (Liang and Pauly, 2019) using trophic level reference data from FishBase (www.fishbase.org) and the Sea Around Us Project Database (www.seaaroundus.org). We calculate MTL following Pauly et al. (1998):

$$\mathrm{MTL}_k = \sum_{i=1}^{m} (TL_i \cdot Y_{ik})/Y_k$$

where MTL_k is mean trophic level in year k, TL_i is trophic level of species i, m is number of species in year k, Y_{ik} is catch of species i in year k (kg), and Y_k is total catch in year k (kg).

2.2.5 Fishing-in-balance index

Because it is not rigorous to assess the impact of fishing on marine ecosystems through changes in MTL alone, thereby we use the FiB index of Pauly et al. (2000) to independently identify 'trophic balance' in marine fisheries management. The calculation formula of FiB index is as follows:

$$\mathrm{FiB} = \log[Y_k \cdot (1/TE)^{\mathrm{MTL}_k}] - \log[Y_0 \ddot{\mathrm{A}}\mathrm{n}(1/TE)^{\mathrm{MTL}_0}]$$

where Y_k is total catch in year k (kg), TE is conversion efficiency, usually taken as 0.1 (Pauly and Christensen, 1995), MTL_k is mean trophic level in year k, and 0 is the base year (we use 2006).

3 Results

3.1 Fish abundance

CPUE in the Beibu Gulf decreased from 40.69 kg·h^{-1} in 2006 to 15.48 kg·h^{-1} in 2018 (Figure 2A). Among years, there was a wavy downward trend from 2006 to 2014 at 11.64 kg·h^{-1}·a^{-10} and a sharp decline from 2014–2018 at 29.46 kg·h^{-1}·a^{-10}. Correlations between CPUE and total motorized fishing vessel power, and total land-derived pollutants were negative (Figures 2B, C; $p< 0.05$).

3.2 Percentage of total catch with the different taxonomic groups

Figure 3 depicts interannual variation in the percentage of total catch with the different taxonomic groups in the Beibu Gulf. Figure 3A illustrates interannual trends in proportions of demersal and pelagic species, with the percentage of the former gradually decreasing over 3-year blocks of time (2006–2008 (mean 87.51%), 2009–2011 (mean 84.73%), 2012–2014 (mean 83.34%), 2015–2017 (mean 81.04%)), and remaining low in 2018 (mean 81.04%). While proportions of low-trophic-level species trended upward (Figure 3C), especially after 2010, proportions of high-trophic-level species trended downward and correlated positively with the proportion of demersal species (Figure 3B; $p< 0.05$). Moreover, the proportion of high-trophic-level species also correlated negatively with total motorized fishing vessel power (Figure 3D; $p< 0.05$), and decreased as power increased.

3.3 Dominant species composition

Dominant species composition in the Beibu Gulf changed dramatically from 2006–2018, but *Trachurus japonicus*, *Parargyrops edita*, and *Saurida tumbil* were consistently dominant (Table 1). Dominant species composition and their proportional contributions to community structure varied between years

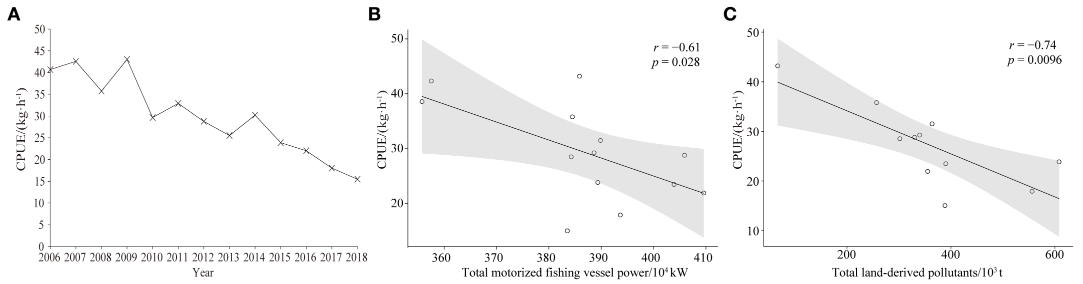

FIGURE 2
Trends of CPUE in Beibu Gulf **(A)**; and correlation analysis of CPUE with: **(B)** total motorized fishing vessel power, and **(C)** total land-derived pollutants.

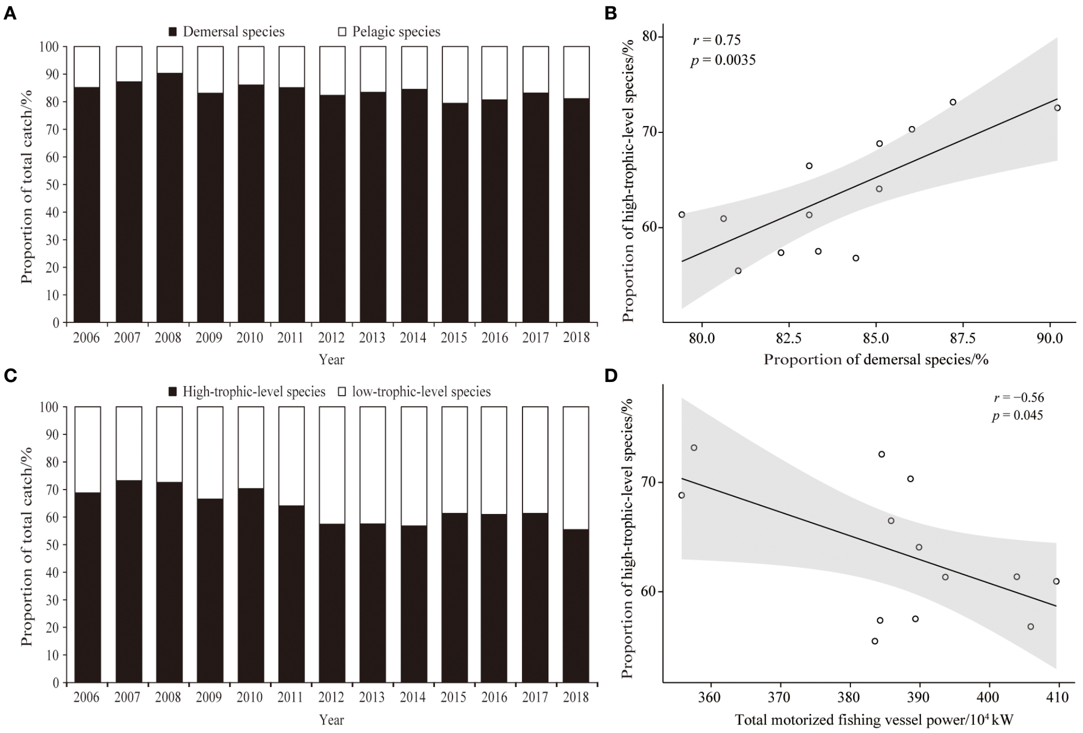

FIGURE 3
Temporal variation in the proportional contributions of demersal and pelagic species to total catch in Beibu Gulf **(A)**; correlation analysis of proportions of high-trophic-level species with demersal species **(B)**; **(C)** proportions of high/low-trophic-level species; **(D)** correlation analysis of proportions of high-trophic-level species and total motorized fishing vessel power.

(Table 1), with demersal species (e.g., *Argyrosomus argentatus*, *A. macrocephalus*, *Johnius belangerii*, *Nemipterus virgatus*) gradually disappearing, and the proportions to total catch of pelagic dominant species (e.g., *T. japonicus*, *P. edita*, *Decapterus maruadsi*) trending upward.

3.4 Diversity indexes

Diversity indexes fluctuated, but generally trended downward (Figure 4). The mean Margalef's richness index value gradually decreased from 2.83 in 2006 to 2.41 in 2012, and then gradually increased to 2.78 in 2018; the mean Shannon–Wiener diversity index gradually decreased from 2.27 in 2006 to 2.09 in 2012, and then gradually increased to 2.26 in 2018. Pearson correlation analysis revealed both Margalef's richness and Shannon–Wiener diversity indexes to correlate significantly ($p < 0.05$).

3.5 Mean trophic level

The MTL showed an overall wavelike downward trend from 3.82 in 2006 to 3.71 in 2018, decreasing by 0.08 trophic-level per decade (Figure 5A); MTL decreased from 2008–2009, 2010–2013,

TABLE 1 Variation in dominant species composition and replacement rate in Beibu Gulf.

Species	TL	percentage of total catch/%												
		2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
replacement rate/%	—		66.67	57.14	46.15	18.18	46.15	57.14	46.15	46.15	33.33	33.33	46.15	57.14
Saurida undosquamis	4.5		3.38	4.29			3.69			2.56	2.41	3.46		3.71
Trichiurus lepturus	4.4	8.96	4.33	3.92				1.92	2.48	2.96	3.41	3.05	2.86	3.79
Saurida tumbil	4.4	3.79	2.87	7.57	3.22	5.47	6.96	4.51	2.39	5.46	4.89	6.46	5.87	4.67
Muraenesox cinereus	4.4										2.82		4.36	
Argyrosomus argentatus	4.1	8.42												
Argyrosomus macrocephalus	4.1	4.33	9.82	11.69	9.74	12.07	7.52	9.00	7.90	5.32	2.91			
Johnius dussumieri	4.1		2.32											
Priacanthus macracanthus	4.1							2.61		2.52				
Nemipterus virgatus	4.0	2.36					2.36							3.96
Trichiurus brevis	4.0		2.44			3.09								
Psenopsis anomala	4.0			9.33	5.70	6.21	7.42	11.93	8.43	8.57	12.59	14.04	12.25	2.96
Epinephelus fario	4.0								2.20					
Lophiomus setigerus	4.0											2.06	2.59	
Gnathophis nystromi	3.9									2.27				4.28
Alutera monoceros	3.8				3.55	2.76								
Gastrophysus spadiceus	3.7	2.31												
Dasyatis zugei	3.5		2.85		2.75	2.98								
Therapon theraps	3.5		2.64				2.23		2.22		3.05	2.71		
Trachurus japonicus	3.4	9.73	7.99	4.02	4.88	6.21	10.58	11.14	8.09	9.11	8.87	12.78	11.30	12.73
Parargyrops edita	3.4	5.92	6.26	6.93	5.78	3.64	9.24	16.50	17.10	17.96	10.24	10.39	6.72	11.98
Decapterus maruadsi	3.4			3.48	8.14	4.45	2.12	3.96	4.99	4.08	8.37	5.11	4.65	5.60
Johnius belengeri	3.3	2.60		2.63	2.82	2.74	3.58					2.11		
Acropoma japonicum	3.3	2.26						2.38					2.52	
Dasyatis kuhli	3.3				2.15									
Upeneus sulphureus	3.1			2.45					2.21					2.89
Siganus oramin	2.8							2.43					3.12	

The symbol "—" is used to represent the meaningless value.

and 2016–2018, and increased from 2006–2008, 2009–2010, and 2013–2016. The correlation between MTL and proportion of high-trophic-level and demersal species (Figures 5C, D; $p < 0.05$) was positive, and negative with SST (Figure 5B; $p < 0.05$).

3.6 Fishing-in-balance index

The FiB index showed a wavy downward trend (Figure 6A), was closely related to changes in MTL and fish abundance (Figures 6B–D; $p < 0.05$), and decreased with decreased MTL and fish abundance. This index peaked from 2006 to 2007, and gradually declined to its lowest point from 2007–2018.

4 Discussion

4.1 Declining fish stocks

In recent decades, overfished, aquaculture, pollution, industrialization, and Climate change have all contributed to declining fisheries resources in the Beibu Gulf (Zou et al., 2013; Su et al., 2021). The decline in fisheries stocks is shown as a decrease in fish abundance (Su et al., 2021). The total motorized fishing vessel power and total marine catch in the SCS have gradually increased from 2006–2016 (Wei et al., 2019), while fish abundance in the Beibu Gulf has trended down, especially from 2014–2018 during which time CPUE decreased by 27.50 $kg \cdot h^{-1} \cdot a^{-10}$, indicating

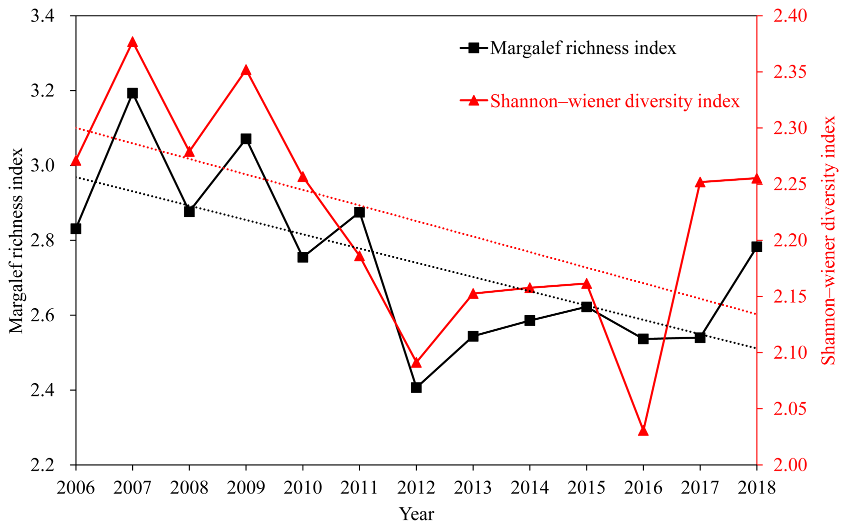

FIGURE 4
Interannual variation in fish diversity indexes, Beibu Gulf.

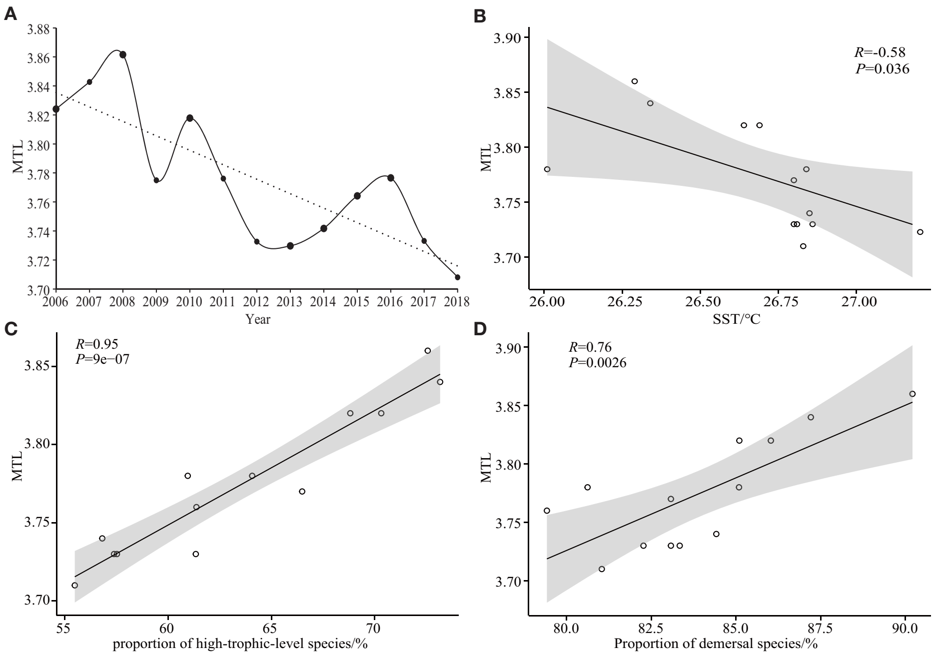

FIGURE 5
Trends in mean trophic level of Beibu Gulf fish communities **(A)**; correlation analysis of MTL with: **(B)** SST, and proportions of **(C)** high-trophic-level species, and **(D)** demersal species.

that fishing had significantly impacted fish abundance (Figure 2B; $p< 0.05$). However, the total motorized fishing vessel power and total marine catch in the SCS decreased from 2016–2018 (still at a high level) (Wei et al., 2019), while fish abundance in the Beibu Gulf declined at an increased rate, indicating that declining fish abundance was influenced by a combination of other factors.

Habitat loss may contribute to declining fish stocks (Nakagiri et al., 2001; Safina and Duckworth, 2013; Zhang et al., 2020b). Large-scale reclamation, port construction and aquaculture in the Beibu Gulf have changed coastal contours, affected sediment deposition, and altered natural habitats (Sun et al., 2020; Wen et al., 2022). Coastline in the Beibu Gulf has generally advanced seaward, and mangrove habitat has declined from the 1990 to 2007 (Li et al., 2015; Sun et al., 2020; Tian et al., 2021). Pollutants from residential, industrial and agricultural activities have also contributed to eutrophication and harmful algal blooms, significantly affecting the ecology, reducing natural habitat and losing native species (Liu et al., 2019; Leng et al., 2020; Ning and Chen, 2021).

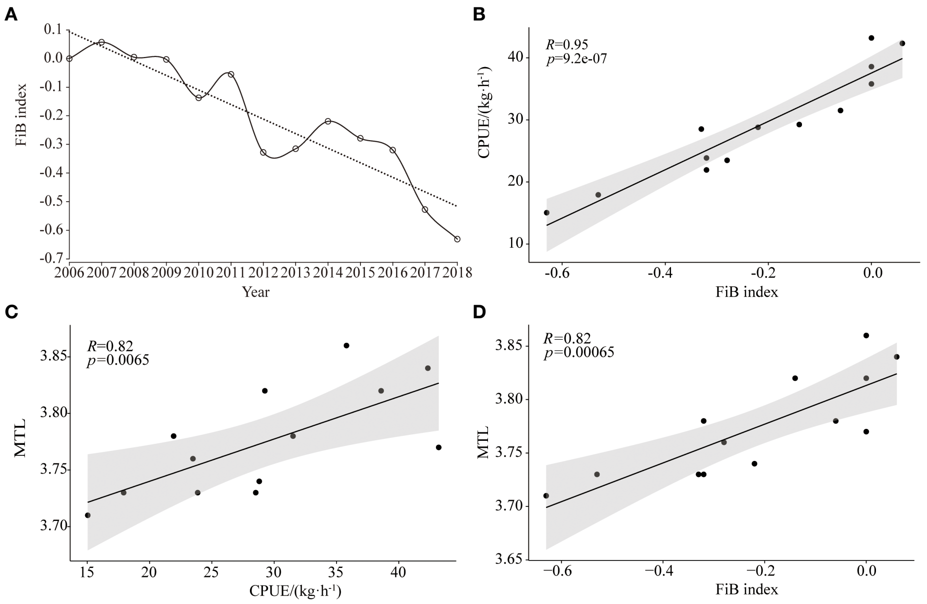

FIGURE 6
Trends in FiB index in Beibu Gulf **(A)**; and correlation analysis of: CPUE with FiB index **(B)**, MTL with CPUE **(C)**, and MTL with FiB index **(D)**.

For instance, there was a significant negative correlation between fish abundance in the Beibu Gulf and increased land-derived pollutants from 2006–2018 (Figure 2C; $p < 0.05$).

4.2 Shifts in fish community composition

Dominant species composition in the Beibu Gulf has changed dramatically between 2006 and 2018 (Table 1), with high-trophic-level species (e.g., *A. argentatus*, *A. macrocephalus*, *J. belangerii*, *N. virgatus*) gradually disappearing from the list of the 10-most dominant species, and the proportion of low-trophic-level dominant species (e.g., *T. japonicus*, *P. edita* and *D. maruadsi*) tending to increase. Moreover, the change in proportional contribution of high-trophic-level and demersal species from 2006 to 2018 is closely correlated (Figure 3B; $p < 0.05$), with the decrease in high-trophic-level species occurring with a decrease in demersal species, indicating that most demersal species were high-trophic-level species.

Overall, the fish community in the Beibu Gulf has shifted from demersal to pelagic species, and from large, commercially important, high-trophic-level species to small, lower-value, low-trophic-level species. This shift is likely because of overfishing, the dominance of a trawl fishery, and 'skipper effect,' whereby the decline in high-trophic-level species is accelerated by a captains' preference for high-value species and their attempts to maintain catch of large, high-trophic-level species (Liang and Pauly, 2019). For instance, the proportion of high-trophic-level species in the Beibu Gulf decreased with increased total motorized fishing vessel power (Figure 3D; $p < 0.05$). Obvious consequences of this overfishing are the decline in high-value species and increased difficulty in catching large, high-trophic-level species (Zhang et al., 2020b). Therefore, fisheries in the Beibu Gulf have largely shifted from large, long-lived, high-trophic-level species to small, short-lived, low-trophic-level species.

Unlike Daya Bay, another semi-enclosed marine ecosystem in China (Zhang et al., 2020b), fish communities in the Beibu Gulf have shifted from demersal to pelagic species, possibly because of the dominance of the trawl fishery. Since the 1980s, trawls have been the main fishing gear used in the SCS, with the proportion of landings from trawl fisheries to total landings generally declining each year, from 68% in 1980 to 41% in 2017 (Wei et al., 2019). Demersal species are mainly caught by trawls, reducing their number and leading to their eventual replacement by pelagic species.

4.3 Changes in fish community diversity

Margalef's richness and Shannon–Wiener diversity indexes fluctuated from 2006 to 2018, but their general downward trend indicates a gradual decrease in biodiversity in the Beibu Gulf (Figure 4). Fishing is a major contributor to declining biodiversity (Pauly et al., 1998; Zhang et al., 2020b), and overexploitation of fisheries resources in the Beibu Gulf has caused their continuous decline since the 1980s (Wang et al., 2012b; Wei et al., 2019). Rapid fishery development in the Beibu Gulf, modernization of fishing gear, and the gradual improvement of technology have progressively increased the intensity of fishing to a point that significantly exceeds the ability of stocks to recover, causing changes in community structure, and some economically important species to disappear (Liu et al., 2019; Leng et al., 2020; Ning and Chen, 2021). For instance, some high-trophic-level species (e.g., *A. argentatus*, *A. macrocephalus*, *J. belangerii*, *N. virgatus*) have gradually disappeared from the 10-most dominant species from 2006–2018 (Table 1).

Environmental pollution also affects diversity (Cao et al., 2012; Shan et al., 2016). With development of industry and agriculture, the Beibu Gulf is increasingly affected by discharged industrial wastewater and domestic sewage. Previous studies have shown that tourism, industry and transportation around the Beibu Gulf have rapidly increased pollution (e.g., inorganic nitrogen, phosphate, heavy metals) in nearshore waters, stressing coastal marine ecosystems and changing natural habitats (Liu et al., 2019; Leng et al., 2020; Ning and Chen, 2021). Habitat-sensitive species (e.g., *A. macrocephalus*, *J. belangerii*) are gradually disappearing as dominant species (Table 1).

Diversity in the Beibu Gulf rebounded between 2012 and 2018 (Figure 4). Because mangroves can absorb, filter and precipitate nutrients from land-derived runoff, they improve water quality before it reaches the sea (Fan, 2021; Liu et al., 2022). For many fish species, mangrove habitat also provides breeding grounds and refuge for juveniles, and their presence significantly and positively affects fish community structure and biomass (Fan, 2021; Liu et al., 2022). Mangrove habitat in the Beibu Gulf has increased nearly 4-fold from 2007 to 2012 and remained stable until 2018 (Li et al., 2015; Ning and Chen, 2021; Deng et al., 2022). There appears to have been a 5-year lag in recovery in the Margalef's richness and Shannon–Wiener diversity indexes, which rose from 2012 to 2018.

4.4 Reduction in mean fish community trophic level

The reliability of MTL as a metric for assessing the effects of fishing on fish communities or fisheries resource sustainability depends on the quality and length of time-series data available (Pauly et al., 2001). Our data span 13 consecutive years and are collected from a single survey vessel using consistent gear, so we regard them to be of both excellent quality and long-term duration.

Long-term changes in MTL can indicate changes in fish community structure and fishery resources (Su et al., 2021). The MTL in the Beibu Gulf shows an overall wavelike downward trend from 3.82 in 2006 to 3.71 in 2018, and to have decreased by 0.08 trophic-level per decade (Figure 5A). This indicates that fish communities have changed and that fish stocks are declining. The rate of decline in MTL in the Beibu Gulf exceeds the rate throughout China (0.02 trophic-level per decade) (Du et al., 2014), but is lower than the global rate (0.1 trophic-level per decade) (Pauly et al., 1998) and that for other regions, where the rates of decline were between 0.09 and 0.17 (Zhang et al., 2007; Connell et al., 2014; Wu et al., 2017). Compared with Quanzhou Bay (0.1 trophic-level per decade) (Du et al., 2010) and Persian Gulf (0.11 trophic-level per decade) (Razzaghi et al., 2017), the decline of MTL in the Beibu Gulf is moderate.

The FiB index tends to be less than 0 (Figure 6A), indicating that fish stocks in the Beibu Gulf have been overfished (Su et al., 2021). Variation in the FiB index is closely related to changes in MTL and fish abundance (Figures 6B–D; $p< 0.05$), decreasing with a decrease in both MTL and fish abundance. The main reason for the decline in MTL is overfishing, with the main catch shifting from high-value, long-lived, high-trophic-level, demersal species to lower-value, small-sized, low-trophic-level, pelagic species, which is present in many aquatic ecosystems worldwide (Pauly et al., 1998; Liang and Pauly, 2019). The proportion of high-trophic-level species to total catch in the Beibu Gulf has decreased with an increase in total motorized fishing vessel power (Figure 3D; $p< 0.05$), and the proportion of high-trophic-level and demersal species in the total catch correlates positively with MTL (Figures 5C, D; $p< 0.05$). Therefore, because of overfishing, fish communities in the Beibu Gulf have changed from long-lived, high-value, high-trophic-level, demersal species to short-lived, low-value, low-trophic-level, pelagic species, then leading to a decline in MTL. Similar 'fishing down marine food webs' has been reported elsewhere in China (Liang and Pauly, 2017; Liang and Pauly, 2019).

Furthermore, climate-change may have contributed to observed changes in community composition and structure. For example, while the diversity index trended upwards from 2016 to 2018, each of MTL, the FiB index, and fish abundance trended down (Figures 1A, 4, 5A, 6A). Ocean SST and eutrophication are affected by climate change (Painting et al., 2013; Mediodia et al., 2020). We report SST to correlate negatively with MTL (Figure 5B; $p< 0.05$), and for higher temperatures to simplify food-web structure and shorten the path of energy between consumers and resources, accelerating the decrease in MTL (O'Gorman et al., 2019). Pollution from residential, industrial and agricultural activities may also exacerbate eutrophication in the Beibu Gulf (Ning and Chen, 2021), increasing primary productivity, significantly increasing the abundance of phytophagous, low-trophic-level species (Caddy, 1993; Caddy et al., 1998; Connell et al., 2014). While this increase in low-trophic-level species contributes to a statistical recovery in diversity, it also led to decreased MTL, FiB index, and fish abundance (Caddy, 1993; Caddy et al., 1998; Connell et al., 2014).

There were some uncertainties in MTL. As fish grow and develop, their diet can change, resulting in changes in their trophic level (Jennings et al., 2002). The MTL calculation does not take into account the size of individual fish. Therefore, changes in trophic level due to individual growth can have an effect on the MTL.

5 Conclusion

Multiple external disturbances (e.g., overfishing, trawl fisheries, 'skipper effect', habitat damage, pollution, and anthropogenic-induced temperature changes) may all have collectively contributed to changes in fish community composition and trophic structure in the Beibu Gulf. Fish abundance and diversity in the Beibu Gulf has trended down from 2006 to 2018. Dominant species composition has changed dramatically, and low-trophic-level dominant species have tended to become increasingly, proportionally prevalent in the total catch. Fish communities have changed from those dominated by demersal species to those dominated by pelagic species, and from large, high-value, high-trophic-level to small, lower-value, low-trophic-level species.

Additionally, MTL has decreased from 3.82 in 2006 to 3.71 in 2018, and the FiB index has tended be less than 0, suggesting that the Beibu Gulf fish stocks are overfished. Therefore, fish stocks in the Beibu Gulf are in a state of continuous decline and overexploitation. We suggest reducing the fishing intensity and strengthening the pretreatment and supervision of land-derived pollutants before their discharge.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The animal study was reviewed and approved by South China Sea Fisheries Research Institute, Chinese Academy of Fishery Sciences.

Author contributions

SP: methodology, data processing and writing the manuscript. XW and FD: reviewing, editing, and funding acquisition. DS, YW, PC and YQ: conceptualization and reviewing. All authors contributed to the article and approved the submitted version.

Funding

This work was supported by Hainan Provincial Natural Science Foundation of China (422MS156) and Science and Technology Basic Resources Investigation Program of China (2018FY100105, 2017FY201405).

Acknowledgments

We thank Steve O'Shea, PhD, from Liwen Bianji (Edanz) (www.liwenbianji.cn) for editing a draft of this manuscript.

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.

Publisher's note

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frontiers | Frontiers in Marine Science

TYPE Brief Research Report
PUBLISHED 28 April 2023
DOI 10.3389/fmars.2023.1175316

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OPEN ACCESS

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RECEIVED 27 February 2023
ACCEPTED 13 April 2023
PUBLISHED 28 April 2023

CITATION
Luo B, Nong Y, Zhang T, Zhang S and Hu R (2023) The use and sustainable development of marine animal drugs by the Kinh people in Beibu Gulf. *Front. Mar. Sci.* 10:1175316.
doi: 10.3389/fmars.2023.1175316

The use and sustainable development of marine animal drugs by the Kinh people in Beibu Gulf

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The Kinh people of China have historically migrated from Tushan and other areas of Vietnam since the 16th century. They are now settled in Fangchenggang City in the Beibu Gulf region of Guangxi, China. The local Kinh people have lived by fishing and have a rich fishing culture. Accordingly, the Kinh people of China have a long history of using traditional marine animal drugs for their daily medicinal needs. However, with the advent of modern medicine, there is a risk of losing the valuable traditional knowledge of marine animal drugs. Thus, this study aimed to document the types of marine animal drugs and related traditional knowledge of the Kinh people and explore the sustainability of their access to marine animal drugs. Ethnobiological methods, including snowball sampling and semi-structured interviews are used to collect information about the animal drugs used locally during the study. Through field investigations in the "Three Islands of Kinh," we collected ethnozoological data on 61 marine animal drugs belonging to 52 families across six animal phyla. Chordata and Mollusca are the most represented phyla, while Arthropoda, Echinodermata, Sipuncula, and Cnidaria are less represented. According to the analysis, animal meat is the most frequent medicinal part; the Kinh prefer decoction or making soup, and internal administration is the most frequent use mode. Our statistical analysis revealed that nourishing was the most common purpose for the recorded marine animal drugs in the study area. Our study found that 6 documented species are listed as threatened on the IUCN Red List but receive little targeted protection. The article provides recommendations for protecting traditional knowledge, promoting sustainable development of marine resources, and conserving endangered species.

KEYWORDS

Kinh people, marine drug, sustainability, Beibu Gulf, traditional knowledge

10.3389/fmars.2023.1175316

1 Introduction

Marine drugs are effective medications made from marine organisms and minerals, which possess unique characteristics and functions due to their marine origins (Papon et al., 2022; Cappello and Nieri, 2021). Some marine drugs have demonstrated excellent efficacy in treating complex diseases such as cancer, diabetes, cardiovascular and cerebrovascular diseases, immunodeficiency diseases, and Alzheimer's disease (Papon et al., 2022; Cappello and Nieri, 2021). Marine medicine has become an essential source of new drugs for preventing and treating these conditions. With more than 70% of the Earth's surface covered by the ocean, it boasts an extraordinary species diversity and resource potential, particularly regarding marine animals. In modern society, animal therapy has become a vital alternative to traditional treatments worldwide, and wild and domestic animals and their by-products are essential components in the preparation of drugs (Adeola, 1992; Angeletti et al., 1992). Therefore, acquiring a greater understanding of traditional marine animal drugs will aid in the rational formulation and development of marine drug resources. Otherwise, studying how the locals acquire or apply marine resources, especially marine animals, is of great help in protecting the related traditional culture and the marine ecosystem (Alves and Rosa, 2013).

The Kinh people of China have historically referred to themselves as "Kinh" and "Yue"(He, 2008). Since the Ming Dynasty (AD 1511), many Kinh people from Tushan and other areas in Vietnam have migrated and settled in Fangchenggang City in the Beibu Gulf region of Guangxi, China. They are mainly concentrated in Wanwei, Shanxin, and Wutou villages, collectively known as the "Three Islands of Kinh" (He, 2008). The Kinh people live along the coast, and fishing in the sea has naturally become their main livelihood. The local diet is based on rice, and they are good at cooking seafood such as fish, shrimp, and crab; local women have the habit of chewing betel nuts (He, 2008). Over a long period of historical development, the Kinh people have established a range of unique customs combined with local environmental features, such as welcoming ocean gods during the Ha Festival and fishing on stilts in shallow waters (He, 2008). The unique island environment makes it difficult for Kinh people to access medical treatment, so they have become adept at using local materials, coastal plants, and marine life for their daily medicinal needs (He, 2008; Du et al., 2015).

The Kinh people are the only ethnic minority in China with a significant focus on the marine fishery economy, and their traditional knowledge and experience in the acquisition, use, and sustainable development of marine resources are worth in-depth study. However, traditional fishery-related knowledge is threatened as the Kinh people begin to develop other industries, such as tourism. Thus, there is an urgent need to research and rescue the culture, management, and protection of marine animal drugs used by the Kinh people, which has not been systematically documented. Thus our study aims to 1) document the types of marine animal drugs and related traditional knowledge of the Kinh people and 2) explore the sustainability of the Kinh people's access to marine animal drugs.

2 Methods

2.1 Study area

The Kinh ethnic group is one of the smallest ethnic minorities in Southern China and is primarily located in Dongxing City, a subdivision of Fangchenggang City in the Beibu Gulf area of Guangxi Province of China. They mainly reside in the "Three Islands of Kinh" in Jiangping Town, which includes Wutou, Shanxin, and Wanwei villages, as depicted in Figure 1. Due to the ocean and the Shiwandashan Mountains, the "Three Islands of Kinh" experience abundant sunshine and rainfall.

2.2 Collection and identification of ethnozoological data

From June 2020 to November 2022, we conducted six field investigations in Wutou, Shanxin, and Wanwei. During the visits, we primarily used the semi-structured interview method to collect information about Kinh marine medicine, including its biological source, vernacular name, medicinal part, usage, treatment of diseases, and resource acquisition (Jaroli et al., 2010; Borah and Prasad, 2017). The selection of information reporters included village cadres, community leaders, inheritors of traditional medicine culture, and experienced fishermen. We used the "snowball sampling method" to select a total of 65 informants, including 37 males and 28 females, all over 30 years old. Before the interview, each participant was informed of the nature and purpose of the study, and their consent was obtained. Throughout the survey, we strictly observed the ethical guidelines of the International Society for Ethnobiology (http://www.ethnobiology.net/). We also obtained consent and trust from each participant by presenting the main theme of the study to them, allowing them to communicate more freely and openly. The recorded information was subsequently reviewed by the informants to avoid errors and falsifications.

For species identification, we mainly used three methods: (1) analysis of specimens donated by the interviewees, (2) analysis of photos of animals and raw animal medicines collected during the interview, (3) use of vernacular names with the assistance of taxonomists familiar with the local situation. Professor Fajun Jiang, from Guangxi Beibu Gulf Marine Research Center of Guangxi Academy of Sciences, helped to confirm the species' taxonomic identification. Additionally, we used the Global Biodiversity Information Facility (https://www.gbif.org) and the Catalogue of Life (https://www.catalogueoflife.org) to verify and correct the scientific names of species.

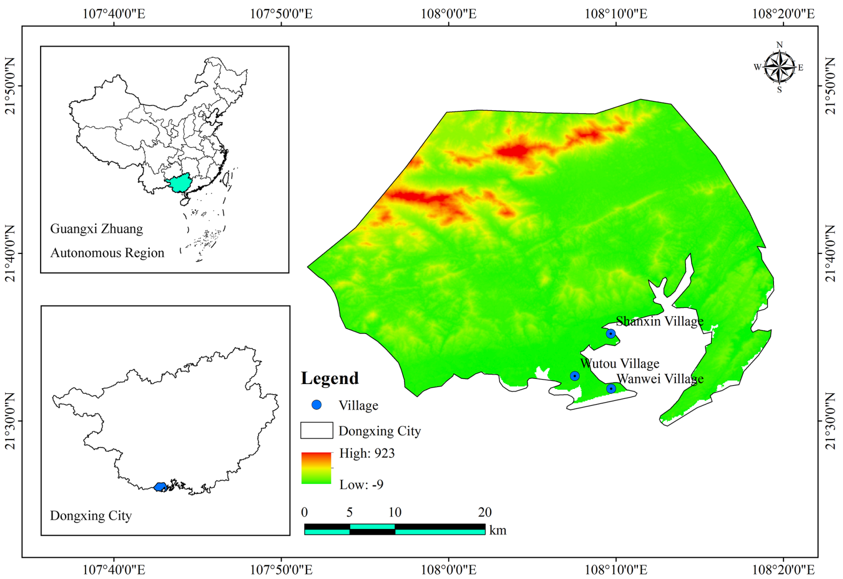

FIGURE 1
The study area.

3 Result

In this study, we documented 61 marine animal drugs (Table S1) used by the Kinh people for daily medical care, which belong to 52 families across six animal phyla. Chordata (32 species) and Mollusca (20 species) are the most represented phyla, while Arthropoda (4 species), Echinodermata (2 species), Sipuncula (2 species), and Cnidaria (1 species) are less represented.

The Kinh people use animal meat (33, 34.0%) as the most frequent medicinal part, followed by shells (18.6%) and whole animal objects (18.6%). Fish swim bladder (5, 5.2%), liver (3, 3.1%), skin (3, 3.1%), tail (3, 3.1%), gallbladder (3, 3.1%), sepia (2, 2.1%), gills (2, 2.1%), as well as other parts like scales, eel head, eel blood, fins, teeth, pearls, and fat are less common.

Decoction or making medicinal soup (52, 65.00%) is the primary processing method for marine animal drugs among the Kinh people, followed by grinding into powder (15, 18.75%), stewing in porridge (6, 7.50%), calcining into ash (3, 3.75%), soaking in wine (3, 3.75%), and water steaming (1, 1.25%) which are less commonly used. Internal administration (66, 81.48%) is the primary mode of use for marine animal drugs, followed by an external application (14, 17.28%), while exterior washing (therapeutic washing) was mentioned only once, accounting for 1.24% of the total frequency.

We identified 128 ailments treated by marine animal drugs used by the Kinh people, which were categorized into ten ailment categories (Table 1) based on the medication characteristics of the Kinh people and the International Classification of Diseases 11th (https://icd.who.int/en).

Our statistical analysis revealed that nourishing (61, 24.90%) was the most common purpose for the recorded marine animal drugs in the study area, followed by the treatment of digestive system illnesses (45, 18.37%), nervous and psychosomatic problems (28, 11.02%), and skin diseases (20, 8.16%). Other health problems, such as immune system diseases, respiratory system diseases, and urinary system diseases, were relatively less commonly treated.

Based on the List of Wild Animals under National Key Protection in China (No. 3 of 2021) (http://www.forestry.gov.cn/main/5461/20210205/122418860831352.html), only one of the marine animal drugs used by the Kinh nationality is listed as a national II protected animal, which is *Tachypleus tridentatus*. So at present, only this species is prohibited from fishing and use nationally and locally. In addition, our study revealed that 27 of the documented species are listed on the IUCN Red List of Threatened Species. Out of these, *Larimichthys croce* and *Sphyrna mokarran* are classified as critically endangered (CR), while *Tachypleus tridentatus*, *Chelonia mydas*, and *Holothuria nobilis* are listed as endangered (EN), and *Hippocampus kelloggi* is categorized as vulnerable (UV). Furthermore, 11 species are classified as least concerned (LC), and there is insufficient data to evaluate ten species (DD).

4 Discussion

4.1 The potential risks of using marine animal drugs

The use of marine animals in traditional Kinh medicine has been practiced for centuries and is deeply rooted in the culture and beliefs of the Kinh people (Zhang et al., 2022). According to our documentation, when it comes to processing marine animal drugs, the Kinh people prefer decoction or making soup, and internal administration is the most frequent use mode. The Kinh people believe that "spiritual injury means illness, while a spiritual loss means death"(Huang and Xu, 2014), and as a result, they attach great importance to the use of marine animal drugs to strengthen the body and regulate the spirit to enhance

TABLE 1 Categories of diseases in the study area.

Category	Recorded frequency	Percentages
Strong body (nourishing)	61	24.90
Digestive system	45	18.37
Muscle, skeletal system problems and traumatic injury	33	13.47
Nerves and psychosomatic problems	27	11.02
Skin diseases	20	8.16
Immune diseases	13	5.31
Gynecological and pregnancy problems	10	4.08
Respiratory system	9	3.67
Urinary system	6	2.45
Inner heat	7	2.86
Other Uses	14	5.71

their immunity and resist diseases. This long-term use of marine resources may have certain scientific connotations, but many have not been proven scientifically.

Otherwise, the long-term use of marine resources for medicinal purposes may pose a significant risk for zoonotic disease transmission. To prevent the spread of zoonotic diseases, reducing the consumption of wild animals and promoting sustainable alternatives is crucial (Ferreira et al., 2016; Van Vliet et al., 2017). This can involve promoting plant-based diets and alternative protein sources and supporting the development of sustainable aquaculture and fish farming practices (Van Vliet et al., 2017). Additionally, promoting evidence-based medicine and ensuring that traditional remedies are rigorously tested for safety and efficacy can contribute to protecting marine life and preventing zoonotic disease transmission.

4.2 Conservations status of reported species

According to our documentation, 27 species are listed on the IUCN Red List of Threatened Species. However, only *Tachypleus tridentatus* is nationally and locally prohibited from fishing and use. In order to protect the resources of *T. tridentatus*, the Chinese government has implemented a series of research and conservation measures, such as evaluating *T. tridentatus* resources, establishing protected areas, and improving breeding techniques, which have promoted the sustainable utilization of *T. tridentatus* resources (Zhu et al., 2020). Based on the research results, it can be concluded that some medicinal species we documented, such as those listed as "Critical Endangered" on the IUCN Red List, are even more endangered than *T. tridentatus*. However, no additional targeted protection measures were found during our investigation. It also appears that Jing fishermen did not carry out targeted releases during fishing operations.

The impact of fishing on the endangerment of some exploited species cannot be accurately determined due to insufficient data in this study. Factors such as fishing, anthropogenic pollution, and climate change may contribute to the endangerment of some species. The population status of these endangered species, especially those in the wild, is largely unknown and may face ongoing threats. Therefore, we believe it is urgent and necessary to prohibit the fishing and use of threatened populations through regulations. On the one hand, in terms of scientific research, we should conduct population surveys and conservation-related studies of wild species. On the other hand, increasing relevant policies and regulations and involving communities in management and restraint can further enhance the sustainable utilization of relevant marine resources.

Although prohibiting fishing for endangered species may negatively impact the preservation of traditional knowledge regarding their usage, we need to document it as comprehensively as possible for future reference. Moreover, it is crucial to enhance the implementation of benefit-sharing mechanisms by local governments.

4.3 The sustainability of the local marine ecosystem

During interviews with the local Kinh people, it was evident that they have developed a simple concept of sustainable utilization of marine resources due to their longstanding relationship with the sea. They are well-versed in the practice of abstinence and have customs such as releasing big fish back into the sea after catching their first net fish to ensure a good harvest with the protection of the Dragon King. Moreover, they sort fish by species, put back any that are unnecessary, and exchange their catches according to their needs to prevent overfishing. These practices highlight the Kinh people's deep respect for the environment and commitment to sustainable fishing practices.

As a traditional coastal nation, the Kinh people have long relied on shallow sea fishing as their primary livelihood. However, with the development of national policies and economic growth, their livelihoods have diversified to include sea product aquaculture, processing, commerce, and tourism. This transition has provided the necessary conditions for the sustainable development of local marine ecology. The support of national policies and the diversified development of local livelihoods provide new opportunities to mitigate the environmental impacts of single-fishing and crop cultivation practices.

Despite these positive developments, the Kinh people face challenges posed by pollution and damage to the coast caused by living pressures, sewage discharge, and tourism pollution resulting from population growth. Thus, there is an urgent need to prioritize protecting and preserving the marine ecosystem and promote responsible and sustainable development in the region.

5 Prospects

In conclusion, the Kinh people of China have a long history of utilizing marine animal drugs for medicinal purposes, with a significant focus on the marine fishery economy. This study aimed to document the types of marine animal drugs and related traditional knowledge of the Kinh people and explore the sustainability of their access to these drugs. Through six field investigations, 61 marine animal drugs belonging to 52 families across six animal phyla were documented. The study emphasizes the importance of preserving the traditional knowledge and experiences of the Kinh people, especially as they begin to develop other industries, threatening their traditional fishery-related knowledge. The documentation of traditional marine animal drugs provides a foundation for the rational formulation and development of marine drug resources.

Based on our findings, the traditional knowledge of using marine animal drugs in Kinh medicine is facing potential threats. To protect this knowledge and the sustainable application of marine animal populations it relies on, we suggest the following:

1) Systematically conduct ethnobiological studies to document the traditional use of marine animal species in Kinh medicine to preserve related knowledge as much as possible.
2) Utilize modern scientific techniques and collaborate with traditional medicine practitioners, as well as chemical or medical researchers, to identify active compounds and validate the medicinal properties of marine animal-derived drugs.
3) Enhance research on dynamic monitoring and conservation of endangered wild species, and strive to restore the population of relevant species as much as possible.
4) Promote sustainable use of marine resources through community-based management, regulations, and policies that protect marine resources and the livelihoods of local communities from pollution, overexploitation, and other threats. Implement measures related to benefit-sharing.

By implementing these suggestions, we can preserve cultural heritage, discover new treatments, and promote sustainable development in traditional Kinh medicine.

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 authors.

Ethics statement

The studies involving human participants were reviewed and approved by the Ethics Committee of the Guangxi Institute of Traditional Medical and Pharmaceutical Sciences. Written informed consent for participation was not required for this study in accordance with national legislation and institutional requirements.

Author contributions

BL, RH, and SZ contributed to the conception and design of the study. YN and TZ performed the data collection and statistical analysis. BL and RH wrote the first draft of the manuscript. All authors contributed to the manuscript's revision and read and approved the submitted version.

Funding

This study has been supported financially by the Open Program of Guangxi Key Laboratory of Traditional Chinese Medicine Quality Standards (202007); Survey and Collection of Germplasm Resources of Woody and Herbaceous Plants in Guangxi, China (GXFS-2021-34), and Clinical Medical Research Center of Jingzu Medicine (Fangke AA21014041).

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.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2023.1175316/full#supplementary-material

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frontiers | Frontiers in Marine Science

TYPE Original Research
PUBLISHED 15 May 2023
DOI 10.3389/fmars.2023.1186106

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Determination of phytoplankton community structure and biomass with HPLC-CHEMTAX and microscopic methods during winter and summer in the Qinzhou Bay of the Beibu Gulf

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OPEN ACCESS

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RECEIVED 14 March 2023
ACCEPTED 28 April 2023
PUBLISHED 15 May 2023

CITATION
Pan H, Xu M, Lan C, Ma J, Li J, Lu J and Lai J (2023) Determination of phytoplankton community structure and biomass with HPLC-CHEMTAX and microscopic methods during winter and summer in the Qinzhou Bay of the Beibu Gulf.
Front. Mar. Sci. 10:1186106.
doi: 10.3389/fmars.2023.1186106

The Qinzhou Bay, a typical semi-enclosed bay, is facing environmental pressure from local fast-growing industrial and aquacultural development. Dominant species of phytoplankton community (based on microscopic examination) show a trend of miniaturization, while pico-phytoplankton (based on CHEMTAX analysis) is widely distributed in Qinzhou Bay. However, most previous investigations of phytoplankton community based on microscopic method that undetected small-sized cell (< 3 μm), and limited by scarce studies on CHEMTAX analysis, the long-term dynamic data of small-size phytoplankton are lacking in Qinzhou Bay. It is recognized that combining microscopic examination with CHEMTAX analysis could provide a good taxonomic reliability for large cells and valuable information about small-size groups. In this study, microscopic examination and High Performance Liquid Chromatography (HPLC)-CHEMTAX analysis were employed to characterize the spatiotemporal variability of the phytoplankton community structure in Qinzhou Bay in winter and summer of 2021. The results of microscopic observations showed that the phytoplankton community was characterized by diatoms and dinoflagellates mainly. Diatoms dominated in both seasons, of which *Skeletonema costatum* bloom occurred in the summer. CHEMTAX analysis not only agreed well with microscopy data for diatoms and dinoflagellates, but also helped identification of other small-sized flagellates and cyanobacteria that hard to observe by microscope. The results of CHEMTAX analysis found that diatoms, prasinophytes and cryptophytes co-dominated the total chlorophyll *a* in winter while diatoms became the dominant group in summer. In addition, our results indicate that the proportion of small-sized flagellates has increased in the past decade in Qinzhou Bay, especially for cryptophytes. Temperature, nutrient availability, and selective grazing of oyster affected the succession of phytoplankton community from co-dominance of diatoms and flagellates in winter to absolute diatoms dominance in summer. The distribution of prasinophytes and cryptophytes on a spatial scale were related to the location of shellfish culture area and estuary, respectively, rather than by nutrients. Eutrophication, selective grazing of oyster and warming were the driving factors of long-term changes in phytoplankton composition in Qinzhou Bay. This study enhanced our understanding of entire phytoplankton community dynamics and its relationship with environmental factors in Qinzhou Bay.

KEYWORDS

phytoplankton, pigments, environmental factor, HPLC-CHEMTAX, microscopy, Qinzhou Bay

1 Introduction

Phytoplankton acts as a primary producer in marine ecosystems and maintains the balance of the global ecosystem by supplying organic matter to higher trophic levels (Paerl et al., 2003). Phytoplankton community reflects environmental changes sensitively and rapidly, and variation in the structure of phytoplankton community could affect the global climate in terms of carbon flux (Sarmiento et al., 1988), cloud albedo (Charlson et al., 1987), light flux, and heat flux (Sathyendranath et al., 1991). Therefore, quantifying the variations in phytoplankton biomass and taxonomic composition and analyzing the relationship between phytoplankton and the environment are important for the evaluation of ecosystem function and status, as well as for the study of global biogeochemical cycles (Eker-Develi et al., 2008).

The widespread techniques regarding phytoplankton monitoring are morphological observation, pigment analysis, and high throughput sequencing analysis (Egge et al., 2015; Pan et al., 2020). The traditional identification and quantification of phytoplankton *via* microscopy techniques can provide accurate taxonomical information (at species or genus) of phytoplankton (Brito et al., 2015b). However, phytoplankton cells in small size (<3 μm) and unobvious morphological characteristics are difficult to identify accurately, which restricts the application to the species of small size group, such as prasinophytes and cyanobacteria (Chen et al., 2016). In addition to morphological characteristics, some photosynthetic pigments (such as fucoxanthin, peridinin, zeaxanthin and alloxanthin), determined by high-performance liquid chromatography (HPLC), can also be used as taxonomic indicators for phytoplankton classification (Zapata et al., 2000). The contribution of different phytoplankton groups to the total chlorophyll *a* can be estimated by combining the photosynthetic pigment data with CHEMTAX, a mathematical program, based on the ratios of mark pigments to Chl *a* (Mackey et al., 1996). This technology overcomes the drawback of the microscopy method. However, the CHEMTAX estimates can only classify phytoplankton into classes or phyla. Many studies have proposed a combination of the two approaches for better understanding of phytoplankton community structures (Agirbas et al., 2015; Brito et al., 2015b; Pan et al., 2020).

Qinzhou Bay (QZB) is a semi-enclosed subtropical bay located in Qinzhou, China. It receives a considerable amount of chemicals, organic matter, and nutrients from Maoling River, Qinjiang River, and Jingu River (Luo et al., 2019). Nutrients usually increased in gradient from south to north and exhibit significant seasonal change in QZB, which reflects the dominant control role of land runoff (Lai et al., 2013). QZB is an important oyster aquaculture area in Guangxi Zhuang Autonomous Region, in-bay oyster farming area has expanded from inner bay (Maowei Sea) to the Qinzhou Port coastal area in recent decades. With accelerated expansion of port transportation, aquaculture industry, and coastal industry in the local rim region, the QZB has undergone a shift from oligotrophic to mild, moderate and even heavy (Maowei Sea) eutrophication status from 1980s to the 2010s (Wei et al., 2002; Lan, 2012; Yang et al., 2012; Lai et al., 2013), inorganic nitrogen showed an obvious increasing trend (Wei et al., 2002; Wei and He, 2008). In addition, the Guangxi Fangchenggang Nuclear Power Plant located in the west coast of QZB (Figure 1) began operating in January 2016, the thermal discharge causes sea surface temperature increase near the water outlet (Pan et al., 2022).

Phytoplankton in terms of biomass, abundance and species information, have been measured in QZB over many decades, many studies have shown that the phytoplankton dynamics is closely related to environmental physical and chemical factors (Wei and He, 2008; Wang et al., 2013; Liu et al., 2020). Under the background of environmental changes over the past decades, phytoplankton responded to qualitative and quantitative changes in community structure; for example, intensified blooms (Qin et al., 2016; Shen et al., 2018; Liu et al., 2020; Su et al., 2022), small-sized diatoms become dominant group and the contribution of non-diatom (especially dinoflagellates) to total species number increased significantly (Jiang et al., 2012; Wang et al., 2013; Luo et al., 2019; Liu et al., 2020). Furthermore, several studies used HPLC-CHEMTAX revealed that smaller phytoplankton groups (pico- or nano-sized), including prasinophytes, cryptophytes, and cyanobacteria, contributed greatly to the total Chl *a* in QZB (Lan et al., 2011; Lan et al., 2013; Lan et al., 2014; Pan et al., 2022). The feeding pressure on oysters is an important factor in the prevalence of nano- and pico-phytoplankton in QZB (Lan et al., 2011; Lan et al., 2013; Lan et al., 2014; Pan et al., 2022), as shellfish mainly

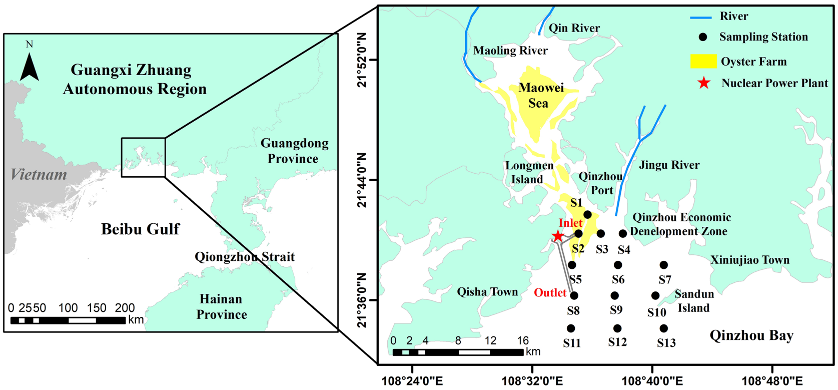

FIGURE 1
Deployment of sampling stations in QZB, the Beibu Gulf, China.

filter larger phytoplankton group (>3 μm) (Ward and Shumway, 2004). We hypothesized that seasonal and spatial changes in phytoplankton biomass and structure in QZB are largely regulated by size-selective grazing of shellfish, nutrients, and temperature, and the long-term size-selective filtration of shellfish may increase the contribution of small-sized phytoplankton groups.

Many previous studies on phytoplankton were based on microscopy examination and small-sized cells were undetected in QZB. However, the studies using HPLC-CHEMTAX to analyze phytoplankton biomass and community in QZB are few (Lan et al., 2011; Lan et al., 2013; Lan et al., 2014), and lack of information on the long-term dynamics of small-sized phytoplankton in this area. To test our hypothesis, we combined microscopic counting (provides information on species and abundance of large cells) and HPLC-CHEMTAX analysis (provides information on classes or phyla and biomass of full-size cells) to investigate the whole phytoplankton community in winter and summer in QZB, and subsequently compared with historical data. Our objectives were: (i) to add to the knowledge on the distribution and structure of phytoplankton community in QZB; (ii) to analyze the leading factors affecting the succession of various phytoplankton groups from summer to winter based on the environmental data; (iii) to explore driving factors of the long-term changes in phytoplankton community structure. Our work is useful to understand the seasonal succession and long-term changes in whole phytoplankton community structure and its controlling factors in this semi-enclosed culture bay of the South China Sea.

2 Materials and methods

2.1 Study area and sampling strategy

QZB (108.45°–18.95°E, 21.50°–21.90°N), a semi-enclosed bay located in the north of the Beibu Gulf, covers an area of 380 km^2 and characterized by a southern subtropical oceanic monsoon climate (Jiang et al., 2012). Recent studies had found that the circulation in north of the Beibu Gulf is mainly counterclockwise all year round (Xia et al., 2001; Cao Z et al., 2019; Li et al., 2022), and the water masses were classified into three types, i.e., the bottom mixed shelf water with low temperature and high salinity, the surface mixed shelf water, and the coastal water with low salinity (Cao Z et al., 2019). QZB is affected by the westward coastal current (Chen and Shi, 2019) and the coastal water masses (Cao Z et al., 2019) in the Beibu Gulf both in winter and summer. The tide in QZB belongs to diurnal tide type, and the tidal current is dominated by reciprocating flow. The flood current enters QZB from south to north, and the velocity of flood current is generally smaller than that of ebb current (Dong et al., 2014; Lyu et al., 2021). Tidal current are stronger in summer than in winter in QZB (Dong et al., 2014).The inflow rivers include Maoling River, Qinjiang River, and Jingu River, with average annual runoff of 2.61×10^9 m^3, 2.47×10^9 m^3 (Lyu et al., 2021), and 1.50×10^8 m^3 (Chen et al., 2016), respectively, which bring in large nutrient loads into QZB. Influenced by runoff, tide and wave (Cao X et al., 2019), sea water exchange capacity in the estuary area of Maowei Sea and offshore area is stronger than that in coastal area. There is a large area of shellfish culture (mainly *Crassostrea rivularis*) in QZB (Lan et al., 2014) (Figure 1).

Two in-bay cruises were conducted at 13 stations in the winter (January 27) and summer (June 23) in 2021. At each sampling station, 2.0-L seawater was collected from near surface (0.5 m in depth) with Niskin bottle, from which 1.0-L seawater was fixed in acidic Lugol's solution for microscopic identification, and the rest 1.0-L seawater was filtered through GF/F filters (0.7 μm, Whatman). The filters were immediately deep-frozen in liquid nitrogen and maintained at −80°C for HPLC analyses, and 100 mL filtrate was stored at −20°C for nutrient analysis. Hydrographic (water temperature and salinity) measurements were performed using AAQ-RINKO (JFE, Japanese).

2.2 Nutrient analysis

Dissolved reactive phosphate (DRP), dissolved inorganic nitrogen (DIN), and dissolved silicate (DSi) were determined with a SKALAR flow analyzer in methodological standard (Strickland and Parsons, 1972). DIN is to the sum of nitrite (NO_2^-), nitrate (NO_3^-), and ammonium (NH_4^+) contents.

2.3 Microscopical detection of phytoplankton

The samples fixed with Lugol's solution were concentrated to 5–15 mL *via* sedimentation, after which the supernatants were discarded. Identification and quantification were conducted under an inverted microscope (Nikon ECLIPSE Ti-S) according to the method of Utermöhl (1958).

2.4 HPLC-pigment analysis

The frozen filters were cut into pieces and then placed in a screw-cap centrifuge tube with 3-5 mL of 95% cold-buffered methanol. The filters were sonicated for 5 min in ice-water bath, and the extracted solution were filtered through PTFE membrane filters (0.2 mm pore size) to remove filter and cell debris. Prior to injection, 200 µL of sample was mixed in 67-µL Milli-Q water in 2.0-mL amber glass sample vials. The procedures of HPLC analyses using an Agilent series 1200 HPLC system fitted with Waters C8 column fully followed the work of Zapata et al. (2000). Standard curves were established using standard pigments from DHI (Institute for Water and Environment, Denmark). The standard pigments included Chl *a*, chlorophyll *b* (Chl *b*), chlorophyll *c*2 (Chl *c*2), chlorophyll *c*3 (Chl *c*3), divinyl chlorophyll *a* (divinyl Chl *a*), fucoxanthin (Fuco), 19′-hex-fucoxanthin (Hex-Fuco), 19′-butfucoxanthin (But-Fuco), 19'-Hexanoyloxy-4-ketofucoxanthin (Hex-kfuco), peridinin (Peri), prasinoxanthin (Pras), alloxanthin (Allo), zeaxanthin (Zea), neoxanthin (Neo), lutein (Lut), diatoxanthin (Diato), diadinoxanthin (Diadino), violaxanthin (Viol), Mg-2,4-divinylpheoporphyrin (MgDVP), pheophorbide *a* (Pheide *a*), β,ϵ-Carotene (βϵ-Car) and β, β-Carotene (ββ-Car).

2.5 CHEMTAX analysis

The relative contribution of different phytoplankton groups to the total Chl *a* biomass was estimated from pigment data using CHEMTAX (version 1.95) (Mackey et al., 1996; Wright et al., 1996; Wright et al., 2009). The input pigment ratios were obtained from Wang et al. (2015) and Mackey et al. (1996). To optimize the input ratios for our data set, a series of 60 derivative pigment ratio matrices were built by multiplying each ratio of the initial matrix using a random function. The best 10% of results were considered as the optimized results. Data from the winter and summer were run separately into 2 bins to consider the potential variations with irradiance and/or nutrient availability in the optimization of CHEMTAX procedures. The initial and final ratios are presented in Table,32] ?> S1. We present the output data as absolute concentrations (µg/L) of Chl *a* and relative proportions attributed to each phytoplankton group.

2.6 Statistical analysis

To test the significant difference of physical, chemical, and biological variables between the two seasons, Student's t-test was conducted using the SPSS Statistics (version 23). A redundancy analysis (RDA) was performed using software CANOCO 5 (Lai, 2013) to explore the relationships between the environmental parameters and phytoplankton data. Correlation between phytoplankton cell abundances and CHEMTAX results was evaluated by regression analyses using the Origin 2017 software.

3 Results

3.1 Oceanographic conditions

In winter, the sea surface temperature ranged from 15.41 to 17.69°C, with an average of 16.15°C, and it showed a trend of high in the west and low in the east, with the maximum in the southwest stations (Table 1; Figure 2A). In summer, the surface temperature significantly increased (with an average of 28.07°C), and it decreased in gradient from south to north in the sampling area (Table 1; Figure 2B). Due to the influence of the fresh water input from Qinjiang River, Maoling River, and Jingu River (Figure 1), sea surface salinity decreased from south to north in the study area in the two cruises (Figures 2C, D). The sea surface salinity in summer (with an average of 28.07) was significantly lower than that in winter (with an average of 30.55) ($P<0.01$; Table 1) because the influence of the runoff was relatively large in summer.

DIN, DRP, and DSi exhibited a similar distribution pattern that increased northward in the study area in both cruises due to influence of terrigenous input (Figures 2E–J). The highest nutrients concentrations were recorded at the northwest stations during both cruises. Although the nutrients concentrations in summer were higher than those of winter, only the differences of DSi between the two seasons was statistically significant ($P<0.05$; Table 1).

3.2 Phytoplankton assemblages

3.2.1 HPLC pigments

The spatio-temporal variability of Chl a and generally-used accessory pigment proxies of biomass for diatoms (Fuco), dinoflagellates (Peri), prasinophytes (Pras), cyanophytes (Zea), and cryptophytes (Allo) are showed in Figure 3. Other pigments (e.g. Lut, Hex-Fuco, But-Fuco, etc.) detected *in situ* at stations were minor and ignorable, and thus were not presented here.

A high-Chl *a* region was noted at the eastern part of the sampling region in a clear gradient of decrease southwestward in the two cruises (Figures 3A, B). Fuco was the dominant accessory pigment at all stations, showing a similar distribution pattern to Chl *a* (Figures 3C, D). The mean concentrations of Chl *a* and Fuco in the summer were significantly higher than those in the winter ($P<0.01$; Table 1). The third accessory pigment was Peri showing no

TABLE 1 Mean values of physical, chemical, and biological variables during winter and summer.

Parameters	Mean values ± Standard deviation (ranges)	
	Winter	Summer
Temperature (°C)	16.15 ± 0.55 (15.41-17.69)	28.07 ± 2.49** (23.57-31.78)
Salinity	30.55 ± 1.22 (27.34-31.78)	27.80 ± 1.86** (24.50-30.50)
DIN (μmol/L)	3.34 ± 3.05 (0.94-11.56)	4.60 ± 4.73 (0.97-18.59)
DRP (μmol/L)	0.48 ± 0.20 (0.25-0.94)	0.59 ± 0.56 (0.28-2.21)
DSi (μmol/L)	5.28 ± 2.92 (2.12-12.86)	12.44 ± 10.53* (3.63-42.31)
Chl *a* (μg/L)	1.11 ± 0.42 (0.46-1.81)	3.24 ± 2.45 ** (0.90-10.21)
Fuco (μg/L)	0.72 ± 0.44 (0.10-1.35)	3.23 ± 2.63** (0.68-10.64)
Peri (μg/L)	0.15 ± 0.10 (0.01-0.30)	0.27 ± 0.3 (0.01-0.99)
Pras (μg/L)	0.07 ± 0.05 (0.02-0.16)	0.02 ± 0.02** (0.00-0.07)
Allo (μg/L)	0.05 ± 0.02 (0.02-0.09)	0.06 ± 0.04 (0.01-0.14)
Zea (μg/L)	0.01 ± 0.005 (0.01-0.02)	0.16 ± 0.06** (0.07-0.27)
Chl *b* (μg/L)	0.13 ± 0.08 (0.04-0.31)	0.07 ± 0.04* (0.03-0.17)
Diatoms (μg Chl *a*/L)	0.52 ± 0.34 (0.07-1.03)	2.53 ± 2.29** (0.44-9.18)
Dinoflagellates (μg Chl *a*/L)	0.11 ± 0.07 (0.01-0.22)	0.23 ± 0.24 (0.01-0.76)
Prasinophytes (μg Chl *a*/L)	0.23 ± 0.14 (0.08-0.54)	0.10 ± 0.06** (0.00-0.20)
Cryptophytes (μg Chl *a*/L)	0.20 ± 0.08 (0.07-0.34)	0.20 ± 0.14 (0.05-0.47)
Haptophytes (μg Chl *a*/L)	0.02 ± 0.01 (0.00-0.05)	0.01 ± 0.01 (0.00-0.04)
Chrysophytes (μg Chl *a*/L)	0	0.02 ± 0.02** (0.00-0.06)
Chlorophytes (μg Chl *a*/L)	0.02 ± 0.02 (0.00-0.07)	0.03 ± 0.03 (0.01-0.10)
Cyanobacteria (μg Chl *a*/L)	0.01 ± 0.004 (0.00-0.02)	0.12 ± 0.05** (0.05-0.22)
Diatoms (10^4 cells/L)	31.33 ± 25.47 (0.51-71.32)	188.13 ± 144.19** (23.80-569.25)
Dinoflagellates (10^4 cells/L)	2.92 ± 3.24 (0.08-10.00)	3.68 ± 4.10 (0.86-14.63)

Asterisks denote the difference between the two seasons. *: P<0.05; **: P<0.01 by t-test.

significant seasonal variation (*P*<0.01; Table 1). The peak Pras level was recorded in the northwest part of QZB, and high-Zea region was noted in the northwestern and southeastern parts of QZB in the two seasons (Figures 3G–J). The mean Pras and Zea concentrations varied significantly between the two seasons (*P*<0.01; Table 1). Allo presented a peak in the estuaries zone (Figures 3K, L), which was not significantly different between the two cruises (*P*>0.05; Table 1).

3.2.2 CHEMTAX results

CHEMTAX analysis identified eight major phytoplankton groups (Table 1). Although the relative contribution of the different phytoplankton groups to the total Chl *a* biomass was variable, diatoms were generally the dominant group (Figure 4). This dominance was accentuated in the summer (Figure 4B). In the winter, on average, the diatoms contributed 43.12% to the total phytoplankton biomass, followed by the prasinophytes (24.18%), cryptophytes (18.54%), and dinoflagellates (9.17%) (Figure 5A). Prasinophytes dominated in the northwest part of the study area (Stations S1, S2, and S5) (Figure 4A). In the summer, a sharp increase was observed in diatom biomass (*P*<0.01; Table 1), which accounted for up to 72.12% of total biomass (Figure 5A). In contrast, the contributions of prasinophytes and cryptophytes decreased significantly from winter to summer (*P*<0.01). The dinoflagellates showed similar relative contributions during both cruises (accounting for 9.17% and 8.03% in the winter and summer respectively). The contribution of cyanobacteria increased significantly from 1.21% in the winter to 5.80% in the summer (*P*<0.01; Figure 5A).

3.2.3 Phytoplankton community: microscope observation

A total of 99 species were identified in both cruises (Table S2), of which 73.7% were diatom species, 22.2% were dinoflagellate species, and 4% were other flagellates. In terms of cell number, diatoms contributed over 90% of total phytoplankton abundance in both the seasons (Figure 5B). Diatoms and dinoflagellates exhibited a similar distribution pattern to those of Fuco and Peri (or to

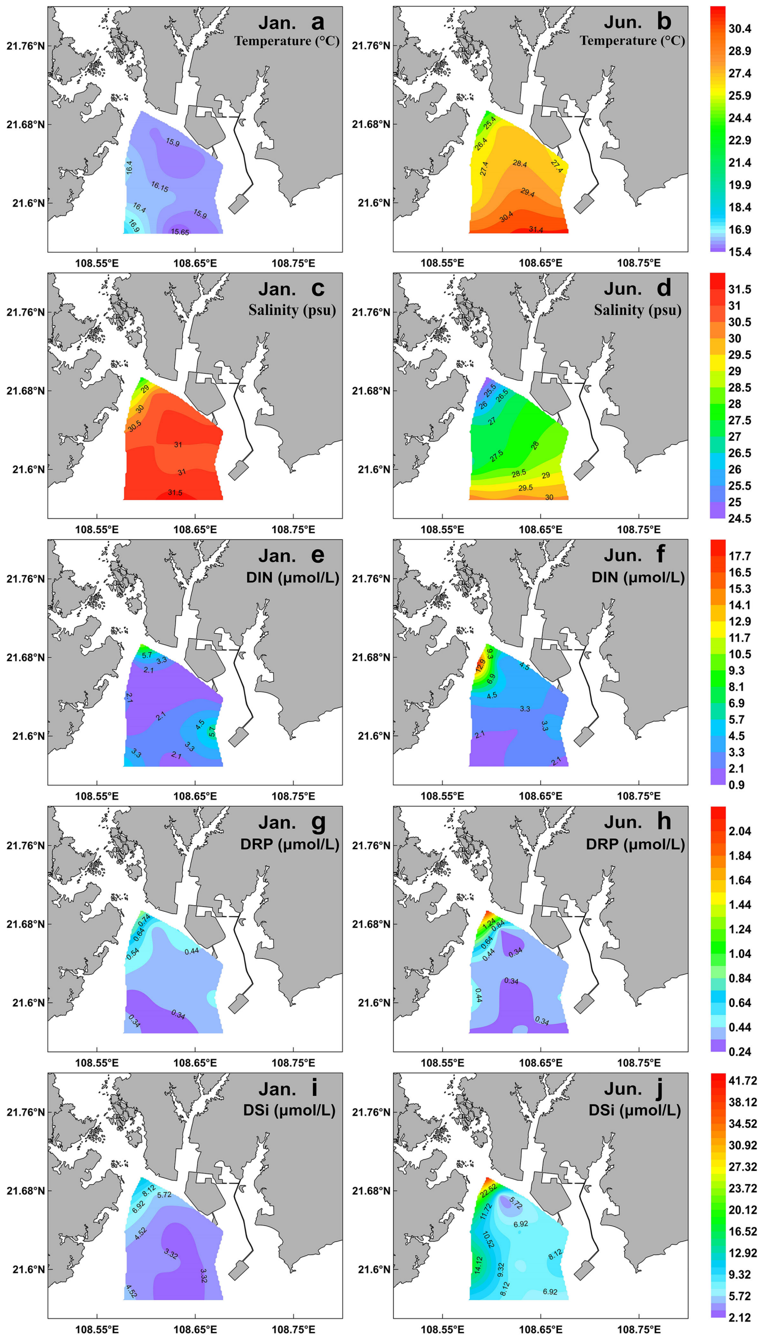

FIGURE 2
Spatial distribution of surface temperature **(A, B)**, salinity **(C, D)**, DIN **(E, F)**, DRP **(G, H)**, and DSi **(I, J)** during winter (left) and summer (right) in the QZB.

diatoms and dinoflagellates biomass using CHEMTAX) in the two seasons, respectively (Figures 6A–D). In the winter, diatoms were composed mostly of *Asterionella glacialis*, *Rhizosolenia sinensis*, *Synedra* sp., *Guinardia delicatula*, and *Skeletonema costatum* (Figure 7A), of which *Asterionella glacialis* was the most dominant species in the winter and concentrated in the eastern part (Figure 6A). Dinoflagellates were composed mainly of *Prorocentrum minimum* (Figure 7A), and was abundant in the eastern part of the study area (Figure 6C). In the summer, the first diatoms dominant species of *Skeletonema costatum* (Figure 7B) concentrated in the eastern part of the study area (Figure 6B), followed by other *Chaetoceros minutissismus*, *Chaetoceros curvisetus*, *Guinardia delicatula*, and *Leptocylindrus danicus* (Figure 7B). The dinoflagellates peaked in the northern part of the study area (Figure 6D).

The abundance of diatoms increased significantly from the winter to summer (P<0.01; Table 1). The abundance of dinoflagellates was not significantly different between the two seasons (P>0.05; Table 1). A high abundant of diatom was observed in the summer, during which the mean phytoplankton

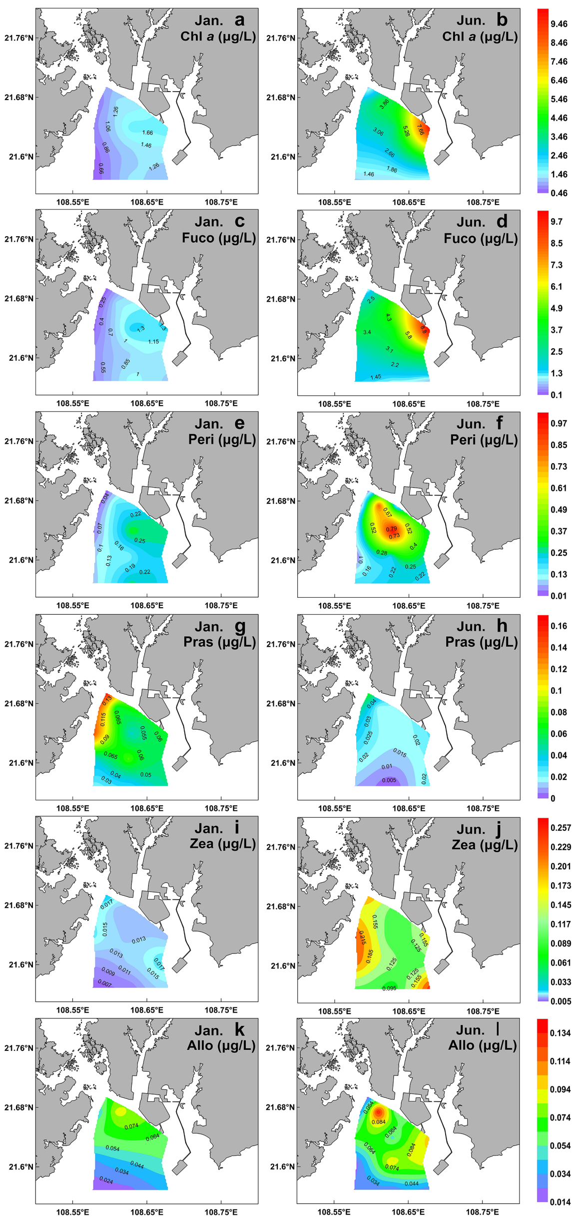

FIGURE 3
Spatial distribution of main surface pigments during winter (left) and summer (right) in the QZB. Chl a **(A, B)**; Fuco **(C, D)**; Peri **(E, F)**; Pras **(G, H)**; Zea **(I, J)**; Allo **(K, L)**.

abundance was 191.81×10^4 cell/L, which was 5.6 times higher than in the winter (Table 1).

3.3 Cell counting *vs*. CHEMTAX estimates

Good agreement was shown between cell counting (abundance) with microscope and CHEMTAX-derived Chl *a* for both diatoms and dinoflagellates (P<0.01; Figure 8).

All the coefficients of correlation were above 0.55 (e.g. R^2 = 0.58 for dinoflagellates in the summer). The highest coefficients were from diatoms in the winter (R^2 = 0.87). The coefficients for diatoms were better than dinoflagellates in both seasons.

3.4 Relationships between phytoplankton composition and environmental factors

A redundancy analysis (RDA) was used to investigate the response of the phytoplankton community (the CHEMTAX) to the environmental variables observed in this study (Figure 9). Results of the Monte Carlo test show that five environmental variables explained significantly the variability of phytoplankton data (P<0.01).

For both the cruises together, the RDA explained 52.9% of the variance associated with the phytoplankton environment relationship. The first canonical axis alone explained 33.71% of the variance. Cyanobacteria, chrysophytes and diatoms correlated positively with temperature. Prasinophytes correlated negatively with temperature. Cryptophytes, haptophytes, and dinoflagellates were strongly associated with lower concentrations of nutrients, and were positively associated with salinity. Chlorophytes biomass increased with nutrients concentrations but decreased with salinity (Figure 9).

4 Discussion

4.1 Phytoplankton community structure as revealed by microscopic methods and CHEMTAX analysis in QZB

Previous investigations on phytoplankton community in QZB using microscopic method showed that diatoms were always the dominant group accounting for over 90% of the total abundance, except during *Phaeocystis globosa* bloom (Jiang et al., 2012; Wang et al., 2013; Luo et al., 2019; Liu et al., 2020). In our study, based on microscopic examination, similar high contribution rate of diatoms for abundances was observed in both the seasons, followed by dinoflagellates (Figure 5B). However, CHEMTAX estimates found that diatom was the most advantageous group during the investigation, but its importance decreased in winter (Figures 4, 5A). Compared to microscopic method, CHEMTAX estimates recognized the important contribution of small-sized flagellates and cyanobacteria to the total phytoplankton biomass, especially during winter period (Figure 5). In fact, due to the limitation of microscopic method, pico- and nano-phytoplankton could not be completely identified for a long time, and it was not until the application of CHEMTAX estimates found that prasinophytes and cyanobacteria had ubiquitous distribution in QZB (Lan et al., 2011; Lan et al., 2013; Lan et al., 2014). A study conducted on January 13, 2021 showed that cryptophytes had the secondly higher contribution (20.25%) to the total biomass in QZB (Pan et al., 2022). Given that the small-sized phytoplankton is responsible for the recycling of the organic matter within the euphotic layer (Seoane et al., 2011) and the partitioning between pico-phytoplankton and larger cells affects the pathway of material transfer to higher trophic levels (Vaquer et al., 1996), we support the use of CHEMTAX as a suitable tool to assess the long-term changes of these small-sized groups in QZB.

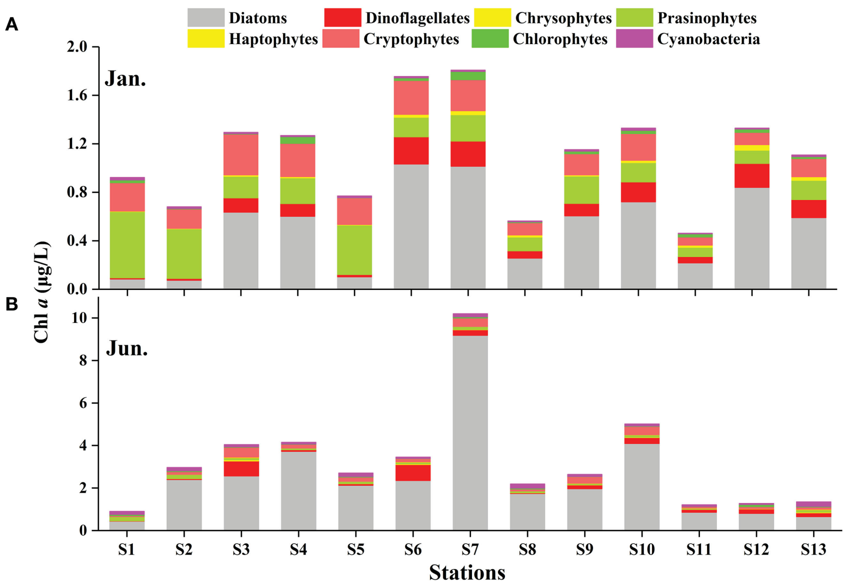

FIGURE 4
The absolute contributions of eight taxonomic groups to Chl *a* (obtained by HPLC-CHEMTAX) in the winter **(A)** and summer **(B)** in the QZB.

Former investigations performed in different seas suggested that the Chl *a* allocation to certain algal groups (e.g., diatoms and dinoflagellates) by CHEMTAX are consistent with those of microscopy (Agirbas et al., 2015; Brito et al., 2015b; Wang et al., 2018). In this study, the correlation between algal cell abundance and CHEMTAX biomass was significant for diatoms and dinoflagellates in both cruises (Figure 8). CHEMTAX estimates is an essential method to identify fragile or small cells (such as prasinophytes, cryptophytes, and cyanobacteria) that would be neglected by microscopic method as shown in Figure 5. Nevertheless, CHEMTAX estimates blind analyses may produce a distorted picture of phytoplankton communities. Irigoien et al. (2004) reported that the dinoflagellates bloom in summer and the haptophytes bloom in spring were interpreted as being composed of diatoms due to the high concentration of fucoxanthin. Furthermore, dinoflagellates might not contain Peri because they are often heterotrophic in summer (Xu et al., 2017). Therefore, it is necessary to understand the species level by microscopic analysis before applying CHEMTAX estimates. In this study, CHEMTAX estimates provided a clear picture of the whole phytoplankton community, especially that of small-sized organisms, whereas microscopy presented accurate taxonomical information (of species or genus) of large-sized phytoplankton, such as diatoms and dinoflagellates.

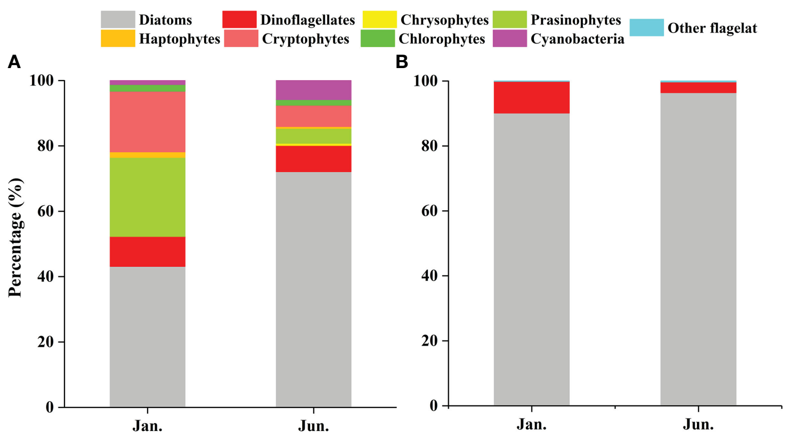

FIGURE 5
The relative contributions of various taxonomic groups in the QZB: CHEMTAX-derived Chl *a* **(A)** and cell abundances **(B)**.

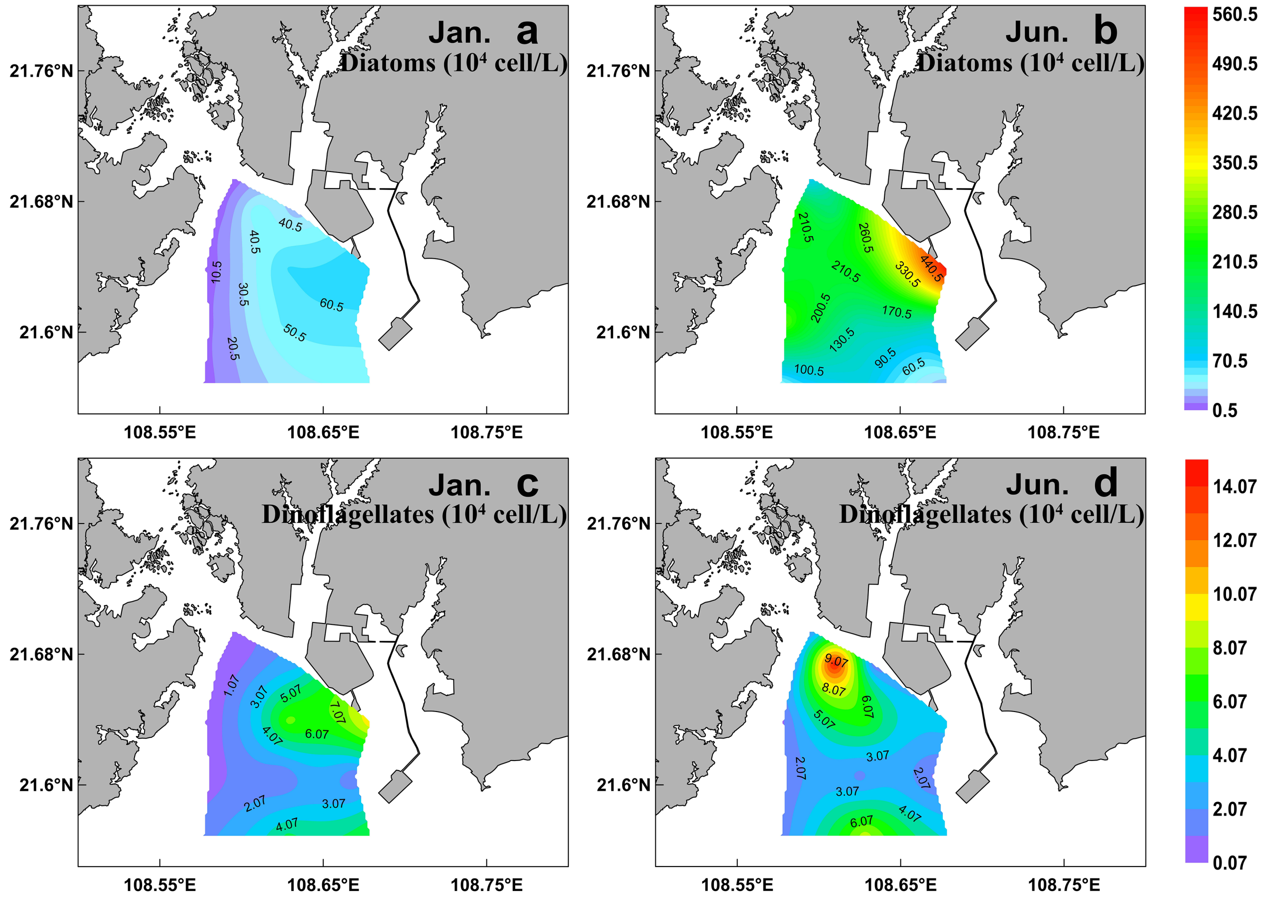

FIGURE 6
Spatial distribution of cell abundance of diatom **(A, B)** and dinoflagellates **(C, D)** (determined by microscope) during winter (right) and summer (left) in the QZB.

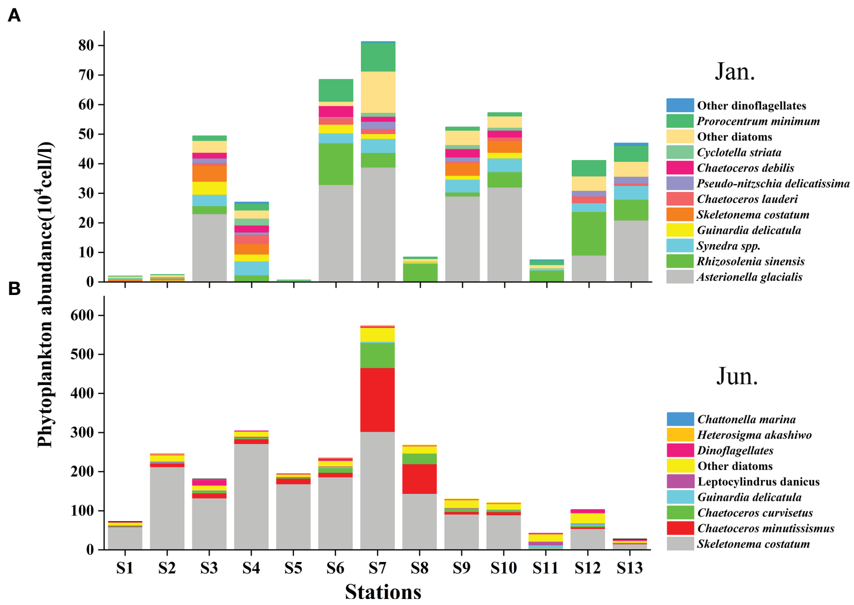

FIGURE 7
Distribution of main phytoplankton species (determined by microscope) during the winter **(A)** and summer **(B)** in the QZB.

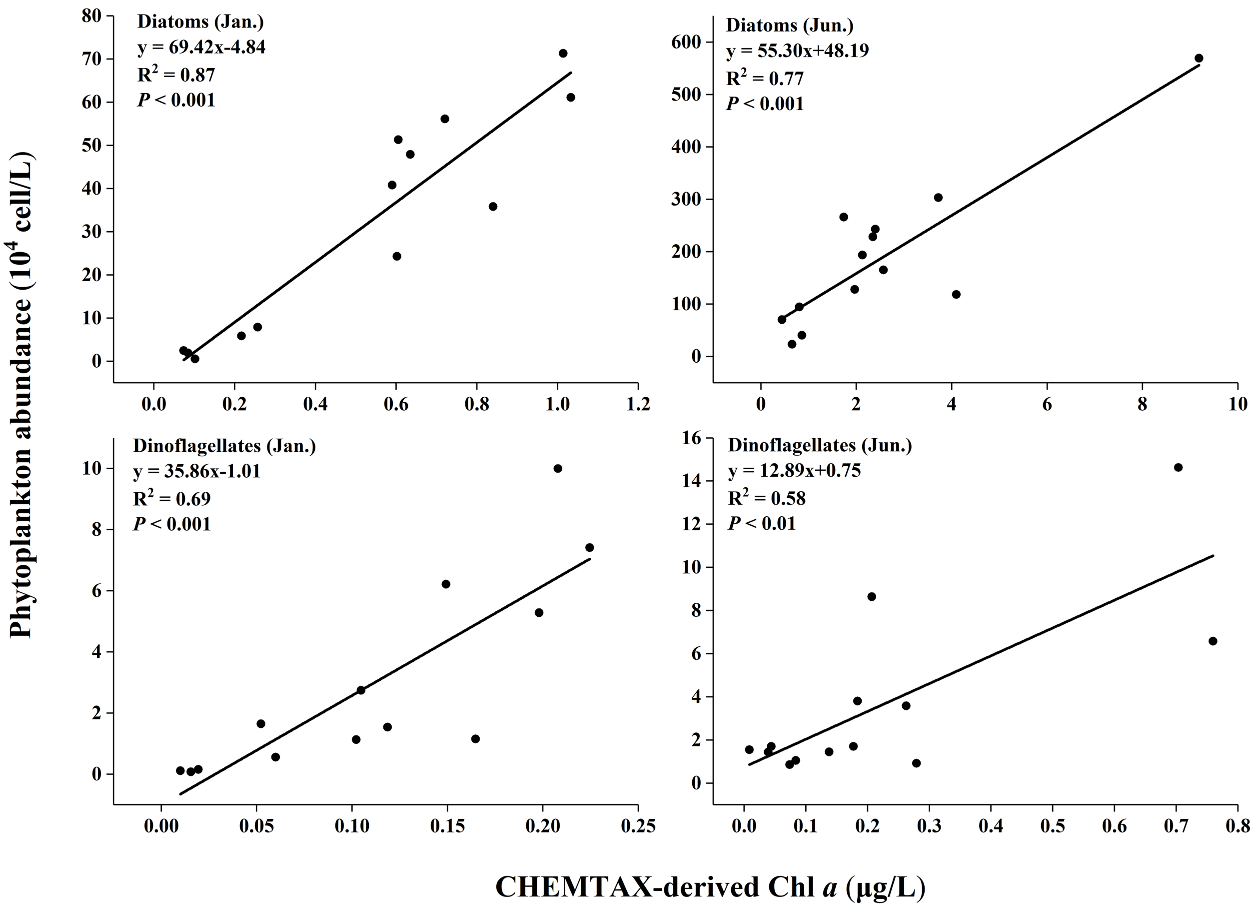

FIGURE 8
Phytoplankton abundance (determined by microscopic counting) against CHEMTAX-derived Chl *a*.

4.2 Phytoplankton groups response to environmental factors

The distributions of physical indicators and nutrients demonstrate that, as a typical estuarine bay, the QZB is vulnerable to terrigenous input and anthropogenic activity whether in dry or wet season (Figure 2). The nutrient concentration in summer is usually much higher than that in winter as terrigenous input spikes in summer. Therefore, phytoplankton biomass is generally greater in summer than in winter in the QZB (Wei and He, 2008; Lai et al., 2013; Wang et al., 2013), the similar seasonal changes in phytoplankton biomass were also revealed by this study (Figure 4, 7). The high biomass of diatoms (Figure 6B) was associated with the bloom of *Skeletonema costatum* in summer (Figure 7B). As a common bloom species in QZB, *Skeletonema costatum* prefer to a warm environment (Chin et al., 1965; Brito et al., 2015b), and usually prevails in summer (Jiang et al., 2012; Wang et al., 2013; Luo et al., 2019; Liu et al., 2020). Temperature played an important role in the variation of diatoms from winter to summer as revealed by RDA (Figure 9). Moreover, diatoms are opportunistic organisms and often show a quick response to nutrient enrichments (Barlow et al., 2004), the DSi in surface seawater replenished by summer runoff may be one of the reasons for the abundant growth of *Skeletonema costatum* (Table 1; Figure 7B) (Brito et al., 2015b). Although the differences of DIN and DRP between the two seasons were not statistically significant (P>0.05; Table 1), it is important to keep in mind that phytoplankton response may be delayed for certain days, when a high abundance of phytoplankton was observed, the nutrients had already been depleted by cells (Davidson et al., 1992; Davidson et al., 1993; Brito et al., 2015b).

Prasinophytes, a group common in temperate and cold waters (Not et al., 2004), were highly abundant during winter in this study (Figures 4A, 5A). The RDA analysis presenting a negative correlation between prasinophytes and temperature, indicateing temperature is one of the main factors affecting the seasonal distribution of prasinophytes (Figure 9). In spatial distribution, prasinophytes concentrated in the oyster culture area in both the seasons (Figures 3G, H). Shellfish preferentially filter larger cells (>3μm) (Ward and Shumway, 2004), thus encouraging the development of the small-size phytoplankton (such as prasinophytes) in shellfish culture area (Dupuy et al., 2000; Jiang et al., 2019; Jiang et al., 2019a). Pico-phytoplankton constitutes an important abundant component of the phytoplankton community in other shellfish aquaculture areas in the world (Safi and Gibbs, 2003; Cranford et al., 2008), which is also mainly ascribed to size-

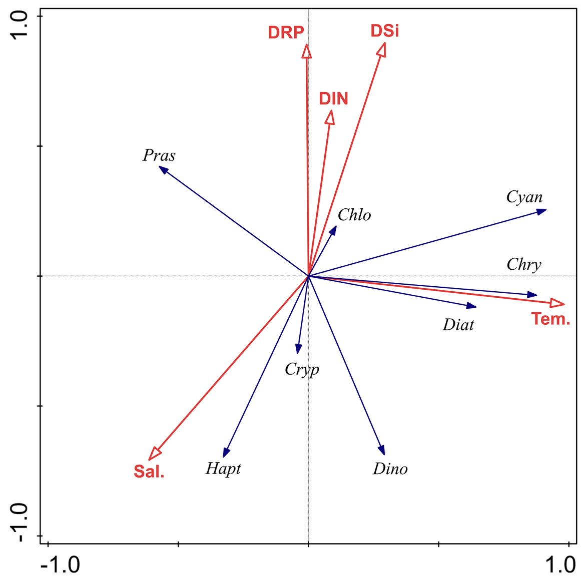

FIGURE 9
Ordination diagram of redundancy analysis for major environmental parameters and phytoplankton groups in the QZB. Red arrows refer to environmental variables. Sal, salinity; Tem, temperature; DIN: DRP and DSi. Variables used: Diat, diatoms; Cryp, cryptophytes; Pras, prasinophytes; Dino, dinoflagellates; Cyan, cyanobacteria; Chlo, chlorophytes; Hapt, haptophytes; Chry, chrysophytes.

selective grazing of shellfish. Lan et al. (2013); Lan et al. (2014) reported that prasinophytes were mainly distributed in oyster culture area during cold seasons. In this study, prasinophytes dominated in oyster culture area (Stations S1, S2, and S5) during winter, where the biomass of larger-size diatoms was very low under the feeding pressure on oyster (Figure 4A). To summarize, oyster aquaculture could stimulate prasinophyte growth, and the seasonal variations are mainly controlled by the water temperature in QZB as shown in the two cruises, which consistent with the results of Jiang et al. (2016).

As a mixotrophic organism, cryptophytes can obtain nutrition through photosynthesis and phagocytosis, especially during the periods of low nutrient concentrations (Lee, 2008). In general, cryptophytes respond to the input of freshwater (Mendes et al., 2013; Brito et al., 2015a) rather than to nutrient enrichment (Balode et al., 1998; Arhonditsis et al., 2007; Mendes et al., 2013). High abundances of cryptophytes were revealed in the Jingu River estuary in both seasons (Figures 3K, L, 4A). Moreover, cryptophytes are an important phytoplankton group in China's coastal waters, such as Jiaozhou Bay (Peng et al., 2010) and Daya Bay (Wang et al., 2018).

The previous study shows that *Synechococcus* and *Prochlorococcus* were common groups of cyanobacteria in the Beibu Gulf (Zhao et al., 2019). In this study, the abundance of cyanobacteria was related to the abundance of *Synechococcus* because divinyl Chl *a*, the exclusive marker pigment of *Prochlorococcus*, was not detected. Although cyanobacteria (mainly *Synechococcus*) were a minority group in terms of average contribution to total Chl *a*, they exhibited strong seasonal fluctuation that thriving in summer and declining in winter (Figures 3I, J, 4). It is known that cyanobacteria are thermophilic (Seoane et al., 2011), and the optimum water temperature range for *Synechococcus* is 27–30°C (Rajaneesh and Mitbavkar, 2013), which is close to the summer water temperature in QZB (Figure 2B). This finding gains support from the RDA analysis presenting a positive correlation between temperature and cyanobacteria (Figure 9).

Nuclear power plant located in the west coast of QZB (Figure 1). According to the horizontal distribution of temperature, the southwestern part of the study area was more affected by the thermal effluent of the nuclear power plant in winter than in summer (Figures 2A, B), which may be related to the strong water exchange capacity during summer in QZB (Dong et al., 2014). Jiang et al. (2019) reported that the thermal discharge from power plants stimulated phytoplankton growth in Xiangshan Bay, China, particularly in cold seasons. However, Pan et al. (2022) found that Chl *a* concentrations were lower in the areas affected by thermal discharge, similar to the results of this study. It is noteworthy that, in addition to thermal pollution, the residual chlorine of the thermal effluent also affects phytoplankton growth (Jiang et al., 2008). Therefore, further attention should be paid to research the response of phytoplankton community structure and biomass to thermal discharge from nuclear power plant in QZB and its mechanism.

4.3 The long-term change in phytoplankton composition and driving factors

The contribution of diatoms to total species number decreased from 90.2% in 1984-1985 (Chen, 1989) to 67.1% in 2014 (annual average), and the proportion of dinoflagellates increased to 28.8% in the same period, so did other groups including haptophytes, chrysophytes, and cyanobacteria etc. (Jiang et al., 2012; Wang et al., 2013; Luo et al., 2019; Liu et al., 2020). On the other hand, the dominant species of phytoplankton in QZB were relatively monotonous, and large-size *Rhizosolenia* spp. were the absolutely dominant species during 1984-1985 (Liu et al., 2020). However, small-sized diatoms, dinoflagellates, and haptophytes gradually were added to the list of dominant species over the last decade (Jiang et al., 2012; Wang et al., 2013; Luo et al., 2019) (Table 2). Our research shows a similar phenomenon that the contribution of dinoflagellates to total species number were 22.2%, small-sized diatoms (*Skeletonema costatum*) and dinoflagellates (*Prorocentrum minimum*) became dominant species (Figure 7). Furthermore, we found that prasinophytes and cryptophytes acted alternatively as the second dominant group during cold season in QZB, and the proportion of small-sized flagellates has been increased since 2010 (excluding data from the Maowei Sea), especially cryptophytes (Table 3). In addition, a study on size-fractionated Chl *a* showed that pico- and nano-phytoplankton were major contributors to Chl *a* in QZB (Mo et al., 2017). These studies suggest that the phytoplankton community of the QZB was developing towards diversification and miniaturization.

The eutrophication of QZB (Wei et al., 2002; Lan, 2012; Yang et al., 2012; Lai et al., 2013) played an important role in the changes of phytoplankton class structure. Generally, increased nitrogen and

TABLE 2 Long-term variation in dominant species and various taxonomic groups contribution (%) to total species number in QZB.

Investigation time	Diatoms	Dinoflagellate	Other groups	Main dominant species	References
1984-1985	90.2%	9.8%	0%	*Rhizosolenia alata f. gracillima Rhizosolenia imbricate Thalassionema nitzschioides*	Chen, 1989
2008*	77.1%	17.6%	5.3%	*Chaetoceros curvisetus Skeletonema costatum Rhizosolenia alata*	Wang et al., 2013
2010-2011*	77.2%	14.5%	8.3%	*Chaetoceros curvisetus Skeletonema costatum Thalassionema nitzschioides*	Jiang et al., 2012
2013-03,07*	86.9%	12.2%	0.9%	*Coscinodiscus radiates Ditylum brightwelii Skeletonema costatum Thalassiosira nordenskioldii*	Luo et al., 2019
2013-2014	67.1%	28.8%	4.1%	*Skeletonema costatum Chaetoceros curvisetus Phaeocystis globosa Thalassiosira nordenskioldii*	Liu et al., 2020
2021-01,06	73.7%	22.2%	4.1%	*Skeletonema costatum Asterionella glacialis Chaetoceros minutissismus Rhizosolenia sinensis*	This study

*The stations data in Maowei Sea are included.

phosphorus in the areas of eutrophication often leads to excessive phytoplankton growth, however, diatoms require silica for their shells in addition to these nutrients. For this reason, non-diatom phytoplankton groups increase in species number and biomass in eutrophic waters; for example, the species number of dinoflagellates were obviously dominant compared to diatoms in the south-eastern Black Sea (Agirbas et al., 2015) and the phytoplankton community changed from the diatoms dominance to co-dominance of diatoms and dinoflagellates in the Bohai Sea (Pan et al., 2020). According to the statistics, several bloom of haptophytes (*Phaeocystis globosa*) and dinoflagellates (e.g. *Noctiluca scintillans*, *Gymnodinium sanguineum*, and *Gymnodinium catenatum* and so on) occurred in QZB over the past decade (Qin et al., 2016; Shen et al., 2018; Liu et al., 2020; Su et al., 2022).

Variation in phytoplankton size scaling usually related to temperature and nutrients (Jiang et al., 2019b). It is widely recognized that small-sized phytoplankton have been considered an indicator to stressful environments, they tend to dominate in oligotrophic sea area because of its large relative surface area and high utilization rate of nutrients (Sabetta et al., 2008), whereas large-celled phytoplankton benefit from a eutrophic environment (González-García et al., 2018). However, in this study, prasinophytes were concentrated in the northwest of the study area where nutrient was enriched the most in both the seasons (Figures 2E–J, 3G, H). As described in section 4.2, in addition to nutrients, phytoplankton community structure also depends on biological factors (grazing of shellfish) in high-density shellfish culture area. Cloern (1982) suggested that phytoplankton is much more controlled by shellfish feeding than by nutrients concentration, indicating that the phytoplankton community structure in oyster culture area of QZB was mainly affected by oyster feeding rather than by high nutrient concentration. Therefore, the long-term size-selective filtration of shellfish stimulated the small-size phytoplankton growth in QZB.

TABLE 3 Long-term variation in various taxonomic groups contribution (%) to phytoplankton biomass in the QZB.

Investigation time	Contribution of various taxonomic groups to phytoplankton biomass obtained by HPLC-CHEMTAX (%)					References
	Diatoms	Prasinophytes	Cyanobacteria	Cryptophytes	Dinoflagellates	
2010-06*	84.61	4.16	4.81	1.00	2.20	Lan et al., 2011
2010-10*	76.67	11.40	5.28	1.18	1.27	Lan et al., 2013
2011-03*	71.89	19.06	1.73	0.36	4.57	Lan et al., 2014
2021-1-13	62.29	9.77	0.96	20.25	3.43	Pan et al., 2022
2021-1-27	43.12	24.18	1.29	18.54	9.17	This study
2021-6-23	72.11	4.53	5.80	6.54	8.03	This study

*The stations data in Maowei Sea are excluded.

Mesocosm experiments (Yvon-Durocher et al., 2011; Peter and Sommer, 2015) and field investigations (Morán et al., 2010) have confirmed a tendency toward smaller size at higher temperatures for different phytoplankton groups, include diatoms, picophytoplankton (*Prochlorococcus*, *Synechococcus*, and picoeukaryotes), and chlorophytes. The water temperature in QZB was up from 1983 to 2003 (He and Wei, 2010), possibly indicating warming in QZB as well under climate change. Moreover, thermal discharge may potentially accelerated the warming trend in QZB. We inferred that increased dominance of small-sized diatoms in QZB is closely related to size-selective grazing of oyster and increased warming. It is noteworthy that the biomass and proportion of cyanobacteria may also increase in the future driven by these two factors. Overall, size-selective grazing of oyster farming and warming might the main reasons causing phytoplankton miniaturization in QZB, especially in oyster culture area.

5 Conclusions

The microscopy and HPLC-CHEMTAX was combined to obtain complete information about species composition and spatial distribution of entire phytoplankton community in QZB. Microscopy analysis revealed that diatoms were absolute dominant group in summer and winter, 2021, followed by dinoflagellates. As a complementary method, HPLC-CHEMTAX detected other small-size flagellates and cyanobacteria, of which prasinophytes and cryptophytes were important groups in winter. This study confirms our hypothesis that the spatiotemporal distributions of various phytoplankton groups were affected by physicochemical factor and size-selective grazing of shellfish. High temperature and adequate nutrients in summer could promote the algal blooms of *Skeletonema costatum*. A high grazing pressure of shellfish and low temperature were the driving force to the prevalence of prasinophytes in the winter. The distribution of cryptophytes was related to the location of estuary. Driven by high temperature, cyanobacteria (mainly *Synechococcus*) thrived in summer while declined in winter. In addition, the negative impact of thermal discharge on phytoplankton occurred mainly in winter. Compared with previous reports, the proportion of small-sized flagellates has been increased over the past decade. The change of phytoplankton taxonomic structure may be related to the eutrophication of QZB, phytoplankton miniaturization was largely regulated by grazing of oyster and climate warming. The microscopy derived cell abundances and CHEMTAX analysis information for diatoms and dinoflagellates were in good agreement. Microscopy provided accurate species information for large cells, while HPLC-CHEMTAX provided detailed data of small-sized phytoplankton groups. However, no single technique is ideal for the investigation of the structure and dynamics of phytoplankton community. We suggest that in future, research should combine CHEMTAX estimates with microscopic counting to improve the long-term understanding of phytoplankton community dynamic in QZB.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

HP, MX and JLai wrote the original manuscript. CL, JM, JLi and JLu attended the experiments and took part in the data analysis. All authors contributed to the article and approved the submitted version.

Funding

This study was funded by the Guangxi Special Fund Project for Local Science and Technology Development Guided by the Central Government (No.ZY21195027) and the Science and Technology Major Project of Guangxi (No. AA17202020).

Acknowledgments

The authors wish to thank Mr. B. J. Meng and Miss L. T. Huang, L. W. Chen, Q. Q. Liang who provide assistance in sample collection during field investigations.

Conflict of interest

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2023.1186106/full#supplementary-material

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frontiers | Frontiers in Marine Science

TYPE Original Research
PUBLISHED 18 May 2023
DOI 10.3389/fmars.2023.1196196

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OPEN ACCESS

EDITED BY
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RECEIVED 29 March 2023
ACCEPTED 08 May 2023
PUBLISHED 18 May 2023

CITATION
Li Y, Sun L, Wu Z and Liu H (2023) Evaluation and obstacle factors of marine resources and environment carrying capacity in Beibu Gulf Urban Agglomeration.
Front. Mar. Sci. 10:1196196.
doi: 10.3389/fmars.2023.1196196

Evaluation and obstacle factors of marine resources and environment carrying capacity in Beibu Gulf Urban Agglomeration

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With the strong support of the Chinese government, the Beibu Gulf Urban Agglomeration has responded positively to the national call to vigorously develop the marine economy. However, a series of marine resource and environmental problems such as over-exploitation of marine resources and excessive discharge of marine pollutants in the Beibu Gulf Urban Agglomeration has also arisen along with the rapid development of the marine economy, limiting the space for the development of the marine economy in the Beibu Gulf Urban Agglomeration. Based on the panel data of seven coastal cities in the Beibu Gulf urban agglomeration from 2011-2021, the DPSIR model was used to construct a marine resources environmental carrying capacity evaluation index system including five dimensions of driving force, pressure, state, impact and response, and the TOPSIS model with combined weighting was used to make a comprehensive evaluation of the marine resources carrying capacity of the Beibu Gulf urban agglomeration, and then the barrier degree model was used to explore the barriers to the carrying capacity of marine resources and environment in the Beibu Gulf Urban Agglomeration. The empirical results show that, on the whole, the marine resources and environment carrying capacity of the seven coastal cities in the Beibu Gulf Urban Agglomeration show an upward trend. From the situation of each subsystem, the pressure subsystem and response subsystem have greater evaluation values, while the evaluation of the driving force, state, and influence subsystem needs to be improved; from the analysis of obstacle factors, the main single indicator obstacle factors include per capita coastline length, total import and export volume, and port cargo throughput, etc. The status subsystem is the main classification indicator barrier factor affecting the improvement of the marine resource and environmental carrying capacity of the Beibu Gulf Urban Agglomeration. Based on the results of the empirical analysis, corresponding suggestions are put forward.

KEYWORDS

Beibu Gulf Urban Agglomeration, marine resources and environmental carrying capacity, marine economy, DPSIR-TOPSIS model, obstacle model

1 Introduction

Since the beginning of the 21st century, China has been paying more attention to the marine economy, and various marine undertakings are developing steadily, with China's gross marine product reaching RMB 9.04 trillion in 2021 (Liu et al., 2023). With the strong support of the Chinese government, the Beibu Gulf Urban Agglomeration has responded to the national call to vigorously develop the maritime economy, with the initial formation of port-side industrial clusters with petrochemicals, metallurgy, energy, and grain and oil processing as pillars, and the accelerated development of new industries and modern services (Li, 2022). 6,117 trains of the Western Land and Sea New Corridor were operated in 2021, an increase of 33% year-on-year. The urban agglomeration's backbone road network has formed, the growth rate of port cargo throughput is among the highest in China, and the route network covers ASEAN and major domestic ports (Qi et al., 2022). With the deepening of opening up to the outside world, the total import and export volume of the Beibu Gulf Urban Agglomeration has increased significantly, with the total import and export volume of Nanning, the 'leading' city of the cluster, exceeding RMB 120 billion in 2021 (Wang and Liao, 2022). At the same time, the construction of major open platforms such as China (Guangxi) Pilot Free Trade Zone is steadily advancing, and economic, trade, humanistic exchanges, and maritime cooperation between the Beibu Gulf Urban Agglomeration and ASEAN countries continue to deepen. However, a series of marine resource and environmental problems such as overexploitation of marine resources and excessive discharge of marine pollutants have also arisen along with the rapid development of the marine economy. The overexploitation of marine resources and the continuous destruction of the marine environment in the Beibu Gulf Urban Agglomeration will limit the space for the development of the marine economy in the Beibu Gulf Urban Agglomeration (Batty, 2000). Therefore, while achieving the rapid development of the marine economy in the Beibu Gulf Urban Agglomeration, attention should also be paid to the construction of marine resources and the environment. How to improve the carrying capacity of the marine resources and environment and achieve sustainable development of the marine resources and environment while maintaining the rapid development of the marine economy in the Beibu Gulf Urban Agglomeration has become a hot issue of social concern (Li et al., 2022).

The carrying capacity of marine resources and the environment can be divided into three types: industrial carrying capacity, natural carrying capacity, and economic carrying capacity (Song and Du, 2019), which refers to the capacity or limit of marine resources to support human economic activities and social development within a certain period time, provided that the marine environment is not damaged (Stojanovic and Farmer, 2013). Scholars have studied the composition and measurement of the carrying capacity of marine resources and environment, such as the construction of a composite economic-resource-environment system to study the carrying capacity of Guangdong's marine resources and environment (Zhang et al., 2020); the incorporation of ecosystem services into the traditional DPSIR model, and the application of the modified EBM-DPSIR model to the Florida Keys and the Dry Tortugas marine ecosystem (Kelble et al., 2013); measuring marine resource carrying capacity and barriers in 11 coastal provinces of China from 2006-2016 (Song and Ning, 2020); Using image video processing tools and video sequence algorithms to assess the environmental carrying capacity of marine resources (Cisneros et al., 2016); the use of a multidimensional approach to assess the expansion of coastal cities and monitor the process of changes in the carrying capacity of marine resources and the environment, in order to propose solutions to achieve sustainable development goals for coastal cities (Theodora and Spanogianni, 2022). Coordination is an important aspect of the study of the carrying capacity of marine resources and the environment. Using the subjective and objective synthesis method to determine the weight of each indicator, the coupled coordination model can measure the degree of coordination between economic development and the carrying capacity of marine resources and the environment (Wang and Yang, 2021); using the spatiotemporal weight matrix and coupled coordination model can examine the coordination between the marine economy and the carrying capacity of the ocean (Yu and Di, 2020). Integrating spatial data on human activities and ecology and exploring different methods of land-sea interaction are conducive to achieving sustainable development of coastal areas (Hietala et al., 2021); improving the carrying capacity of marine resources and environment should focus on sustainable development of economic, socio-cultural, environmental protection and renewable energy (Liao, 2018), while in concrete practice, coastal area management policies, spatial planning and overall strategic planning generally lack coordination, which affects the improvement of the carrying capacity of the marine environment, and there is a need to develop approaches to marine ecosystem and environmental management and protection (Cantasano et al., 2017); combining scientific, technological, management, legal and policy capabilities across elements can enable dynamic ocean management (Hobday et al., 2014); competing ocean uses and the continued increase in ocean development require ocean management to integrate the environmental, economic and social impacts of all activities to achieve sustainable development of marine resources (Elliott et al., 2017).

The evaluation of the carrying capacity of marine resources and the environment and the study of the barriers are the core and key, and most of the existing research results are based on the determination of index weights through a single subjective or objective assignment method (Wang et al., 2022). At the same time, previous studies have mainly focused on a particular country, province (region), or more mature urban agglomerations, and less research has been conducted on embryonic urban agglomerations with relatively small economic power (Chen and Yao, 2021). Therefore, this paper uses the DPSIR model to construct marine resources and environment carrying capacity evaluation index system that includes five dimensions: driving force, pressure, state, impact, and response, and uses the AHP-entropy method to assign weights to subjective and objective combinations, and adopts the TOPSIS model and barrier degree model to evaluate and analyze the marine resources and environment carrying capacity of the Beibu Gulf urban agglomeration from 2011 to 2020. The study proposes suggestions for further improving the carrying capacity of marine resources and environment in the Beibu Gulf Urban Agglomeration, promoting the high-quality development of the marine economy in the Beibu Gulf Urban Agglomeration, and achieving the development goal of building a first-class blue bay Urban Agglomeration with regional and international influence (Zhang et al., 2022).

2 Materials and methods

2.1 Study area and data sources

According to the Beibu Gulf Urban Agglomeration Development Plan issued in 2017, the planning area of the Beibu Gulf Urban Agglomeration spans Guangxi, Guangdong, and Hainan provinces and includes six prefecture-level cities in the Guangxi Zhuang Autonomous Region: Nanning, Beihai, Qinzhou, Fangchenggang, Yulin, and Chongzuo; three prefecture-level cities in Guangdong Province: Zhanjiang, Maoming, and Yangjiang; and six prefecture (county) level cities in Hainan Province: Haikou, Danzhou, Dongfang, Chengmai, Lingao, and Changjiang. This paper takes its seven coastal cities, namely Zhanjiang, Yangjiang, Maoming, Qinzhou, Beihai, Fangchenggang, and Haikou, as the study area to analyze the level of marine resources and environmental carrying capacity of the Beibu Gulf urban agglomeration and the factors that hinder it. The study area has a land area of 116,600 square kilometers and a coastline of 4,234 kilometers, with the proportion of terrestrial ecological space remaining stable at over 43% and the overall water quality of the near-shore waters reaching Class II standards or above. The Beibu Gulf urban agglomeration, with its back to the southwest, adjacent to Guangdong, Hong Kong, and Macao, and facing Southeast Asia, is an important hub of the Maritime Silk Road and has an important strategic position in the strategic pattern of western development and the general pattern of China's opening up and cooperation with ASEAN (Chen, 2021). 2022, the China Development and Reform Commission officially issued the Fourteenth Five-Year Plan for the Construction of the Beibu Gulf Urban Agglomeration The program states that during the 14th Five-Year Plan period, the maritime economy of the Beibu Gulf Urban Agglomeration will develop at a rapid pace and that it is important to protect the "one bay", that is the coastal area around the Beibu Gulf and the offshore waters, and to strengthen the protection and restoration of the ecosystem. The plan is to strictly delineate the ecological protection red line in the coastal waters and explore the establishment of an integrated coastal, watershed, and sea area management system, setting out a new blueprint for the Beibu Gulf Urban Agglomeration to build a high-level blue ecological bay area (Dong et al., 2022).

Given the relatively short period time for the comprehensive planning and construction of the Beibu Gulf Urban Agglomeration, and because of the availability of data and the principles of objectivity, scientificity, and dynamism, this paper selects the sample data of the Beibu Gulf urban agglomeration from 2011 to 2020 for the study. The original data of the indicators used in this study were obtained from 2011 to 2020 from China Tertiary Industry Statistical Yearbook (http://www.stats.gov.cn/sj/), China Transport Statistical Yearbook (https://www.mot.gov.cn/tongjishuju/), China Transport Yearbook (https://www.mot.gov.cn/tongjishuju/), China Urban Statistical Yearbook (https://data.cnki.net/v3/trade/yearbook/Single/N2022040095?zcode=Z023) and the statistical yearbooks of seven coastal cities; the data on environmental pressure and environmental management were mainly obtained from 2011 to 2020 from China Marine Statistical Yearbook (http://mds.nmdis.org.cn/pages/ocean_list.html), China Environmental Statistical Yearbook (https://navi.cnki.net/knavi/yearbooks/YHJSD/detail), China Urban Construction Statistical Yearbook (http://www.stats.gov.cn/sj/), Guangdong Statistical Yearbook (http://stats.gd.gov.cn/gdtjnj/) and the environmental situation bulletins of seven coastal cities for the past years; Data on resource pressure and resource use were mainly obtained from 2011 to 2020 from the China Energy Statistical Yearbook (https://data.cnki.net/v3/trade/yearbook/Single/N2022060061?zcode=Z023) and the statistical bulletins on national economic and social development of the seven coastal cities in previous years, with data on individual indicators calculated by means of the corresponding formulae.

2.2 Research methodology

2.2.1 The DPSIR model

In 1993, the European Environment Agency (EEA) proposed the DPSIR model by combining two models, DSR (Driving Force-State-Response) and PSR (Pressure-State-Response), and adding an impact factor (Bai et al., 2022). This model has the greatest advantage of explaining the interaction between human and other environmental factors from a system analysis perspective (Shao and Ju, 2010), describing the logical chain between the cause and effect of a problem in a clearer way, and comprehensively constructing the causal relationship between each indicator (Westing, 1989). The DPSIR model, which integrates ecological, economic, and social influences, has been introduced into the field of marine resources and environmental carrying capacity evaluation and is widely used.

In the DPSIR model of the marine resources and environment carrying capacity evaluation system, driving force (D) - pressure (P) - state (S) - impact (I) - response (R) is a series of interacting processes (Figure 1). In this system logic chain, the driving force (D) is the most primitive and critical subsystem of marine resources and environment-carrying capacity change. The driving factors such as regional economic development, intensification of human activities, and population growth drive changes in the marine resources and environment system and exert pressure (P) on the marine resources and environment carrying capacity system (Jia and Wang, 2023). The drivers and pressures cause a series of changes in the state (S) of the marine resource-environment system, resulting in various impacts (I). Ultimately, to adjust the state of the marine resource environment and reduce adverse impacts, the government takes a series of policy measures to respond (R) to the marine resource environment system, and the response (R) backfires on the whole DPSIR system (Shen and Jiang, 2018).

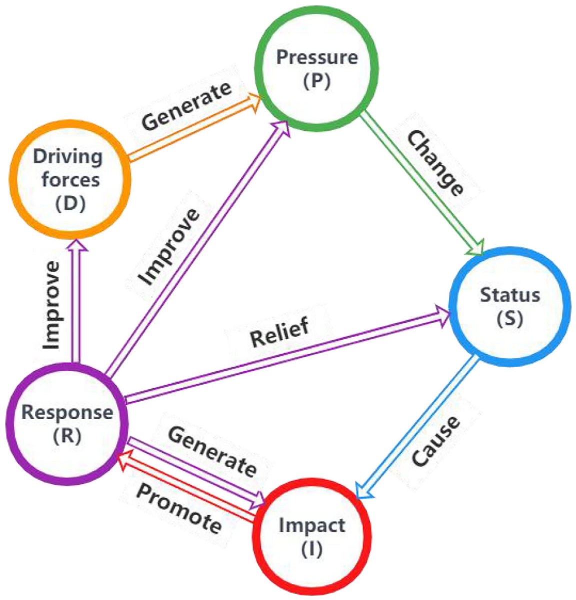

FIGURE 1
Logical mechanism of the DPSIR model for marine resource and environmental carrying capacity evaluation system.

2.2.2 Indicator system construction

The marine resources and environment carrying capacity evaluation index system cover three aspects: resources, economy, and environment (Di and Wu, 2018), which can measure the carrying capacity of the composite system using the coordinated development model of economy, environment, and resources and reflect the relationship between each subsystem (Gai et al., 2018), and the environmental carrying capacity of water and marine resources can be studied in four dimensions: scale, structure, mode, and network (Zhou et al., 2019). Based on the previous research results, this study starts from the basic framework of the DPSIR model, follows the principles of scientificity, comparability, and systematization, and constructs marine resources and environment carrying capacity evaluation index system from five dimensions of "driving force (D) - pressure (P) - state (S) - impact (I) - response (R)", which is shown in Table 1.

2.2.3 Combined weighting method

To more accurately reflect the weight of each indicator of the marine resources and environment carrying capacity of the Beibu Gulf Urban Agglomeration, this paper combines the subjective weighting of the hierarchical analysis method with the objective weighting of the entropy weighting method to determine its combined weight (Gou and Lu, 2020).

The Analytic Hierarchy Process (AHP) was proposed by the American scholar T L Saaty, which can combine quantitative and qualitative aspects to determine the subjective weights of each evaluation index (Liu et al., 2020). The entropy weighting method can determine the objective weights of each evaluation indicator based on the information provided by them, avoiding the bias of results caused by the arbitrariness of subjective assignment.

2.2.3.1 Basic steps of AHP

(1) Build a judgment matrix:

$$U = (a_{uv})_{m\times m} \tag{1}$$

The value range for a_{uv} is 1 to 9.

(2) Calculate the maximum eigenvector of the judgment matrix:

$$U_w = \lambda_{max} w \tag{2}$$

The maximum eigenvalue λ_{max} and the corresponding eigenvector w of the judgment matrix can be obtained according to Eq.

(3) A consistency test was adopted, and the consistency indicator CR was calculated using the following formula:

$$CR = \frac{CI}{RI} \tag{3}$$

When the consistency ratio CR is less than 0.1, it indicates that the judgment matrix passes the consistency test, CI represents the consistency index and RI is the average random consistency index.

(4) The Consistency Index CI is calculated as follows:

$$CI = \frac{\lambda_{max-n}}{n-1} \tag{4}$$

(5) After normalization, the weights of each indicator ω_i' are obtained.

2.2.3.2 Basic steps of entropy weight method

(1) Construction of the original data matrix:

$$Z = (z_{ij})_{m\times n} \tag{5}$$

(2) Standardization of data.

Positive indicators:

$$r_{ij} = {}^{(z_{ij}-minz_{ij})}\Big/_{(maxz_{ij}-minz_{ij})} \tag{6}$$

Negative indicators:

$$r_{ij} = {}^{(minz_{ij}-z_{ij})}\Big/_{(maxz_{ij}-minz_{ij})} \tag{7}$$

(3) Calculate the information entropy of each indicator, with f_{ij} being the characteristic weight of the indicators:

$$H_i = -\frac{1}{\ln m}\sum_{j=1}^{m} f_{ij}\ln f_{ij} \tag{8}$$

$$f_{ij} = \frac{r_{ij}}{\sum_{j=1}^{m} r_{ij}} \tag{9}$$

(4) The calculation yields the entropy weights for each indicator:

$$\omega_i'' = {}^{(1-H_i)}\Big/_{(n-\sum_{i=1}^{n} H_i)} \tag{10}$$

(5) Using equation (11) (Zhou et al., 2017) to determine the final portfolio weights, the results are shown in Table 1.

TABLE 1 Marine resources and environment carrying capacity evaluation index system and index weights.

Target layer: Marine Resources Environmental Carrying Capacity				
Criterion layer	Indicator layer	Measuring unit	Indicator attribute	Portfolio weights
driving force (D)	C_1 (GDP)	billion yuan	+	0.0617
	C_2 (Total imports and exports)	billion dollars	+	0.0585
	C_3 (Port cargo throughput)	10,000 tons	+	0.0620
	C_4 (Urban disposable income per capita)	yuan/person	+	0.0499
	C_5 (Natural population growth rate)	‰	+	0.0298
pressure (P)	C_6 (Electricity consumption per unit of coastline)	million kWh/km	–	0.0426
	C_7 (Industrial wastewater discharge per unit of coastline)	10,000 t/km	–	0.0220
	C_8 (Industrial sulfur dioxide emissions per unit of coastline)	t/km	–	0.0266
	C_9 (Industrial smoke (dust) emissions per unit of coastline)	t/km	–	0.0237
state (S)	C_{10} (Length of coastline per capita)	m	+	0.1030
	C_{11} (Aquatic production per capita)	t	+	0.0779
	C_{12} (Landscaped area)	hm^2	+	0.0352
	C_{13} (Green coverage in built-up areas)	hm^2	+	0.0465
impact (I)	C_{14} (Urban sewage treatment rate)	%	+	0.0340
	C_{15} (Integrated utilization rate of general industrial solid waste)	%	+	0.0104
	C_{16} (Household waste disposal rate)	%	+	0.0215
	C_{17} (Number of persons employed in scientific research, technical services, and geological prospecting)	10,000 people	+	0.0557
	C_{18} (Number of people working in water and environment)	10,000 people	+	0.0518
response (R)	C_{19} (Greenery coverage of built-up areas)	%	+	0.0388
	C_{20} (General public budget expenditures)	10,000 yuan	+	0.0515
	C_{21} (Share of science expenditure in general public budget expenditure)	%	+	0.0520
	C_{22} (Share of education expenditure in general public budget expenditure)	%	+	0.0450

$$W_i = \frac{\omega_i^{'}\omega_i^{''}}{\sum_{i=1}^{n}\omega_i^{'}\omega_i^{''}} \tag{11}$$

2.2.4 TOPSIS model evaluation methods

The TOPSIS model is one of the comprehensive evaluation methods for multi-objective decision making with limited options and is an analytical method applied to the selection of multiple options with multiple indicators (Chen et al., 2022). TOPSIS model obtains more objective evaluation results by calculating the distance between the evaluated object and the corresponding ideal target, and the main evaluation steps are as follows.

(1) Determine the positive and negative ideal solutions. z_i^+ is the maximum value of the i-th indicator during j years, setting z_i^+ as the positive ideal solution; z_i^- is the minimum value of the i-th indicator during j years, setting z_i^- as the negative ideal solution.

Positive ideal solutions:

$$z^+ = \left\{ \max_{1\le i\le n} z_{ij} | i = 1, 2, \cdots, n \right\} = \{z_1^+, z_2^+, \cdots z_n^+\} \tag{12}$$

Negative ideal solutions:

$$z^- = \left\{ \min_{1\le i\le n} z_{ij} | i = 1, 2, \cdots, n \right\} = \{z_1^-, z_2^-, \cdots z_n^-\} \tag{13}$$

(2) Determine the distance between the indicator and the positive and negative ideal solutions. The Euclidean method was used to determine the distances from the indicators to the positive and negative ideal solutions (Hu and Li, 2022), letting D_j^+ be the distance of the i-th indicator from z_i^+ and letting D_j^- be the distance of the i-th indicator from z_i^-.

Distance to the positive ideal solution:

$$D_j^+ = \sqrt{\sum_{i=1}^{n}(z_i^+ - z_{ij}^-)^2} \tag{14}$$

Distance to the negative ideal solution:

$$D_j^- = \sqrt{\sum_{i=1}^{n}(z_i^- - z_{ij}^-)^2} \quad (15)$$

(3) Calculate the comprehensive evaluation index. T_j represents the comprehensive evaluation index of the bearing capacity of marine resources and environment in year j, and takes the value range (0,1]. The closer the value of the index is to 1, the higher the score of the comprehensive evaluation, while the closer it is to 0, the lower the score of the comprehensive evaluation.

$$T_j = \frac{D_j^-}{D_j^+ + D_j^-} \quad (16)$$

2.2.5 Classification of marine resources environmental carrying capacity

This paper adopts the Jenks best natural fracture method to classify the marine resources and environmental carrying capacity. According to the classification method of minimum intra-class difference and maximum inter-class difference, the marine resources and environmental carrying capacity level of the Beibu Gulf Urban Agglomeration is classified into four levels: good, average, sensitive and fragile, and the evaluation levels and corresponding carrying capacity levels are shown in Table 2.

2.2.6 Barrier degree model measurement methods

To study the barrier factors in depth, the barrier degree was calculated for each indicator by applying the barrier degree model (Pan et al., 2019).

Factor contribution F_{ij} is the weight of a single indicator:

$$F_{ij} = w_{ij} \times w_i \quad (17)$$

Deviation I_{ij} is the difference between a single indicator and the target:

$$I_{ij} = 1 - R_i \quad (18)$$

P_{ij} is the degree of impairment for disaggregated indicators and individual indicators in year j:

$$P_{ij} = \frac{F_{ij} \times I_{ij}}{\sum_{i=1}^{n}(F_{ij} \times I_{ij})} \times 100\,\% \quad (19)$$

TABLE 2 Grading criteria for the level of marine resources and environmental carrying capacity of the Beibu Gulf Urban Agglomeration.

Carrying capacity	Evaluation level	Carrying capacity level
T>0.54	Level 1	Good
0.54≥T>0.45	Level 2	Average
0.45≥T>0.40	Level 3	Sensitive
0.40≥T>0.34	Level 4	Fragile

U_j indicates the degree of obstruction of the criterion layer:

$$U_j = \sum P_{ij} \quad (20)$$

w_{ij} is the weight of the j-th indicator in the i-th criterion layer, w_i is the weight of the i-th criterion layer in which the j-th indicator is located, and R_i is the standard value of the individual indicator.

3 Results and analysis

3.1 Analysis of the results of the evaluation of the bearing capacity of marine resources and environment of the Beibu Gulf Urban Agglomeration

3.1.1 Comprehensive evaluation analysis of the carrying capacity of marine resources and environment

By evaluating and analyzing the marine resources and environmental carrying capacity of the seven coastal cities in the Beibu Gulf Urban Agglomeration, a comprehensive evaluation of the marine resources and environment of the seven coastal cities in the Beibu Gulf Urban Agglomeration from 2011 to 2020 was derived (Figure 2).

On the whole, the marine resource and environmental carrying capacity of the seven coastal cities in the Beibu Gulf Urban Agglomeration showed an upward trend from 2011 to 2020, with Qinzhou, Fangchenggang, Haikou, Maoming and Yangjiang rising from fragile to the average level, Beihai rising from sensitive to average level and Zhanjiang rising from average to the good level. Among them, most of the seven cities showed significant fluctuations during the period 2011-2015. Yangjiang and Haikou showed greater fluctuations, and both experienced significant declines in 2015, with the lowest values in both cities at sensitive levels. the marine resource and environmental carrying capacity of the seven coastal cities gradually increased during 2016-2020 and stabilized at average and good levels during 2019-2020.

In 2013, the 12th Five-Year Plan for the Development of the National Marine Industry was officially published, detailing plans for China's marine development, and the transformation of the coastal region's economic and social development patterns and activities from 2011-2016. The plan clearly states that in 2011, China's gross marine product was RMB 4557 billion, accounting for 9.7% of the gross domestic product. Among them, the added value of marine industries was RMB 2,650.8 billion and the added value of marine-related industries was RMB 1,906.2 billion. The growth rate of the marine economy was remarkable, but at the same time, the rough and sloppy way of marine economic development affected the construction of marine resources and the environment, which was the main reason why the bearing capacity of marine resources and the environment of the seven coastal cities in the Beibu Gulf Urban Agglomeration showed significant fluctuations from 2011 to 2015.

As we entered 2016, the issue of marine resource protection and the marine environment attracted widespread attention from

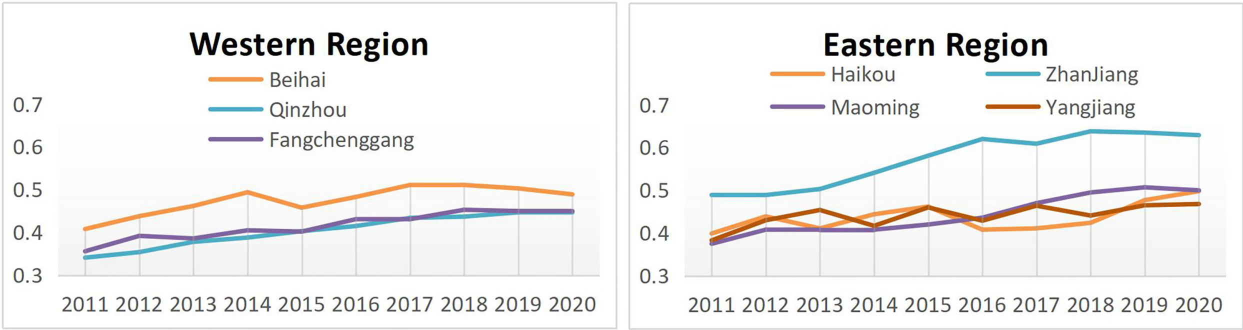

FIGURE 2
Comprehensive evaluation of the marine resources and environmental carrying capacity of seven coastal cities in the Beibu Gulf Urban Agglomeration, 2011-2020.

society and governments at all levels. In 2016, the 13th Five-Year Plan for National Marine Standardization was officially issued to improve China's marine standardization system and marine standardization management mechanism. In 2017, China's National Development and Reform Commission and the State Oceanic Administration jointly issued the 13th Five-Year Plan for National Marine Economic Development, which provides a general plan for the layout of China's marine economic development, the structure of the marine industry and marine ecological civilization for the period 2016-2020, and sets higher requirements for the prevention and control of marine pollution and the use of marine resources in the Southern Ocean Economic Circle. In the same year, the Development Plan for the Beibu Gulf Urban Agglomeration was officially issued, detailing the plans for marine resources management, marine ecological protection, and other work and activities in the Beibu Gulf Urban Agglomeration from 2017 to 2020. The seven coastal cities in the Beibu Gulf Urban Agglomeration have actively responded to the State's call to rationally develop and use marine resources and increase their efforts to manage the marine ecological environment following the relevant work plans. As a result, the marine resources and environment of the Beibu Gulf Urban Agglomeration have gradually improved, and the carrying capacity of marine resources and environment has been restored, with an overall upward trend.

3.1.2 DPSIR subsystem marine resources environmental carrying capacity evaluation analysis

By comparing the assessed values of the DPSIR subsystem of the marine resources and environmental carrying capacity of seven coastal cities in the Beibu Gulf Urban Agglomeration from 2011 to 2020, an in-depth analysis of the DPSIR subsystem is carried out, taking into account the specific conditions of the marine resources and environment of the seven coastal cities in the Beibu Gulf Urban Agglomeration.

Driving force subsystem: The evaluation value of the marine resources and environment driving force subsystem of the seven coastal cities in the Beibu Gulf Urban Agglomeration shows an overall upward trend and a large increase. Zhanjiang and Maoming have given full play to their geographical advantages and have great potential for the development of the marine economy, and their economic and social development has provided sufficient impetus for the marine economy, which has led to an increase in the value of each subsystem. The average annual increase of the marine resources and environment driving force subsystem in Beihai, Qinzhou, Fangchenggang, and Haikou is relatively small. The growth rate of various economic and social development indicators is slowing down, and the development of the marine economy is showing a stable trend. In general, the level of the marine resources and environment driving force subsystem of the

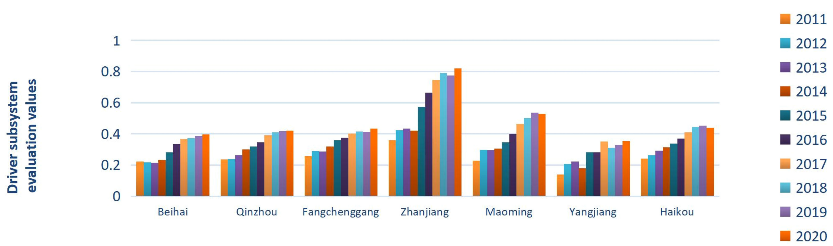

FIGURE 3
Evaluation of the subsystem of marine resources and environmental drivers in seven coastal cities in the Beibu Gulf Urban Agglomeration, 2011-2020.

seven coastal cities in the Beibu Gulf Urban Agglomeration has been improving and has achieved a better driving effect (Figure 3).

Pressure subsystem: During the period 2011-2020, the evaluation value of the marine resources and environment driver subsystem of the seven coastal cities in the Beibu Gulf Urban Agglomeration was generally at a high level, but generally showed a fluctuating trend. Beihai, Qinzhou, and Maoming have improved the quality of the marine environment by promoting the development of marine ecological industries and strictly controlling the discharge of industrial wastewater, waste gas, and waste, and the evaluation value of the marine resources and environment pressure subsystem has been increasing. Fangchenggang, Zhanjiang, Yangjiang, and Haikou are generally on a downward trend in the evaluation value of the marine resources and environment driver subsystem during 2017-2020, with problems such as over-exploitation of marine resources and inadequate marine environment governance and protection coming to the fore, and facing greater pressure on marine resources and marine environment. Overall, marine environmental pollution has put great pressure on the marine resources and environmental carrying capacity of the Beibu Gulf Urban Agglomeration. In recent years, the coastal cities in the Beibu Gulf urban aggressively responded to the national call and gradually increased their investment in marine environmental management, but the problems facing the marine resources and environment can hardly be significantly improved in a short time (Figure 4).

Status subsystem: Under both driving force and pressure, the state of marine resources and the environment in Qinzhou, Maoming, Yangjiang, and Haikou is at a poor level. In the face of marine environmental problems brought about by marine economic development, the effectiveness of the governance measures taken is not significant, resulting in an inadequate supply of marine resources and the lack of obvious advantages of green ecological regulation, and the existing governance measures cannot effectively improve the state of marine resources and environment in which they are located. Beihai, Fangchenggang and Zhanjiang have in recent years strictly implemented marine functional area planning, actively cultivated strategic new marine industries, and improved the marine ecological red line system, effectively eliminating some of the negative impacts and better maintaining the state of marine resources and environment. At present, the state of marine resources and environment in most of the seven coastal cities in the Beibu Gulf Urban Agglomeration is more severe, and the problems of marine resources and environment are prominent. To improve the state of marine resources and environment, marine resources and marine environment need to be further rationalized, managed, and protected (Figure 5).

Impact subsystem: From the impact on the quality of the marine environment and the number of related workers in the seven coastal cities of the Beibu Gulf urban agglomeration, the impact subsystem evaluation value of the marine resources and environment of the Beibu Gulf urban agglomeration needs to be improved. In general, the marine resources and environment impact subsystem evaluation value of the Beibu Gulf Urban Agglomeration shows a rising trend year by year, but the rising trend is not obvious. Zhanjiang, Maoming, Yangjiang, and Haikou had relatively good marine resources and environmental impact subsystems in recent years, with high treatment and utilization rates of pollutants and relatively stable increases in the number of relevant practitioners, and the quality of the marine environment and the number of relevant practitioners has not yet imposed limits on the carrying capacity of marine resources and the environment. Beihai, Qinzhou, and Fangchenggang are more negatively affected, the treatment rate and utilization rate of pollutants in the process of marine economic development is low, and the number of relevant employees has gone low, causing difficulties in breaking through the bottleneck in the assessment value of the marine resources and environmental impact subsystem. Therefore, to alleviate the negative impact of marine economic development, attention should be paid to green development and the development and use of new clean energy in the development and use of marine resources; in the monitoring of the marine ecological environment, a reasonable evaluation mechanism of marine resources and environment should be established, the monitoring of the marine environment should be increased, the discharge of marine industrial pollutants should be strictly controlled and the utilization rate of pollutants should be increased (Figure 6).

Response subsystem: The seven coastal cities in the Beibu Gulf Urban Agglomeration have taken measures of varying degrees of response in the face of the drivers and pressures on marine resources and the environment. Zhanjiang, Maoming, and Yangjiang have achieved better management results by building marine nature reserves, expanding the greening coverage of built-up areas, promoting the implementation of various marine environmental management projects, increasing government funding for marine environmental management, and increasing investment in marine science and technology to promote the

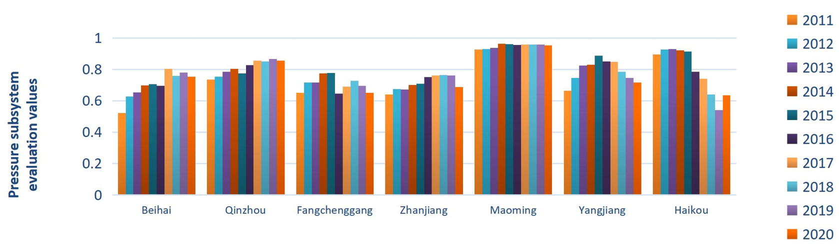

FIGURE 4
Sub-system evaluation of marine resources and environmental pressure in seven coastal cities in the Beibu Gulf Urban Agglomeration, 2011-2020.

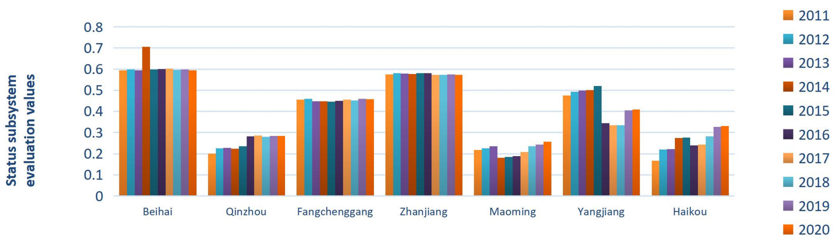

FIGURE 5
Sub-system evaluation of the status of marine resources and environment in seven coastal cities in the Beibu Gulf Urban Agglomeration, 2011-2020.

transformation and application of scientific and technological achievements, which has led to the continuous improvement of the marine resources and environment response subsystem assessment value. Beihai, Qinzhou, and Haikou's marine resources and environment response subsystem evaluation value is generally maintained in the range of 0.3-0.5, and the marine management policies and measures have achieved better results and the response factors have continued to improve; the marine management policies and measures implemented by Fangchenggang have achieved lower response effects, and the marine environment governance capacity and marine science and technology research and development level can hardly adapt to the needs of Fangchenggang's rapid marine economic growth in recent years. The government's investment in marine environmental governance, marine science, technology, and education needs to be improved (Figure 7).

3.2 Analysis of barriers to the carrying capacity of marine resources and environment in the Beibu Gulf Urban Agglomeration

3.2.1 Analysis of the barriers to individual indicators

In this paper, we use the barrier degree calculation formula to measure the barrier degree of individual indicators of marine resources and environment-carrying capacity of seven coastal cities in the Beibu Gulf Urban Agglomeration in 2020. As can be seen from Table 3, the main single indicator barriers to the marine resources and environment carrying capacity level of the Beibu Gulf Urban Agglomeration in 2020 include the length of coastline per capita, aquatic production per capita, total import and export volume, port cargo throughput, scientific research and technical services and the number of employees in the geological exploration industry. Combined with the changes in the marine resources and environmental carrying capacity of the seven coastal cities in the Beibu Gulf Urban Agglomeration from 2011 to 2020, although the Beibu Gulf Urban Agglomeration has actively adopted and implemented various policies and measures for the environmental protection and management of marine resources, the implementation of the existing policies and measures has had limited effect with the high growth of the marine economy. To adapt to the rapid development of the marine economy, the Beibu Gulf Urban Agglomeration should mitigate the negative impact of the rapid growth of the marine economy on the marine resources and environment through the rational development and utilization of marine resources, the transformation of the traditional marine industry structure, and increasing the training and introduction of talents in the field of marine development.

3.2.2 Analysis of obstacles to classification indicators

According to the calculation results of the barrier degree of individual indicators, further measure the barrier degree of each classification indicator of the marine resources and environment carrying capacity of the seven coastal cities in the Beibu Gulf Urban Agglomeration in 2020, study and analyze the barrier situation of each classification indicator, the specific measurement results are shown in Table 4.

According to the measurement results of the barrier degree of the marine resources environment bearing capacity of the seven coastal cities in the Beibu Gulf Urban Agglomeration in 2020,

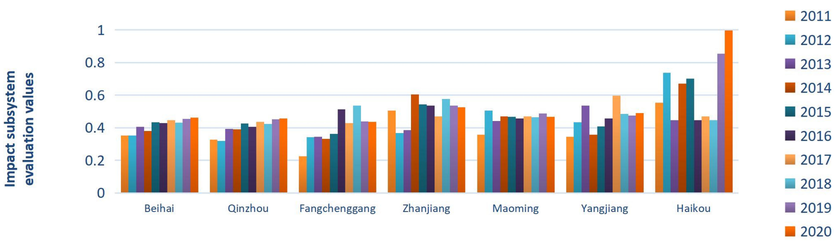

FIGURE 6
Sub-system evaluation of the environmental impact of marine resources in seven coastal cities in the Beibu Gulf Urban Agglomeration, 2011-2020.

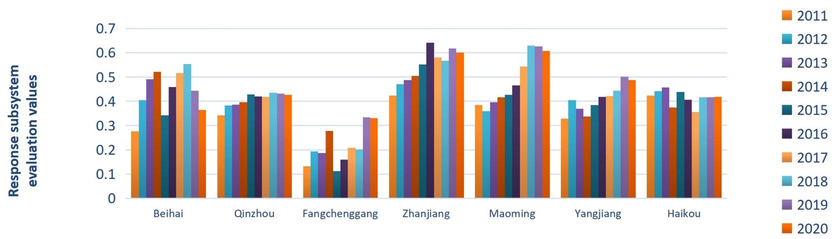

FIGURE 7
Evaluation of the marine resources and environmental response subsystem of seven coastal cities in the Beibu Gulf Urban Agglomeration, 2011-2020.

combined with the changes of the marine resources environment subsystem bearing capacity of the seven coastal cities in the Beibu Gulf Urban Agglomeration from 2011 to 2020, we can see that although the specific values of the barrier degree of each subsystem of the marine resources environment bearing capacity of the seven coastal cities in the Beibu Gulf Urban Agglomeration are different, the overall From an overall perspective, the state subsystem is the main categorical indicator obstacle factor for the carrying capacity of marine resources and environment in the seven coastal cities of the Beibu Gulf Urban Agglomeration, followed by the driving force subsystem and the impact subsystem, and the specific ranking of the categorical indicator obstacle degree is: state > driving force > impact > response > pressure. Therefore, against the background of rapid development of the marine economy and increasing pressure on marine resources and the environment, the Beibu Gulf Urban Agglomeration should focus on improving the state subsystem, improving the effectiveness of the governance of marine resources and environment, and optimizing the state of marine resources and environment, while taking into account the driving force subsystem and impact subsystem, to achieve steady economic and social development and strict monitoring of the marine environment, and jointly play an active role in improving the marine resources and environment of the Beibu Gulf Urban Agglomeration. This will help to achieve steady economic and social development and strict monitoring of the marine environment, and together play an active role in improving the marine resource and environmental carrying capacity of the Beibu Gulf Urban Agglomeration.

4 Conclusion

From the evaluation results of the marine resources and environmental carrying capacity, the marine resources and environmental carrying capacity of the seven coastal cities in the Beibu Gulf Urban Agglomeration fluctuated to a certain extent from 2011 to 2020, indicating that socio-economic development has a greater impact on the development of marine resource protection. After entering 2016, marine resources and marine environment issues have attracted more and more attention from society and governments at all levels, and the seven coastal cities in the Beibu Gulf Urban Agglomeration have actively responded to the national call to reasonably develop and use marine resources and increase the management of the marine ecological environment so that the marine resources and environment carrying capacity has been restored and generally shows an upward trend. Among the various subsystems of marine resources and environment, the pressure subsystem and response subsystem have higher evaluation values, while the evaluation of the driving force, state, and impact subsystem needs to be improved, indicating that the

TABLE 3 Ranking of the barrier degree of individual indicators of marine resources and environmental carrying capacity of seven coastal cities in the Beibu Gulf Urban Agglomeration in 2020.

Order		Beihai	Qinzhou	Fangchenggang	Zhanjiang	Maoming	Yangjiang	Haikou
1	Barrier factors	C_3	C_{10}	C_1	C_{11}	C_{10}	C_{10}	C_{10}
	Barrier degree	10.92%	13.63%	9.56%	14.37%	20.43%	14.35%	20.43%
2	Barrier factors	C_2	C_{11}	C_{17}	C_{21}	C_{11}	C_3	C_{11}
	Barrier degree	10.55%	10.85%	9.35%	13.69%	13.08%	10.55%	15.45%
3	Barrier factors	C_{21}	C_2	C_{21}	C_{17}	C_3	C_{17}	C_2
	Barrier degree	10.02%	9.65%	9.05%	12.29%	11.74%	8.53%	10.41%
4	Barrier factors	C_{17}	C_{17}	C_{18}	C_{18}	C_{18}	C_{18}	C_3
	Barrier degree	9.34%	8.60%	8.90%	11.98%	9.74%	8.01%	7.79%
5	Barrier factors	C_{18}	C_{18}	C_2	C_{12}	C_{17}	C_1	C_{21}
	Barrier degree	9.20%	8.60%	7.98%	9.20%	8.92%	7.63%	7.68%

TABLE 4 Barriers to marine resources and environmental carrying capacity classification indicators for seven coastal cities in the Beibu Gulf Urban Agglomeration in 2020.

Province	Barrier degree				
	Driving force subsystem	Pressure subsystem	Status subsystem	Impact subsystem	Response subsystem
Beihai	32.92%	4.72%	18.95%	18.97%	24.44%
Qinzhou	27.54%	2.64%	33.10%	17.46%	19.26%
Fangchenggang	26.75%	5.11%	25.25%	18.70%	24.19%
Zhanjiang	12.20%	9.81%	33.05%	24.92%	20.02%
Maoming	24.15%	0.83%	42.66%	19.21%	13.15%
Yangjiang	32.89%	3.87%	28.91%	16.57%	17.75%
Haikou	30.46%	6.35%	41.00%	0.03%	22.15%

marine environment pollution in the Beibu Gulf Urban Agglomeration is more serious and puts greater pressure on the carrying capacity of marine resources and environment, and the Beibu Gulf Urban Agglomeration has actively taken response measures to alleviate the pressure on the carrying capacity of marine resources and environment with better results, but more effective governance measures should be taken to increase the supply of marine resources, give full play to the advantages of green ecological regulation, improve the treatment rate and utilization rate of pollutants, stabilize the increase in the number of relevant practitioners, and promote comprehensive socio-economic development.

From the results of the barrier factor measurement and analysis, among the specific indicators of each subsystem, the main single indicator barrier factors affecting the marine resources and environment carrying capacity of the Beibu Gulf Urban Agglomeration include per capita coastline length, per capita fish production, total import and export volume, port cargo throughput, scientific research and technical services and the number of employees in the geological exploration industry. The measurement results of the barrier degree of each classification indicator reflect that the state subsystem is the main classification indicator barrier factor of the marine resources and environment carrying capacity of the seven coastal cities in the Beibu Gulf Urban Agglomeration, followed by the driving force subsystem and the influence subsystem, and the specific ranking of the classification indicator barrier degree is state > driving force > influence > response > pressure. Therefore, to further improve the marine resources and environment carrying capacity of the Beibu Gulf Urban Agglomeration, we should focus on the state subsystem, balance the driving force subsystem and the impact subsystem, and mitigate the negative impacts brought about by the growth of the marine economy by improving the effectiveness of marine resources and environment management, promoting steady economic and social development, and strictly monitoring the marine environment.

5 Discussion

According to the empirical results and the actual development of the Beibu Gulf urban agglomeration, the three aspects of developing marine industries, building coastal economic zones, and protecting the marine environment should be taken as the starting point to improve the level of marine resources and environmental carrying capacity of the Beibu Gulf urban agglomeration and promote the comprehensive social and economic development of the Beibu Gulf urban agglomeration.

Cultivate and develop modern marine industries and build a modern marine industrial system. Based on the advantages of marine resources in the Beibu Gulf Urban Agglomeration and the actual needs of marine development and utilization, and relying on the manufacturing base and science and technology of each coastal city, we will build a marine industry system with modern marine industries as the core. Through the cultivation and development of modern marine industries, the dependence of economic growth on traditional marine industries will be gradually reduced, making modern marine industries the pillar of the marine industrial system; through the method of steadily optimizing the primary marine industry, strongly supporting the secondary marine industry and focusing on the development of the tertiary marine industry, the proportion of the tertiary marine industry will be increased, realizing the restructuring and optimization of the marine industry and promoting the construction of a modern marine industrial system. The process of the marine industry restructuring and optimization, promoting the construction of a modern marine industry system, and effectively alleviating the pressure on marine resources and environment.

Accelerate the construction of the coastal economic belt and increase the openness of the marine economy. Building the coastal economic belt is a key task for the future development of the Beibu Gulf Urban Agglomeration. We will accelerate the formation of a maritime open channel starting from the Beibu Gulf port cluster and a land open channel supported by border crossings, and orderly promote the construction of open platforms such as key development and opening-up pilot zones, border economic cooperation zones and the "two-country double park" between China and Malaysia. We will give full play to the advantages of land and sea links with ASEAN countries, strengthen the construction of the China - South China Peninsula land-based international corridor, build a hub of international corridors with convenient links to ASEAN countries, strengthen the development of linkages with the Guangdong-Hong Kong-Macao Greater Bay Area and the Pearl River-Xijiang Economic Belt, optimize regional cooperation mechanisms, and accelerate the formation of a new pattern of coordinated interaction and complementary advantages between the eastern, central and western regions. The new development pattern of the Beibu Gulf Urban Agglomeration will improve the degree of openness of the marine economy and provide a sufficient driving force for the development of the marine economy of the Beibu Gulf Urban Agglomeration.

Carry out marine environmental protection comprehensively and holistically to achieve high-quality development of the marine economy. Governments at all levels in the Beibu Gulf Urban Agglomeration should consider all types of ecological factors and carry out marine environmental protection in a holistic manner. At present, the coastal cities in the Beibu Gulf Urban Agglomeration have taken a series of measures and methods to improve the quality of the marine environment through the construction of the "Marine Ecological Civilization Demonstration Zone" and the "Blue Ecological Bay Area", and have achieved certain the expected results have been achieved. Governments at all levels in the Beibu Gulf Urban Agglomeration should ensure all-round protection of the marine environment and realize high-quality development of the marine economy in the Beibu Gulf Urban Agglomeration by improving the ecological monitoring and control mechanism, perfecting the coordination mechanism for pollution control, and emphasizing the combination of systematic restoration and comprehensive treatment.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: the original data of the indicators used in this study were obtained from 2011 to 2020 from China Tertiary Industry Statistical Yearbook (http://www.stats.gov.cn/sj/), China Transport Statistical Yearbook (https://www.mot.gov.cn/tongjishuju/), China Transport Yearbook (https://www.mot.gov.cn/tongjishuju/), China Urban Statistical Yearbook (https://data.cnki.net/v3/trade/yearbook/Single/N2022040095?zcode=Z023) and the statistical yearbooks of seven coastal cities; the data on environmental pressure and environmental management were mainly obtained from 2011 to 2020 from China Marine Statistical Yearbook (http://mds.nmdis.org.cn/pages/ocean_list.html), China Environmental Statistical Yearbook (https://navi.cnki.net/knavi/yearbooks/YHJSD/detail), China Urban Construction Statistical Yearbook (http://www.stats.gov.cn/sj/), Guangdong Statistical Yearbook (http://stats.gd.gov.cn/gdtjnj/) and the environmental situation bulletins of seven coastal cities for the past years; Data on resource pressure and resource use were mainly obtained from 2011 to 2020 from the China Energy Statistical Yearbook (https://data.cnki.net/v3/trade/yearbook/Single/N2022060061?zcode=Z023) and the statistical bulletins on national economic and social development of the seven coastal cities in previous years, with data on individual indicators calculated by means of the corresponding formulae.

Author contributions

YL and LS conceptualized the study framework and prepared the original draft, acquired funding and supervised the study. ZW organized the data and resources. HL proofread the article for formatting and grammar. All authors contributed to the article and approved the submitted version.

Funding

This study was funded by Beibu Gulf Ocean Development Research Center under Key Research Base of Humanities and Social Sciences in Guangxi Universities and Marine Science Program for Guangxi First-Class Discipline, Beibu Gulf University.

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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frontiers | Frontiers in Marine Science

TYPE Original Research
PUBLISHED 15 September 2023
DOI 10.3389/fmars.2023.1222806

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Identifying the wetlands of international importance in Beibu Gulf along the East Asian – Australasian Flyway, based on multiple citizen science datasets

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RECEIVED 15 May 2023
ACCEPTED 18 August 2023
PUBLISHED 15 September 2023

CITATION
Tang N, Ma Y, Li S, Yan Y, and Citizen Science Project Team of Guangxi Biodiversity Research Conservation Association, Cheng C, Lu G, Li F, Lv L, Qin P, Nguyen HB, Nguyen QH, Le TT, Wee SQW, He T, Yong DL and Choi C-Y (2023) Identifying the wetlands of international importance in Beibu Gulf along the East Asian – Australasian Flyway, based on multiple citizen science datasets. *Front. Mar. Sci.* 10:1222806. doi: 10.3389/fmars.2023.1222806

The Beibu Gulf (Gulf of Tonkin, Vinh Bac Bo in Vietnamese), located midway along the East Asian-Australasian Flyway (EAAF), is a critical stopover and wintering region for migratory waterbirds. This transboundary coastal region, spanning between China and Vietnam, harbors diverse wetland habitats that provide refuge to waterbird species, including highly threatened species such as the spoon-billed sandpiper (CR) and the black-faced spoonbill (EN). However, the scarcity of comprehensive assessments regarding waterbird abundances, distribution, key wetland habitats, and regional threats hinders our understanding of its conservation significance at the flyway level. Further research is needed to address these knowledge gaps and facilitate effective conservation efforts in the Beibu Gulf. By synthesizing accessible citizen science datasets and published records from wetland sites in south China and northeast Vietnam, we concluded that at least 97 waterbird species used the Gulf's wetlands during their annual cycle. Among surveys conducted from 2014 to 2022, 6 and 13 waterbird species were considered as first and second class protected species under the National Key Protected Wild Animal List in China; 2 species were listed as Critically Endangered on the IUCN Red List, 5 as Endangered and 2 as Vulnerable, underlying the critical importance of the Beibu Gulf for the survival of these species. Our study identified 25 sites in the Beibu Gulf that met the criteria for designation as internationally important wetlands. Alarmingly, less than a quarter (*n* = 6, or 24%) of these sites benefit from national or international protection. Localized threats, including aquatic resource harvesting, hunting, and aquaculture/fisheries, were widespread in the region. This study provides a crucial scientific baseline for continued waterbird monitoring, site prioritization, and the development of effective habitat management plans to conserve vital coastal wetland habitats in the Beibu Gulf in China and Vietnam.

KEYWORDS

waterbird, bird conservation, the Gulf of Tonkin, conservation priorities, East Asian-Australasian Flyway (EAAF), citizen science

1 Introduction

Animal migration is a global phenomenon (Dingle and Drake, 2007). Migratory animals, particularly birds, play indispensable ecological roles across multiple ecosystems worldwide (Bauer and Hoye, 2014). Their remarkable journeys, spanning vast distances across large spatial scales and often crossing diverse habitats, contribute to the interconnectedness and functioning of various ecosystems. Throughout their annual cycles, avian species require a sequence of connected sites along their migration routes where they can rest, forage, and accumulate energy reserves (Alerstam and Lindström, 1990). The presence of intact fueling sites along migratory flyways is of paramount importance for migratory birds, as they are essential for refueling and replenishing energy reserves. As among the largest of 9 global flyways, the East Asian-Australasian Flyway (EAAF) stretches at a continental scale from the Arctic Circle across East and Southeast Asia, to Australia and New Zealand and supports over 50 million migratory waterbirds from more than 250 different populations (access by June 25, 2023; https://www.eaaflyway.net). Waterbirds, particularly shorebirds (order Charadriiformes), strongly depend on coastal wetlands along their migratory routes as critical habitats. Unfortunately, these waterbird populations are facing alarming declines primarily attributable to a multitude of threats, such as hunting (Gallo-Cajiao et al., 2020), pollution (Ma et al., 2022), and habitat loss (Zhang et al., 2018) and degradation (Ma et al., 2014; Studds et al., 2017) and other forms of unsustainable use such as wetland reclamation (Yang et al., 2020). The imperative to ensure the conservation of migratory bird populations and effectively address the challenges faced by transboundary migrants calls for the urgent establishment of a comprehensive continental network of wetland sites. Relying solely on the protection of a few selected key sites proves insufficient in providing an adequate framework to safeguard these avian species and their habitats (Runge et al., 2014; Dhanjal-Adams et al., 2017; Xu et al., 2020).

The identification and protection of important wetlands for waterbirds will ensure an effective conservation 'safety net' for many species and the long-term survival of migratory waterbirds within the EAAF (Dinerstein et al., 2023). The Convention on Wetlands of International Importance, also known as the Ramsar Convention, provides internationally recognized criteria to identify wetlands of international importance (Ramsar sites) during the past 50 years (Stroud and Davidson, 2022). Further, some of the sites are already inscribed on the World Heritage List (UNESCO) due to Outstanding Natural Values (e.g., https://whc.unesco.org/en/list/1606/multiple=1&unique_number=2304), as well as the sites identified by the Convention of Migratory Species (CMS) and other international agreements and institutional arrangements (i.e., East Asian–Australasian Flyway Partnership, hearafter as 'EAAFP'), base recognition on the 2 criteria specifically related to waterbird populations. So far, 152 sites, spread over 19 countries, have been included in this Flyway Site Network of EAAFP (access by June 25, 2023; https://www.eaaflyway.net). In particular, priority sites along the EAAF, such as those located within the Yellow/Bohai Sea and Australia, and their ecological importance to migratory waterbirds are relatively well studied, profiled, and monitored (Barter, 2002; China Coastal Waterbird Census Group, 2011; Clemens et al., 2016; Wang et al., 2022), and in 2019, several wetland sites such as Yancheng and Dafeng Milu National Nature Reserves were inscribed as UNESCO World Heritage Sites (UNESCO, 2019). Yet, the comprehensive conservation of migratory waterbirds hinges upon the adequate protection of interconnected sites spanning the entire EAAF, including regions such as southern China and Southeast Asia. Despite the importance of these regions, they have often received relatively less attention from conservationists and researchers (Chan et al., 2019; Yong et al., 2022).

The Beibu Gulf (also known as the Gulf of Tonkin, Vịnh Bắc Bộ as it is known in Vietnam; 北部湾 in Chinese) spans the frontiers of China and Vietnam and serves as one of the most important migration stopover and wintering areas for many waterbirds at the interface of Southeast Asia and south China along the EAAF, including critically endangered species such as spoon-billed sandpiper *Calidris pygmaea* (Pedersen et al., 1996; Chang et al., 2020; Nguyen et al., 2021). It is a large, semi-enclosed bay located northwest of the South China Sea, drained by several major rivers such as the Nanliu in China and the Red River in Vietnam. In China, it is bounded by the provinces of Guangxi and Guangdong and the island province of Hainan. In Vietnam to the south-west of the Bay, it is bounded by several provinces of northeast and central Vietnam from Quang Binh to Quang Ninh. With coastal habitats such as bare tidal flats, salt marshes, mangroves, reefs, and seagrasses, the Beibu Gulf is rich in marine biodiversity, supports key fisheries and aquaculture activities, recreation and tourism, ports, as well as a wide range of ecological services, e.g., storm surges (MacKinnon et al., 2012; United Nations Environment Programme (UNEP), 2014; Teng et al., 2022). More specifically, this region provides nursery habitats for "living fossils", namely horseshoe crabs (Kwan et al., 2021), and critical habitats for migratory species such as black-faced spoonbill *Platalea minor*, spoon-billed sandpiper and spotted greenshank *Tringa guttifer* (Nguyen et al., 2021; Nguyen et al., 2023). Despite the ecological importance of the Beibu Gulf, research on migratory waterbirds in this part of the EAAF remains relatively limited. Based on the ringing and flag resighting records in Guangxi, Yi et al. (2023) demonstrated the migration connectivity between the Beibu Gulf and Tasmania in Australia, Chukotka in Russia, and Jiangsu in China. In Vietnam, Xuan Thuy National Park (NP) has been well recognized for its importance to the black-faced spoonbill and spoon-billed sandpiper and has been regularly surveyed since the 1990s (Pedersen and Nielsen, 1998). Besides, there are substantial knowledge gaps in Southeast Asia, including Vietnam (Choi et al., 2016; Yong et al., 2022; Nguyen et al., 2023). Vietnam has a well-established network of protected areas, but very few coastal wetlands are included (Rambaldi et al., 2001). According to Yong et al. (2022), Vietnam has 13 coastal Important Bird and Biodiversity Areas (IBAs), supporting 12 threatened bird species. Globally threatened species, such as Saunders's gull *Saundersilarus saundersi*, have been recorded in the Red River Delta of north Vietnam (Pedersen and Nielsen, 1998), while great knot *Calidris tenuirostris* and spoon-billed sandpiper were recorded in the Mekong Delta, Southern Vietnam (Zöckler et al., 2016; Nguyen et al., 2023).

The densely populated Beibu Gulf has historically played a vital role in the economies of China and Vietnam, being particularly important for the production of seafood for both countries while supporting important biodiversity, including waterbirds (Qiu et al., 2008; Teng et al., 2022). Given an accelerating pace of development in both countries, particularly with the implementation of the Beibu Gulf Economic Rim, there is an urgent need to synthesize the distribution and abundance of waterbirds across the Gulf based on emerging knowledge and data and expand the identification of priority sites in the Beibu Gulf to guide effective conservation actions. Although 4 sites within the Gulf have been recognized as IBAs or Ramsar sites in China and several more in Vietnam (see Pedersen et al., 1996), recent bird surveys have indicated or discovered that additional sites may be important, and these sites should be included in the protected area network. Thus far, the absence of systematic waterbird survey data poses a significant challenge in accurately demarcating and defining the important coastal wetlands within the Beibu Gulf. This data gap hampers the implementation of effective conservation plans and policies to preserve these ecologically significant areas. Compounding the issue is the limited accessibility of related publications, which are predominantly available in vernacular languages. This language barrier impedes the smooth exchange of information and hinders effective communication and collaboration among international stakeholders (Amano et al., 2023).

In this study, we compile survey data from multiple sources of citizen science datasets across both countries and apply these data against internationally recognized criteria of the Ramsar Convention and the East Asian-Australasian Flyway Partnership. We delineate several new sites of significance to waterbird conservation. Based on all citizen science and open-access records collected from China and Vietnam, we aim to: 1) review the priority sites for waterbird conservation based on waterbird abundance and distribution; 2) identify the threats and conservation status of these sites in the region.

2 Methods

2.1 Study area

The Beibu Gulf is a semi-enclosed bay in the northwest of the South China Sea, bounded to the north by southeast China (Leizhou Peninsula, Qiongzhou Strait, and Hainan Island) and to the south by the provinces of northeast and central Vietnam (Figure 1, Zou, 2005). It covers an area of approximately 12.8 × 10^4 km^2. Being an important node of the EAAF, the Beibu Gulf provides crucial stopover, wintering, and staging grounds, including temporary resting places and foraging areas sites for migratory waterbirds.

2.2 Data sources and processing

The data used in this study were obtained from the Guangxi Biodiversity Research and Conservation Association, the Zhanjiang Mangrove National Nature Reserve in Guangdong Province, Haikou Duotan Wetlands Institute & Hainan Bird Watching Society in China. In Vietnam, data was compiled from Xuan Thuy National Park and ongoing projects from Vietnam National University, BirdLife International and Vietnam Nature Conservation Centre (Viet Nature). The dataset covers the years from 2014 to 2022, with survey data from Guangxi province for 6 years (2017-2022), data from Hainan Island for 2021 and 2022, and data from Zhanjiang in Guangdong Province for 2019, 2020, and 2022. Data from northern Vietnam ranged from 2014 to 2022, covering sites including Xuan Thuy National Park, Thai Binh Wetland Conservation Area (now administratively merged with a part of Tien Hai Nature Reserve), An Hai IBA (2021), Tien Hai IBA (2021), and Tra Co IBA (2014, 2016 and 2017). Generally, one or two surveys were conducted in each site per year, details see Table S1. Based on the data from the Guangxi Biodiversity Research and Conservation Association's public monitoring report on the biodiversity of coastal wetlands from 2014 to 2020 and research on the threats faced by coastal wetlands in Vietnam, as well as data in the published literature (Li et al., 2020), we summarized the threats within this region. The data was analyzed using Python (3.10.6; Python Software Foundation, 2022) tools, including Panda (1.4.2; Pandas Development Team, 2022) and Numpy (1.23.1;

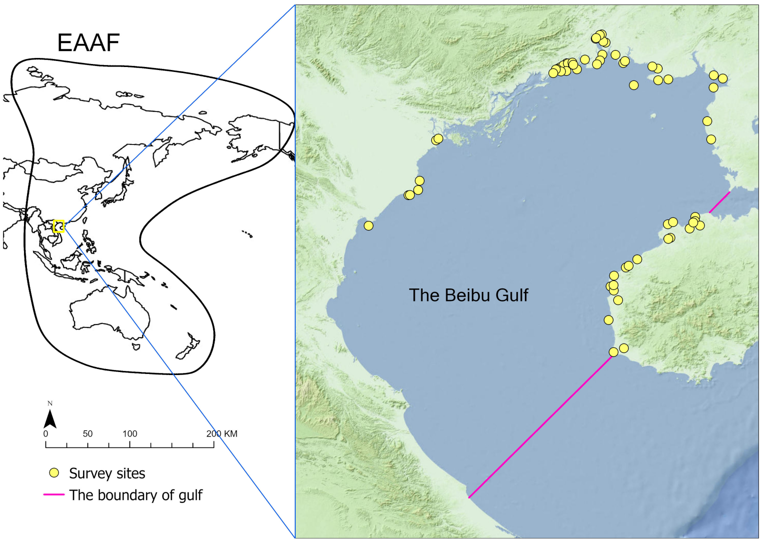

FIGURE 1
The survey sites of Beibu Gulf in this study. The yellow dots represent the locations where waterbird surveys were conducted. The black line represents the boundary of the East Asian-Australasian Flyway. The purple line indicates the boundary of the Beibu Gulf. Map layers were provided by Esri, FAO, NOAA, and USGS.

Harris et al., 2022), and the spatial information was integrated and analyzed using ArcGIS Pro 3.0.2 (Esri, 2018).

2.3 Criteria for areas of significance for waterbird conservation

In this study, the criteria for wetlands of international importance under the Ramsar Convention were employed to assess the significance of sites for the conservation of waterbirds. If a site met at least one of the criteria at any point, it was considered significant for waterbird conservation. By applying these criteria, we aimed to identify and prioritize sites that are crucial in supporting waterbird populations and their conservation efforts. Specifically, based on the Ramsar Convention Secretariat (2016), two criteria related to waterbirds and one to species and ecological communities, namely 'A wetland should be considered internationally important if it supports vulnerable, endangered, or critically endangered species or threatened ecological communities (Criteria 2)', 'A wetland should be considered internationally important if it regularly supports 20,000 or more waterbirds (Criteria 5)' and 'A wetland should be considered internationally important if it regularly supports 1% of the individuals in a population of one species or subspecies of waterbird (Criteria 6)'.

3 Results

3.1 Identification of sites of International Importance

From October 2014 to January 2022, a total of 66 sites were surveyed in the Beibu Gulf, with a total of 4571 records noted. Based on the criteria, 25 sites were identified as of Importance and met either Criteria 2 or Criteria 6, as no site met Criteria 5 (Figure 2, details can be found in Table 1). Specifically, 7 Chinese sites (Jintan, Bailangtan, Shaluoliao, Haiwei-Yangwu, Xichang, Fengjiajiang-Xiacun, Danzhou Bay) and 2 Vietnamese sites (Xuan Thuy NP and An Hai IBA) satisfied two criteria. The site of Zhulin Saltpan fulfilled Criteria 6, while the other 15 sites (Thai Binh Wetland Conservation Area, Beilun Estuary NNR, Guiming-Jiabang, Yuzhouping, Shanxinsha Island, Sanniang Bay, Tongwei, Shankou, Gaoqiao Town, Suixi Jiaotou, Qishui Chidouliao, Houshui Bay, Changhua River Estuary, Sigeng, Yinggehai) met Criteria 2. Besides, Xuan Thuy NP (in 2021 and 2022), Shaluoliao (years from 2020 to 2022), and Shanxinsha Island (in 2021 and 2022) qualified as important sites for more than two years.

3.2 Species abundance and distribution along the Beibu Gulf

According to the comprehensive analysis of survey data, a total of 97 bird species were observed and documented (refer to Table S2). Considering the highest recorded count for each species, the findings revealed several noteworthy avian species that exhibited a significant level of abundance within the observed area. The most abundant species, based on their maximum recorded counts from a single survey at specific site, included black-headed gull *Chroicocephalus ridibundus* (*n* = 4710, Haiwei-Yangwu, 2018), lesser sand plover *Charadrius mongolus* (n = 4200, Danzhou Bay, 2022), Kentish plover *Charadrius alexandrinus* (n = 3151, Fengjiajiang-Xiacun, 2022), black-tailed godwit *Limosa limosa* (n = 2900, An Hai IBA), and dunlin *Calidris alpina* (n = 2200, Haiwei-Yangwu, 2021). These findings highlighted the significance of the surveyed sites for these species in the Beibu Gulf. Six of the 97 observed bird species belonged to the first class, while 13 fell under

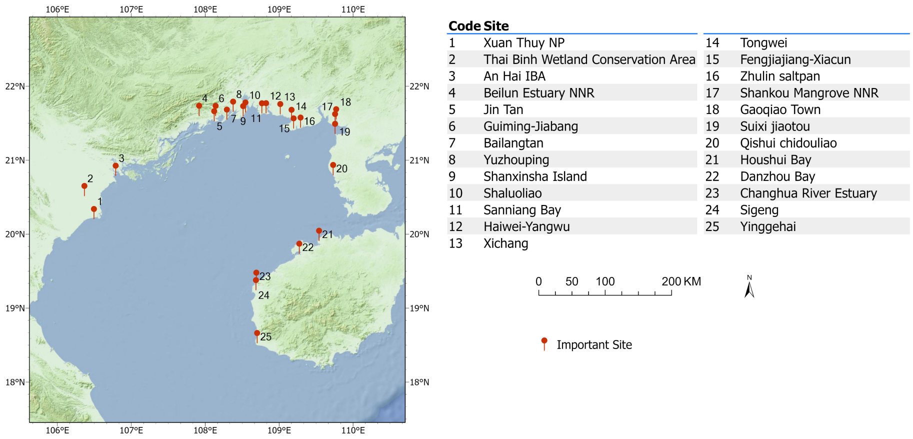

FIGURE 2
Sites that met at least one criterion for Wetlands of International Importance in the Beibu Gulf. Map layers were provided by Esri, FAO, NOAA, and USGS. NNR, National Nature Reserve; NP, National Park; IBA, Important Bird and Biodiversity Areas.

the second class of the National Key Protected Wild Animal List of China. Notably, the IUCN Red List (IUCN, 2023) provided valuable insights into the conservation status of certain bird species. The spoon-billed sandpiper and Christmas Island frigatebird *Fregata andrewsi* were categorized as Critically Endangered (CR), indicating an extremely high risk of extinction. Additionally, four species, namely the black-faced spoonbill, Far Eastern curlew *Numenius madagascariensis*, great knot, and spotted greenshank, were classified as Endangered (EN), denoting a significantly high risk of extinction. Furthermore, two species, the Saunders's gull and black-legged kittiwake *Rissa tridactyla*, were designated as Vulnerable (VU). These findings underscored the significance of the Beibu Gulf in safeguarding the survival and well-being of wintering and/or staging populations of these species, emphasizing the urgent need for conservation efforts. The species and their distribution can be found in Table 1.

A noteworthy observation emerged recently as 11 species exhibited population sizes surpassing the 1% threshold (The specific observed year and survey data see Table S3). Specifically, the lesser sand plover in Danzhou Bay in Hainan, China, reached 2.1% of its flyway population. With respect to criterion 2, which focuses on threatened species (Table 2), notable sightings were recorded for the spoon-billed sandpiper (IUCN, 2023, CR) and the black-faced spoonbill (IUCN, 2023, EN). The spoon-billed sandpiper was observed in 9 sites, while the black-faced spoonbill was sighted in 11 sites. It is worth highlighting that Xichang and Haiwei-Yangwu in Guangxi, China, were found to support a population of spoon-billed sandpipers (n = 8) exceeding 1% of its global population estimate. Using the most conservative 1% estimate, thus 4 individuals instead of 8 for spoon-billed sandpipers (Green et al., 2021), the number of sites qualified as internationally important remains the same. But an additional seven sites (Bailangtan, Shanxinsha Island, Haiwei-Yangwu, Shaluoliao, Danzhou Bay, Xuan Thuy NP and An Hai IBA) should be considered as important to the conservation of this species. Similarly, Saunders's gull populations exceeding 1% of its global population estimate were observed in these regions. Moreover, Xuan Thuy NP in Vietnam supports a wintering congregation of black-faced spoonbills surpassing the 1% threshold. These findings underscored the significance of these specific sites in supporting these threatened bird species.

3.3 Conservation Status

Out of the 25 designated wetland sites recognized as internationally significant, three sites located in China have been designated as national nature reserves, namely Sigeng located in Sibi Bay National Wetland, Beilun Estuary NNR, and Shankou Mangrove NNR. In Vietnam, 2 of these important wetland sites are protected, namely Xuan Thuy NP and Thai Binh Wetland Conservation Area (including Thai Thuy and Tien Hai, which were defined formerly as separate IBAs). These collective efforts contribute to the conservation and protection of wetland habitats in the region. Yet, the remaining 19 sites (76%) are located outside the national protected area system. 13 unprotected areas in China (Jintan, Bailangtan, Shanxinsha Island, Shaluoliao, Sanning Bay, Haiwei-Yangwu, Gaoqiao Town, Suixi Jiaotou, Qishui Chidouliao, Houshui Bay, Danzhou Bay, Changhua River Estuary, and Yinggehai, Figure S1) were located within or close to Ecological Redline boundaries (Choi et al., 2022), which is a spatial planning framework to protect areas that provide essential ecosystem services while biodiversity conservation could be a byproduct, thus providing some level of protection to these 6 unprotected sites. In Vietnam, An Hai IBA, which overlaps with the major city of Hai Phong, supports some of the most extensive intertidal flats left in north Vietnam, but remains unprotected and is now being partly reclaimed for development (Nguyen et al., 2023).

Two unprotected sites located in Guangxi, China, namely Xichang and Haiwei-Yangwu, and An Hai IBA in Vietnam were of particular concern (Tables 2, S3). The urgency stems from the fact that these sites host a populations of threatened bird species that exceed the 1% threshold. More specifically, surveys in Xichang has documented the presence of 8 spoon-billed sandpipers and

TABLE 1 Summarized details of sites identified as of Importance in Beibu Gulf.

Code	Site	Chinese/ Vietnamese	Longitude	Latitude	Fulfilled criteria	Species	Threats	References
1	Xuan Thuy NP*	Vườn quốc gia Xuân Thủy	106.49502	20.196527	C2,C6	black-faced spoonbill (80), Kentish plover (1050), **spoon-billed sandpiper (4), spotted greenshank (1)**	Not applicable	
2	Thai Binh Wetland Conservation Area* (formerly Thai Binh and Tien Hai IBAs respectively)	Khu bảo tồn đất ngập nước Thái Bình	106.653056	20.608061	C2	**black-faced spoonbill (1)**	Fishing, killing and harvesting aquatic resources; Storms and flooding; Increased fragmentation within protected area; Agricultural and forestry effluents; Aquaculture/fisheries; Disturbance to birds; hunting (mist net and gun)	Thai Thuy_ecosystem Health Index_methodology_EN
3	An Hai IBA*	IBA An Hải	106.78919	20.781943	C2,C6	black-tailed godwit (2900), broad-billed sandpiper (930), Kentish plover (1093), spotted redshank (300), **great knot (370), spoon-billed sandpiper (4), Saunders's gull (40)**	Illegal hunting (mist nets and traps); land reclamation and infrastructure expansion	
4	Beilun Estuary NNR	北仑河口国家级自然保护区	107.91759	21.592412	C2	**black-faced spoonbill (1)**	Not applicable	
5	Jintan	金滩	108.12175	21.518719	C2,C6	Kentish plover (1319), **Saunders's gull (6)**	Harvesting aquatic resources; tourism; Habitat fragmentation	Public Report on Coastal Wetland Biodiversity; Monitoring in the Beibu Gulf, China (2019-2020; 2014-2019)
6	Guiming-Jiabang	贵明-佳邦	108.14083	21.590397	C2	**spotted greenshank (1), Saunders's gull (1)**	Verchle disturbance, Aquaculture/fisheries; hunting (mist net)	Public Report on Coastal Wetland Biodiversity; Monitoring in the Beibu Gulf, China (2019-2020; 2014-2019)
7	Bailangtan	白浪滩	108.29303	21.539825	C2,C6	Caspian tern (265), **spoon-billed sandpiper (4), great knot (6), spotted greenshank (1)**	Harvesting aquatic resources; tourism; habitat fragmentation	Public Report on Coastal Wetland Biodiversity; Monitoring in the Beibu Gulf, China (2019-2020; 2014-2019)
8	Yuzhouping	渔洲坪	108.37771	21.647684	C2	**great knot (50)**	Harvesting aquatic resources; Aquaculture/ fisheries; hunting (mist net); miscatch; Habitat fragmentation, plastic debris; pollution; Loss and fragmentation of habitat	Public Report on Coastal Wetland Biodiversity; Monitoring in the Beibu Gulf, China (2019-2020; 2014-2019)
9	Shanxinsha Island	山心沙岛	108.51315	21.587464	C2	**spoon-billed sandpiper (7), great knot (250), black-legged kittiwake (1), Saunders's gull (20)**	Harvesting aquatic resources; Aquaculture/ fisheries; hunting (mist net); miscatch; Habitat fragmentation, plastic debris; pollution; Loss and fragmentation of habitat	Public Report on Coastal Wetland Biodiversity; Monitoring in the Beibu Gulf, China (2019-2020; 2014-2019)

(Continued)

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TABLE 1 Continued

Code	Site	Chinese/ Vietnamese	Longitude	Latitude	Fulfilled criteria	Species	Threats	References
10	Shaluoliao	沙螺寮	108.54464	21.636425	C2,C6	grey plover (1200), **spoon-billed sandpiper (5), great knot (155), black-legged kittiwake (1), Saunders's gull (25)**	Not applicable	
11	Sanniang Bay	三娘湾	108.76697	21.625484	C2	**black-faced spoonbill (9)**	Not applicable	
12	Haiwei-Yangwu	海尾-杨屋	108.82326	21.626847	C2,C6	Caspian tern (395), kentish plover (2400), lesser sand plover (2204), Saunders's gull (500), **spoon-billed sandpiper (5), Far Eastern curlew (11), great knot (350), spotted greenshank (1), black-faced spoonbill (9)**	Not applicable	
13	Xichang	西场	109.01563	21.615008	C2,C6	Kentish plover (1500), **spoon-billed sandpiper (8), Saunders's gull (30)**	Harvesting aquatic resources; Aquaculture/ fisheries; hunting (mist net); miscatch; plastic debris; pollution; Loss and fragmentation of habitat, Spartina invasion	Public Report on Coastal Wetland Biodiversity; Monitoring in the Beibu Gulf, China (2019-2020; 2014-2019)
14	Tongwei	峒尾	109.16816	21.53705	C2	**Christmas Island frigatebird (1)**	Habitat fragmentation, plastic debris; pollution; Loss and fragmentation of habitat, Spartina invasion	
15	Fengjiajiang-Xiacun	冯家江-下村	109.19611	21.421667	C2,C6	Kentish plover (3151), sanderling (575), **spoon-billed sandpiper (1), spotted greenshank (1)**	Not applicable	
16	Zhulin Saltspan	竹林盐场	109.29008	21.432297	C6	Kentish plover (2706)	Harvesting aquatic resources; Aquaculture/ fisheries; hunting (mist net); miscatch; plastic debris; pollution; Loss and fragmentation of habitat, Spartina invasion	Public Report on Coastal Wetland Biodiversity; Monitoring in the Beibu Gulf, China (2019-2020; 2014-2019)
17	Shankou	山口	109.75697	21.479992	C2	**Saunders's gull (2)**	Harvesting aquatic resources; Aquaculture/ fisheries; hunting (mist net); miscatch; plastic debris; pollution; Loss and fragmentation of habitat, Spartina invasion	Public Report on Coastal Wetland Biodiversity; Monitoring in the Beibu Gulf, China (2019-2020; 2014-2019)
18	Gaoqiao Town	高桥镇	109.77182	21.545079	C2	**black-faced spoonbill (2)**	Harvesting aquatic resources	Zhang et al. (2013)
19	Suixi Jiaotou	遂溪角头	109.75663	21.347464	C2	**Saunders's gull (2)**	Harvesting aquatic resources; Aquaculture/ fisheries; hunting (mist net); miscatch; plastic debris; pollution; Loss and fragmentation of habitat, Spartina invasion	Public Report on Coastal Wetland Biodiversity; Monitoring in the Beibu Gulf, China (2019-2020; 2014-2019)
20	Qishui Chidouliao	企水赤豆寮	109.73076	20.791424	C2	**black-faced spoonbill (5), great knot (32)**	Harvesting aquatic resources	

(Continued)

TABLE 1 Continued

Code	Site	Chinese/ Vietnamese	Longitude	Latitude	Fulfilled criteria	Species	Threats	References
21	Houshui Bay	后水湾	109.54024	19.902695	C2	**black-faced spoonbill (46)**	Harvesting aquatic resources; Aquaculture/ fisheries; hunting (mist net); miscatch; plastic debris; pollution; Loss and fragmentation of habitat	Li et al. (2020)
22	Danzhou Bay	儋州湾	109.27283	19.727545	C2,C6	broad-billed sandpiper (305), lesser sand plover (4200), Caspian tern (421), **spotted greenshank (2), great knot (79), spoon-billed sandpiper (6), black-faced spoonbill (38)**	Harvesting aquatic resources; Aquaculture/ fisheries; hunting (mist net); plastic debris; pollution	Public Report on Coastal Wetland Biodiversity; Monitoring in the Beibu Gulf, China (2019-2020; 2014-2019)
23	Changhua River Estuary	昌化江口	108.6917	19.335443	C2	**great knot (21)**	Harvesting aquatic resources; Aquaculture/ fisheries; hunting (mist net); miscatch; plastic debris; pollution; Loss and fragmentation of habitat	Li et al. (2020)
24	Sigeng	四更	108.68649	19.23434	C2	**black-faced spoonbill (47), Far Eastern curlew (1)**	Harvesting aquatic resources; Aquaculture/ fisheries; hunting (mist net); miscatch; plastic debris; pollution; Loss and fragmentation of habitat	
25	Yinggehai	莺歌海	108.70255	18.519624	C2	**black-faced spoonbill (7)**	Harvesting aquatic resources; Aquaculture/ fisheries; hunting (mist net); miscatch; plastic debris; pollution; Loss and fragmentation of habitat	

*: sites belong to Vietnam. Species in bold indicated species on the IUCN redlist (IUCN, 2023).

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TABLE 2 Globally threatened waterbirds reported at the identified sites, Beibu Gulf.

Common name	Scientific name	IUCN status	Number of sites with record	Identified Site >1% population
spoon-billed sandpiper	*Calidris pygmaea*	CR	9	Xichang, Guangxi, China
Christmas Island frigatebird	*Fregata andrewsi*	CR	1	
black-faced spoonbill	*Platalea minor*	EN	11	Xuan Thuy NP, Vietnam
Far Eastern curlew	*Numenius madagascariensis*	EN	2	
great knot	*Calidris tenuirostris*	EN	9	
spotted greenshank	*Tringa guttifer*	EN	6	
black-legged kittiwake	*Rissa tridactyla*	VU	2	
Saunders's gull	*Chroicocephalus saundersi*	VU	9	Haiwei-Yangwu, Guangxi, China

1500 Kentish plovers, while Haiwei-Yangwu has reported sightings of 2400 Kentish plovers, 2204 lesser sand plovers, and 500 Saunders's gulls. In Vietnam, the An Hai IBA is estimated to support populations of 2900 black-tailed godwits *Limosa limosa*, 1093 Kentish plovers, 930 broad-billed sandpipers *Calidris falcinellus*, 370 great knots, 300 spotted redshanks, 4 spoon-billed sandpipers, and 40 Saunders's gulls. These numbers highlight the significance of these sites for the survival and conservation of these threatened species (details see Table 2).

3.4 Threats to sites in the Beibu Gulf

By far, the most severe and irreversible threat to biodiversity in this gulf is anthropogenic disturbances. We identified 15 types of threats. The most common ones included harvesting aquatic resources (16 sites), hunting (14 sites), and aquaculture/fisheries (13 sites; Tables 1, S4). Hunting through bycatch (mainly reported in Guangxi, China); illegal mistneting (e.g., in An Hai, Vietnam; multiple sites in Hainan, China) also threaten waterbirds in the region.

4 Discussion

Coastal wetlands surrounding the Beibu Gulf are important wintering and stopover areas for threatened migratory waterbird species, particularly the spoon-billed sandpipers. The Beibu Gulf, along with the Leizhou Peninsula (Leung et al., 2022), represents the northernmost wintering region for the spoon-billed sandpipers. Notably, 4 flagged spoon-billed sandpipers were repeatedly re-sighted at Xichang between 2016 and 2019, indicating the importance of this site in connecting with birds in Chukotka in Russia and Jiangsu in China where the birds are usually tagged (Yi et al., 2023). Consistent with this finding, Xichang supported >1% population of spoon-billed sandpipers for their stopover. The Beibu Gulf region also supports the wintering or stopover populations of three other endangered shorebird species, namely Far Eastern curlew (present in at least 2 sites), great knot (10 sites), and spotted greenshank (6 sites). The region is probably the most north-easterly wintering region for all these species and probably a newly identified wintering region for Far Eastern curlews (Higgins and Davies, 1996; Zöckler et al., 2018). Furthermore, the Beibu Gulf is a well-known, important wintering region for the endangered black-faced spoonbills, with records from 11 sites. This region is considered one of the southernmost wintering regions for this species. Given its location at the northern and southern limits of the wintering ranges for several migratory waterbird species, continuous long-term monitoring of these waterbirds in the gulf can provide insights into their responses to climate change (Lehikoinen et al., 2021). The conservation of these endangered waterbird species and their habitats within the Beibu Gulf is of utmost importance for their long-term survival, in parallel with ongoing work to understand the impacts of environmental changes on migratory waterbird populations.

Following the criteria for wetlands of international importance defined by the Ramsar Convention Secretariat (2016), we identified 25 sites that met the criteria of significance to waterbird conservation along the Chinese and Vietnamese coasts of the Beibu Gulf through the integration of citizen science data. Over three-quarters of these important sites were located outside the existing Ramsar or protected areas. In 2014, China introduced the Ecological Conservation Redline (ECRL) policy, which holds exceptional national significance and has a proven history of effective enforcement by regional and local governmental authorities (Bai et al., 2016). Examining the implications of the ECRL, it becomes evident that 13 sites fall within or near the designated redline areas. This indicates the potential for these sites to receive protection under the ECRL policy, as development activities are prohibited in ECRL. The ECRL policy provides a framework for safeguarding these sites and underscores their importance in conserving ecological integrity and promoting sustainable development practices. In 2022, Vietnam passed the directive, 'urgent tasks and solutions to conserve wild and migratory birds', which provides new and important guidance to address conservation issues for migratory species such as hunting, and strengthening the national framework of policies and legislation addressing the protection of threatened species (Directive 4/CT-TTg, 2022; Nguyen et al., 2023).

Our results reinforce the need for urgent protection of important waterbird habitats in the Beibu Gulf to avert further declines of waterbird populations along the EAAF. Increasingly efficient harvesting tools and approaches for seafood products cause greater harvests of invertebrates that may lead to reduced food availability and increased energy cost for waterbirds due to disturbances, while heightening the risk of bycatches (Verhulst et al., 2004; Yasué, 2005; Yasué, 2006). Many areas of intertidal flats are actively being used for the fishery (Verhulst et al., 2004), therefore putting migratory birds in direct conflict with fisheries in both China and Vietnam. Livestock, poultry, and aquaculture were identified as dominant sources of pollutants, e.g., antibiotics in the Beibu Gulf (Wu et al., 2022). Furthermore, other pollutants, including heavy metals and organic contaminations are reported in this region, posing an ecological risk to waterbird species foraging here (Gan et al., 2013; Li et al., 2015). Besides, to reduce the dependency on imported fossil fuels in the Beibu Gulf, wind energy infrastructures can be expected to become more common in the near future. In addition, coastal wetlands along Guangxi province were reclaimed and caused significant habitat fragmentation due to infrastructure needs (e.g., port), commercial developments and coastal engineering (Liu et al., 2023). Similar changes are ongoing in An Hai, Vietnam (Nguyen et al., 2023). Therefore, a sustainable economic development policy balancing environmental protection is urgently needed (Chen et al., 2020).

The protection of the coastal wetland ecosystem and bird habitats in the Beibu Gulf is of utmost importance and requires collaborative efforts from governments, agencies, businesses, and citizens. Strengthening cooperation among these stakeholders is crucial to effectively conserve and manage the ecological environment of the region (Yong et al., 2018). Recent studies utilizing satellite tracking methods have initiated efforts to address these research gaps (Chan et al., 2019). These studies serve as a valuable complement to ground-based field surveys (Putra et al., 2019; Nguyen et al., 2021). However, there is an ongoing and pressing need for further field-based research to address several critical aspects of waterbird conservation in Beibu Gulf. Firstly, understanding the habitat use and local movement by various bird species in different sites is crucial. Secondly, investigating migratory routes and establishing knowledge about migratory connectivity among waterbird populations is imperative. Such research outcomes can guide the identification of priority sites, including IBAs, and inform the planning and establishment of protected areas. Continued field-based investigations are therefore necessary to address these research objectives effectively. Lastly, sustainable development practices that prioritize the preservation of intertidal and supratidal habitats (Jackson et al., 2020) in the Beibu Gulf and ensure the safety of bird populations should be considered and implemented. This includes measures to minimize habitat degradation, pollution, and disturbance. Additionally, efforts should be made to promote the diversity of bird species by conserving their habitats and addressing any potential threats they may face. By fostering collaboration and implementing environmentally friendly practices, it is possible to strive towards the long-term protection and sustainable management of the coastal wetland ecosystem and bird habitats in the Beibu Gulf.

It is important to note that relatively few surveys were conducted in Vietnam (58 sites in China; 8 sites in Vietnam were surveyed). Additionally, some sites, such as IBAs of Tien Hai and Tra Co, were only surveyed once, thus, our limited datasets due to low survey capacity could be a reason why some former important sites appeared to support insignificant waterbird congregations. On the other hand, sites such as Sanning Bay met the important wetland criteria only once, thus, long-term monitoring is needed to see if the record of large number of waterbirds was a rare incident or the site indeed supports a substantial number of waterbirds regularly. Furthermore, the data used in this study encompassed a combination of citizen science observations, publicly available bird records, and unpublished data from local observers. The quality of the data is influenced not only by the resources and capabilities but also by the skills and expertise of the observers. As information about the observers was often lacking, the verification of certain data points may have been challenging, potentially impacting the overall data quality. To address these limitations, future research, monitoring, and conservation effort should consider providing training and learning opportunities for local surveyors, enhancing the resources available to conservation and research organizations in both countries, and promoting transboundary collaboration between researchers, managers, and local observers. Moreover, the information collected in local languages, predominantly Chinese and Vietnamese, should be translated, analyzed, and published to facilitate accessibility and foster effective transboundary conservation efforts for migratory waterbirds (Liu et al., 2020; Amano et al., 2021; Fuller et al., 2021).

In conclusion, the Beibu Gulf, situated along EAAF and shared between China and Vietnam, is a vital stopover and wintering region for migratory waterbirds. Our study, which synthesized citizen science datasets and published records from wetland sites in both countries, revealed the presence of at least 97 waterbird species in the Gulf during the migration period. Among these species, some are highly threatened, such as the spoon-billed sandpiper and the black-faced spoonbill, are highly threatened and face significant conservation challenges. In addition, our research identified 25 sites within the Beibu Gulf that qualify as internationally important wetlands, including many for the first time and therefore underscoring the region's significance for waterbird conservation. However, it is concerning that only a small fraction of these sites receive adequate protection, with less than a quarter benefiting from national or international protection and recognition. This study also shed light on localized threats faced by these waterbird habitats, including aquatic resource harvesting, hunting, and aquaculture/fisheries, which are widespread in the region. Addressing these threats is essential to ensure the survival and well-being of the diverse waterbird species that rely on the gulf's wetlands. With the findings from this study, we emphasize the urgent need for continued waterbird monitoring, effective site prioritization, and the development of comprehensive habitat management plans. By bridging knowledge gaps and implementing conservation measures, stakeholders in both China and Vietnam can work collaboratively to protect and preserve the critical waterbird habitats in the Beibu Gulf, securing the future of these migratory species and maintaining the ecological integrity of this important coastal region.

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 authors.

Author contributions

C-YC and YM contributed to the conception and design of the study. CA, CC, GL, FL, HN, QN, TL, SW, and TH participated in data collection through fieldwork in their respective countries. NT, SL, YY, LL, and PQ organized and analyzed the database. YM performed the statistical analysis. NT and YM wrote the first draft of the manuscript. DY and C-YC edited the manuscript. All authors contributed to the manuscript revision, read, and approved the submitted version.

Funding

C-YC was financially supported by the National Natural Science Foundation of China (grant no. 31970496), Shenzhen Science and Technology Program (JCYJ20190809115207397, JCYJ20210324104205014, JSGG20210802153535002). YM was supported by Key Laboratory of Ecology of Rare and Endangered Species and Environmental Protection (Guangxi Normal University), Ministry of Education, China (grant no. ERESEP2022Z08), Basic Ability Enhancement Program for Young and Middle-aged Teachers of Guangxi (grant no. 2023KY0066) and Guangxi Science and Technology Base and Talent Special Project (grant no. AD23026102). Field surveys in N Vietnam are partly supported by a small grant from the Royal Society for the Protection of Birds.

Acknowledgments

We are grateful to many volunteers and colleagues for their survey effort in the field. We thank two reviewers for valuable comments. We are also indebted to the Zhilan Foundation – a mainland China funding agency that has promoted the transboundary monitoring, conservation and management of endangered wildlife at the Beibu Gulf for many years.

Conflict of interest

Author QN is employed by WildTour Ltd.

The remaining 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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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2023.1222806/full#supplementary-material

SUPPLEMENTARY TABLE 1
Summary of survey sites and survey effort along the Beibu Gulf.

SUPPLEMENTARY TABLE 2
Recorded avian species and their maximum counts observed during a survey at a specific site in the Beibu Gulf.

SUPPLEMENTARY TABLE 3
Waterbird species exhibited population sizes surpassing the 1% threshold.

SUPPLEMENTARY TABLE 4
Summary of threats recorded in the Beibu Gulf.

SUPPLEMENTARY FIGURE 1
Sites within or close to Ecological Redline boundaries.

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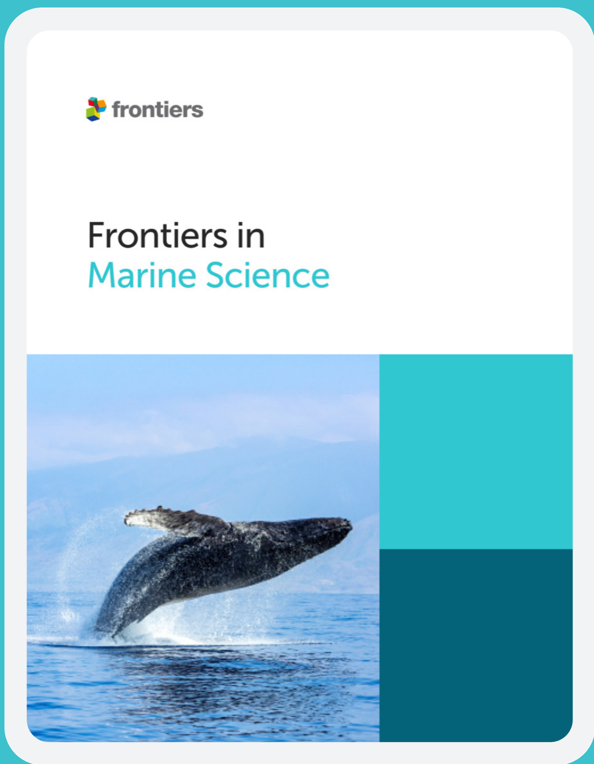

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