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Health assessment of mangrove ecosystem of natural protected areas in Guangdong Province, China

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Introduction: Multiple factors, including human disturbance and environmental change, have caused a significant global mangrove resource loss. Therefore, the Chinese government has restructured mangrove habitats and restored the ecosystem functionality through establishing naturally protected mangrove areas. Despite efforts spanning several years, over 90% of mangrove forests in China have been now integrated into the natural protected area system, with the health status and influencing factors of mangrove ecosystem remaining a pertinent subject for further exploration. Given the intricacies of mangrove ecosystems with complex nonlinear relationships among evaluation factors, it is imperative to adopt scientific methodologies to assess their health status.

Methods: To illustrate this, we conducted a mangrove ecosystem health assessment of natural protected areas of Guangdong Province, China. By employing a fuzzy comprehensive evaluation method and establishing an index system for mangrove ecosystem health assessment.

Results: The results revealed the following findings. (1) Various factors exert differing degrees of influence on mangrove ecosystem health. Notably, the mangrove habitat pattern (weight 47.95%), bird diversity (weight 20.97%), mangrove community (weight 14.31%), water environment (weight 11.76%), and soil sedimentary environment (weight 5.01%) were identified. (2) Overall, the mangrove ecosystem within protected areas of Guangdong exhibited unhealthy signs. There were 4 healthy protected areas (20.00%), 4 areas classified as sub-healthy (20.00%), and 12 were deemed unhealthy (60.00%). (3) Key factors contributing to the compromised health of mangrove ecosystems included the homogenization of mangrove plants, decreased habitat diversity, and exogenous pollution.

Discussion: By planting local mangrove species, scientifically managing the ratio of mangrove cover area to mudflat area, and controlling pollution sources and treating pollutants, the structure of the mangrove ecosystem can be optimized, and the quality of mangrove forest can be improved. These findings can enhance mangrove ecosystem management practices, assist mangrove natural reserve managers in performing targeted mangrove ecological protection and restoration, promote effective management, and contribute to the realization of "harmonious symbiosis" between humanity and nature within mangrove ecosystems.

KEYWORDS

natural protected areas, mangrove, ecosystem, health assessment, fuzzy comprehensive evaluation method

1 Introduction

Mangroves are woody plant communities naturally distributed in the intertidal regions of tropical and subtropical coasts, and have significant ecological and economic value. In terms of ecological value, they are a distinctive forest type along marine beaches, offering essential functions, such as wind and wave prevention, silt promotion and land formation, coastal stabilization, sea wall protection, pollution reduction, and environmental purification. In terms of economic value, for example, mangroves support the reproduction and growth of predators such as fish and shrimp in the region, creating favorable conditions for improving the income of local residents. Additionally, they serve as important sites for mangrove natural education, stimulating the growth of the local economy (Thompson and Rog, 2019; Yang et al., 2021; Yessoufou and Stoffberg, 2015).

Owing to various factors, such as human disturbance and environmental changes, mangrove resources worldwide have faced significant losses. To effectively protect mangrove ecosystems, several countries have initiated protection and restoration projects for degraded mangrove forests in recent decades to rapidly reshape mangrove structures and restore mangrove ecosystem functions (Barnuevo et al., 2017; Leung, 2015), including Australia (Saenger, 1987), Vietnam (Tri et al., 1998), Sri Lanka (Kodikara et al., 2017), and Indonesia (Syahid et al., 2023). In China, efforts have been made through the issuance of the *Specific Project for the Protection and Restoration of Mangroves* (2020–2025), which aims to restore approximately 18,800 ha of mangroves by 2025 (Yang et al., 2021). However, due to the fragility of mangrove ecosystems, the restoration of their original state is challenging once destroyed (Ren, 2009). Hence, the Chinese government has integrated over 90% of mangroves into the natural protected area system, establishing natural reserves, wetland parks, and other protected areas (Li et al., 2013).

The assessment of the health of wetland ecosystems has become a prominent topic in wetland research and management. As a new method to analyze ecosystem structure and functionality, ecosystem health assessment has gained recognition as a global management objective and a leading area of interest within the academic community (Jin et al., 2016; Liu et al., 2023; Muangthong et al., 2012; Song et al., 2022; You et al., 2019). In recent years, this assessment method has been applied to mangrove wetland ecosystems (Aguirre et al., 2018; Bakhtiyari et al., 2019; Pribadi, 2019), yielding valuable insights for stakeholders to measure their health statuses. These findings facilitate effective management and protection efforts, ultimately fostering harmonious coexistence between humans and nature (Prabakaran et al., 2014).

Currently, assessments of mangrove ecosystem health primarily adopt two methods: the indicator organism method and indicator system method (Zheng et al., 2010). The indicator organism method relies mainly on field biological surveys, utilizing species such as *Chromatium Perty* (Essien and Antai, 2009), phytoplankton (Choudhury et al., 2014), sesarmid crab (Dehghani et al., 2021), *Scylla serrata* (Walton et al., 2007), and mangrove species to evaluate the health of these ecosystems (Chaube et al., 2019). However, because of its reliance on individual species, this method struggles to fully capture aspects such as biodiversity conservation, pollutant filtration, and the ecosystem structure and function. The comprehensive index evaluation method identifies key indicators affecting ecosystem health through hierarchical analysis. Most studies have initially established a mangrove ecosystem health evaluation index system (Sheikh et al., 2023). Subsequently, methods such as the ecological footprint chain method (Zheng et al., 2023), remote sensing analysis (Vaghela et al., 2018), pressure-state-response model have been applied (Zheng et al., 2010). Alternatively, regarding to the assessment method outlined in the *Technical Regulation on Evaluation for Mangrove Wetland Health* (LY/T 2794-2017) for mangrove ecosystem health evaluation. These methods assume linearity and uniformity among factors. However, the mangrove ecosystem health assessment encompasses multiple factors and complex interrelations, rendering it a complex nonlinear system. It is difficult to define the good or bad of an indicator with a single linear relationship. Therefore, addressing the challenges faced by this nonlinear system to conduct mangrove ecosystem health assessments is an intriguing research direction.

The fuzzy comprehensive evaluation method is based on fuzzy mathematics and applies the principle of fuzzy relation synthesis to quantify factors with unclear boundaries and difficulties in quantitative evaluation. This method involves listing the multiple factors that affect the overall goal to form a factor set (evaluation index) and establishing an evaluation set (evaluation level). A single-factor evaluation is then performed, and a fuzzy judgment is made for each factor in the factor set according to the evaluation set. The membership degree of each factor at each evaluation level in the evaluation set is determined to form a fuzzy matrix. Different weights are assigned to each factor in the factor set to form a weight vector, resulting in the final evaluation result. The fuzzy comprehensive evaluation method, known for its clear results and strong systematic approach, is widely employed in ecosystem health assessment (Wang et al., 2011; Li and Zheng, 2017). Therefore, addressing the complex relationships among health assessment factors in mangrove ecosystems using the fuzzy comprehensive evaluation method warrants thorough investigation.

Consequently, we utilized the mangrove ecosystem health assessment of natural protected areas in Guangdong Province, China, as a case study. By establishing a mangrove ecosystem health assessment index system, we employed a fuzzy comprehensive evaluation method to assess the health status of these ecosystems. Building upon this, we conducted further analysis to identify the primary factors constraining the health of mangrove ecosystems in naturally protected areas. This endeavor enables pertinent authorities to grasp the health status of mangrove ecosystems, provide a scientific foundation for devising control plans and decisions, enhance the management standards of mangrove ecosystems, and facilitate the realization of "harmonious coexistence" between humanity and nature within these ecosystems.

2 Regional overview and methods

2.1 Regional overview

Guangdong Province, situated in the southernmost region of mainland China, boasts a mainland coastline stretching 4114.3 km and an island coastline spanning 1649.5 km. The main mangrove species in Guangdong include *Kandelia obovata*, *Aegiceras corniculatum*, *Avicennia marina*, *Bruguiera gymnorhiza*, *Rhizophora stylosa*, *Acanthus ilicifolius*, *Acrostichum aureum*, and *Sonneratia apetala*. Mangrove resources in the province are dispersed across 46 counties (cities and districts) within 13 prefecture-level cities along the coast, totaling 12092.95 ha. Since the establishment of the Zhanjiang Mangrove National Nature Reserve, the first mangrove reserve in Guangdong Province, in 1997, afforestation and protection efforts have expanded mangrove distribution within protected areas (Ren, 2009). Currently, these mangroves constitute 41.90% of the total mangrove area of China (excluding Hong Kong, Macao, and Taiwan). Notably, 50.20% of the mangroves were distributed in 20 natural protected areas, such as the Zhanjiang Mangrove National Nature Reserve, Zhuhai Qi'ao-Dang'gan island provincial nature reserve, and Maoming Dianbai Mangrove County Nature Reserve (Figure 1). In some of these protected areas, abandoned aquaculture ponds are not used for economic farming, Instead, managers utilize tides to facilitate the exchange of aquatic resources inside and outside abandoned aquaculture ponds, providing food for birds inhabiting mangrove forests. These aquaculture ponds are a crucial part of the mangrove ecosystems. Conversely, the remaining mangrove patches were typically small, often less than 1 ha, and were dispersed along the coastal regions of Guangdong Province. To maintain the assessment integrity, isolated patches were excluded from this study.

2.2 Methods

2.2.1 Establishment of assessment index system

2.2.1.1 Principle of assessment index selection

To objectively assess mangrove ecosystem health in the natural protected areas of Guangdong Province, it is essential to adhere to specific foundational principles in establishing the assessment system. However, there is currently no standardized criteria in place. Therefore, the development of the assessment system should be based on existing research findings, while also considering the structural and functional attributes unique to the mangrove ecosystem in Guangdong Province. Indicators should be selected judiciously and guided by the following principles:

(1) Representativeness: Considering both natural and human disturbances in mangrove forests, it is essential to extract common indicators that can accurately reflect the health status of mangrove ecosystems.

(2) Systematicity: The selected indicators have scientific basis, possess standardized and lucid definitions, and accurately reflect the multifaceted characteristics of the mangrove ecosystem.

(3) Feasibility: This ensures that the indicators are practical, readily available, and facilitates statistical analysis and comparison.

2.2.1.2 Establishment of assessment index system

By combining existing research findings and referring to the *Technical Regulation on Evaluation for Mangrove Wetland Health* (LY/T 2794-2017), based on the specific characteristics of mangrove ecosystems in Guangdong Province, we employed a hierarchical analysis method (Vaghela et al., 2018; Zheng et al., 2023, 2010) to construct a health assessment index system for mangrove ecosystems in the natural protected areas of Guangdong. This index system comprised three levels: target, system, and indicator, encompassing parameters such as bird diversity, mangrove community, habitat pattern, water quality, and sedimentary environment (Table 1). Further details are provided below.

(1) Bird diversity.

Biodiversity stands as a crucial indicator of mangrove ecosystem health, with birds often serving as key representatives (Li et al., 2013; Acampora et al., 2018; Mancini et al., 2018; Yang et al., 2021). Birds occupy a significant position in the nutrient web and

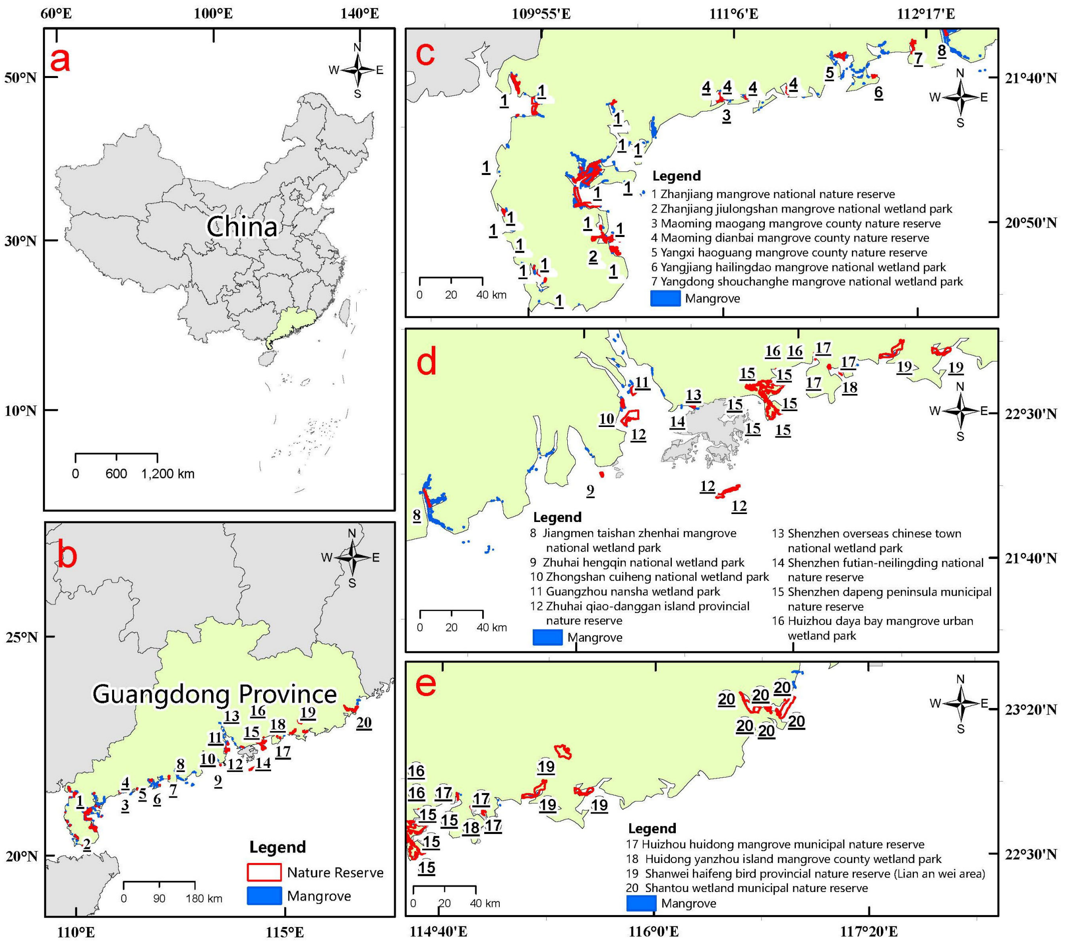

FIGURE 1
Schematic diagram of Guangdong Province, this map shows the distribution of mangrove protected areas in Guangdong Province.

contribute substantially to ecosystem energy dynamics (Ogden et al., 2014), playing essential ecological roles in mangrove ecosystem dynamics (Mancini et al., 2018). Simultaneously, it demonstrates exceptional athletic prowess in challenging circumstances and opportunities while also being relatively straightforward to quantify in terms of both spatial and temporal dimensions. Parameters such as species number, individual number, Shannon-Wiener index, evenness index, and rarity offer effective measures of an ecosystem's health status (Li et al., 2013; Yang et al., 2021).

(2) Mangrove community.

Mangrove forests play a crucial role in providing habitats for various organisms for reproduction and feeding, with habitat utilization reliant on vegetation structure. Evaluating mangrove community structure and function involves assessing parameters such as crown width (cm), crown height (cm), tree height (cm), diameter at breast height (ground diameter) (cm), and species composition of mangrove plants (Etezadifar and Barati, 2013; Leung and Tam, 2013; Mancini et al., 2018).

(3) Mangrove habitat pattern.

Mangrove areas (ha), tidal flat areas (ha), aquaculture pond areas (ha), and open water areas (ha) (excluding aquaculture zones) serve as crucial habitat indicators that influence the quality of the mangrove ecosystem (Ahmed et al., 2023; Wanjiru et al., 2023; Yang et al., 2022, 2021). These are important parameters for evaluating the health status of mangrove ecosystems. Therefore, these indicators were selected to assess the health of mangrove ecosystems in the natural protected areas of Guangdong.

(4) Water environment.

The water quality within mangrove forests serves as a direct indicator of pollution levels and is pivotal for assessing environmental quality. Typically, studies have selected parameters such as pH, water temperature (°C), salinity (%), dissolved oxygen(mg/L), soil salinity (%FS), chemical oxygen demand (mg/L), sulfide(mg/L), nitrite(mg/L), nitrate (mg/L), and ammonia (mg/L) to quantify the capacity of mangroves to purify water pollution (Caussy, 2009). In this study, these indicators were incorporated.

(5) Sedimentary environment.

The physical and chemical attributes of mangrove sediments, including organic carbon (%), suspended matter (%), inorganic phosphorus (mg/L), and active silicate (mg/L), not only indicated the deposition and purification abilities of mangroves against harmful substances but also affected the abundance of biological communities reliant on mangroves (Cannicci et al., 2008; Weinstein and Daniel, 2002). These indicators were also included in this study.

TABLE 1 Health assessment index of mangrove ecosystems in natural protected areas, Guangdong Province.

Target level	System level	Indicator level	Description
Health assessment of mangrove ecosystems in Guangdong Province	Bird diversity	Species number	Measuring bird diversity in the mangrove ecosystem.
		Individual number	Measuring the abundance of birds in the mangrove ecosystem.
		Shannon-Wiener index	Measuring the consistency and diversity of bird distribution in the mangrove ecosystem.
		Evenness index	Measuring the uniform distribution of birds in the mangrove ecosystem.
		Rarity index	Representing the relative number of first-class and second-class national protected species in the evaluated area, and the conservation value of the species in the mangrove ecosystem.
	Mangrove community	Mean crown width	Measuring the structure and function of mangrove communities.
		Mean crown height	
		Mean tree height	
		Mean diameter at breast height (ground diameter)	
		Number of mangrove species	Measuring mangrove species diversity.
		Proportion of native mangrove species	Measuring the extent of invasive mangrove forests.
	Mangrove habitat pattern	Mangrove area	Measuring mangrove growth, the extent of protection from predators, reproduction, and food supply.
		Tidal flat area	Measuring food supply function.
		Aquaculture pond area	Measuring food supplement function.
		Open water area	Measuring the habitat of other organisms and water resource replenishment function.
	Water environment	pH	Measuring the pH content to assess the living environment.
		Water temperature	Measuring the effects of temperature on mangroves and other species.
		Salinity	Measuring the habitat selection requirements of organisms.
		Dissolved oxygen	Measuring the conditions under which aquatic life can survive and the purification of pollutants.
		Soil salinity	Measuring the requirement of mangrove, bird habitat, and benthic survival.
		Chemical oxygen demand	Measuring the pollution purification capacity of mangroves.
		Sulfide	Measuring the purifying effect of mangroves on pollutants.
		Nitrite	Measuring the pollution purification capacity of mangroves.
		Nitrate	
		Ammonia	
	Sedimentary environment	Organic carbon	Measuring the organic carbon accumulation capacity and benthic utilization of mangroves.
		Suspended matter	Measuring the capacity of mangroves to deposit suspended matter.
		Inorganic phosphorus	Measuring the capacity of mangroves to deposit inorganic phosphorus of pollutants.
		Active silicate	Measuring the capacity of mangroves to deposit particulate matter.

2.2.2 Assessment index data acquisition, measurement and processing

2.2.2.1 Bird data acquisition and preliminary processing

In ArcGIS 10.2, the coastal area of Guangdong Province was partitioned into 10 km × 10 km grids using the kilometer grid method (Yang et al., 2021). These grids were overlaid with the boundary ranges of 20 natural protected areas. If an entire protected area fell within a grid, a 6 km line transect traversing the mangrove ecosystem was established within that grid. A total of 41 transect lines were included in the survey. Specifically, 21 line transects were established in the Zhanjiang Mangrove National Nature Reserve, 2 in the Jiangmen Taishan Zhenhaiwan Mangrove National Wetland Park, and 1 in each of the remaining protected areas.

Bird surveys were conducted during both the breeding period (March to May 2022) and wintering period (October to December 2022), with two surveys completed during each period. Field personnel comprised experienced researchers with expertise in bird observation. All surveys were performed by the same staff members to ensure the accuracy of observations. Each survey sample line was 6 km long, and the survey was conducted on foot. Surveys were conducted either in the morning (7:00–11:30) or afternoon (3:00–6:30), each lasting up to 3 h, with low tide identified as the optimal time for assessing bird diversity (Jimenez et al., 2015; Fonseca et al., 2017; Horn et al., 2020). Tide tables from the official website of the China Marine Service Network (Ocean.cnss.com.cn) were checked to determine the low-tide timings for survey scheduling. Field survey equipment included TSN841 20-60x monocular telescopes and 1000 m telephoto lenses for recording assistance. In this study, the species names and individual numbers of birds were collected. Bird identification references included *A Field Guide to the Birds of China* (MacKinnon and Phillipps, 2000). Resident type references include *A Checklist on the Classification and Distribution of the Birds in China* (*Fourth Edition*) (Zheng et al., 2023), with the Shannon-Wiener index, evenness index, and rarity index calculated accordingly.

The Shannon-Wiener index formula was used to calculate shorebird abundance (Weaver, 1963).

$$H = -\sum_{i=1}^{s}\left(\frac{n_i}{N} \times \ln\frac{n_i}{N}\right) \quad (1)$$

where n_i represents the number of individuals in a particular site, N represents the total number of species, and S denotes all species.

The evenness index refers to Pielou's evenness index (Pielou, 1966). The formula is like:

$$J = H\prime/H_{\max} \quad (2)$$

In Equation 2, $H_{max} = \ln S$, where S denotes the same with the one in Equation 1.

The rarity index was applied to determine the number of birds listed in China's national key protected species list for each natural protected area.

2.2.2.2 Mangrove community data acquisition and preliminary processing

Mangrove coverage within each grid was measured using ArcGIS 10.2, and the coverage length was determined. Five 20 m × 20 m quadrats were selected at equal intervals, after the data of 5 quadrats in each protected area were collected, the average was taken to be included in the next analysis. In total 205 survey samples were collected. From March to May and October to December 2022, the crown width (cm), crown height (cm), tree height (cm), and diameter at breast height (ground diameter) (cm) of mangrove plants within the quadrats were measured, and the average values were calculated. The species names of mangrove plants in the protected areas were recorded using the line transect method based on the line transects set in Section 2.2.2.1.

2.2.2.3 Mangrove habitat factor data acquisition and preliminary processing

The 2022 Landsat 8 OLI remote sensing image (30 m spatial resolution) was downloaded from the U.S. Geological Survey website (http://glovis.usgs.gov). Image pre-processing, including geometric and radiometric corrections, was performed using the ENVI 5.3 software. The processed data were then validated on-site, with the mangrove (ha), tidal flat (ha), aquaculture pond (ha), and open water areas (ha) quantified within each natural protection area.

2.2.2.4 Environmental factor data acquisition and measurement

Within the quadrats established in Section 2.2.2.2, data on water quality and soil sediment environmental factors were collected during the wet period (June to August) and dry period (November to December). Five sample points were selected at equal intervals, after the data of 5 sample points in each protected area were collected, the average was taken to be included in the next analysis. In total 205 survey samples were collected. The water environment parameters included pH, water temperature (°C), salinity (%), dissolved oxygen (mg/L), soil salinity (%FS), chemical oxygen demand (mg/L), sulfide (mg/L), nitrite (mg/L), nitrate (mg/L), and ammonia (mg/L). The soil sedimentary environment parameters included organic carbon (%), suspended matter (%), inorganic phosphorus (mg/L), and active silicate (mg/L).

Water environmental factor detection method: At high water levels, water samples (1 L) were collected in brown glass bottles at each sampling point. A portable water quality detector (COD Ammonia Nitrogen Total Phosphorus Total Nitrogen analyzer) was used on-site to test. Data were recorded accordingly.

Sedimentary environmental factor detection method: Samples were collected at low tide, and surface sediment samples (10 cm) were taken from each sampling point. These samples were then brought back to the laboratory for the analysis of sedimentary environmental factors. The following methods were employed in the analysis of various components: thermal conductivity for organic matter, spectrophotometry for suspended matter and active silicate, and digestion-molybdenum-antimony resistance spectrophotometry for inorganic phosphorus.

2.2.3 Data processing

(1) Index weight calculation.

In the fuzzy comprehensive evaluation, the determination of index weights was crucial, as it can reflect the position or significance of each factor in the comprehensive decision-making process, thereby directly affecting the evaluation outcome. The weight values derived through the entropy method exhibited high reliability in comprehensive evaluations and are currently widely employed in ecosystem assessment (Yang and Li, 2017; Hua et al., 2011; Xiao et al., 2020). The calculation method can be as follows.

Data standardization processing: Due to the differences in the dimensions, orders of magnitude, and positive and negative orientations of each indicator, it can be necessary to standardize the initial data. When the index value became larger, the system development was more beneficial, and the positive index calculation method was adopted. When the index value was smaller, the system development can be better, and the negative index calculation method was adopted. The n protected areas and m index were assigned. The x_{ij} represents the score value of the j indicator of the i protected areas. The same degree change of index x_{ij} be $x\prime_{ij}$ was assumed, and the positive index can be

$$x'_{ij} = \frac{x_{ij} - x_{min}}{x_{max} - x_{min}} \tag{3}$$

the negative indicator can be

$$x'_{ij} = \frac{x_{max} - x_{ij}}{x_{max} - x_{min}} \tag{4}$$

where x_{max} represents the maximum value of the j indicator, and x_{min} denotes the minimum value of the j indicator.

$$\text{Calculate the specific gravity of}(x'_{ij}) : y_{ij} = \frac{x'_{ij}}{\sum_{i=1}^{n} x'_{ij}} \tag{5}$$

$$\text{Calculate the entropy of the } j \text{ indicator}(e_j): e_j = -\frac{1}{ln^n}\sum_{i=1}^{n} y_{ij} \times lny_{ij} \tag{6}$$

$$\text{Calculate the difference coefficient of the } j \text{ indicator}(g_j): g_i = 1 - e_j \tag{7}$$

$$\text{Determine the weight of the } j \text{ indicator}(a_j):\ a_j = -\frac{g_j}{\sum_{j=1}^{m} g_j} \tag{8}$$

According to the index weight, the index layer weight vector:

$$C_{ij} = (c_{ij1},\ c_{ij2}, \cdots\cdots c_{ijk}) \tag{9}$$

state layer weight vector:

$$B_{ij} = (b_{ij1},\ b_{ij2}, \cdots\cdots b_{ij}) \tag{10}$$

and system layer weight vector:

$$A = (a_1,\ a_2,\ a_3) \tag{11}$$

are obtained.

(2) Fuzzy comprehensive classification model.

Based on existing research (Yang et al., 2012), the hierarchical membership function method was employed. The "grading table" for each indicator was determined at first. Subsequently, the assessment set was divided into three levels,

$$\begin{aligned} \mathrm{V} &= \{U_{vm}\} = \{u_{v1},\ u_{v2},\ u_{v3}\} \\ &= \{\text{unhealthy, sub}-\text{healthy, healthy}\} \end{aligned} \tag{12}$$

The membership function method can be established as follows:

Determine the nodes X_1, X_2, and X_3.

A practical membership function is given using the data information. Assume the sample observations X_1, X_2, X_n in descending order is $X_{(1)} \le X_{(2)} \le X_{(n)}$. Because the sample observations come from the sample population, they reflect the objective reality of the population:

Sample average is

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{13}$$

sample variance is

$$\sigma^2 = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2 \tag{14}$$

and range is

$$R = X_{(n)} - X_{(1)} \tag{15}$$

Subsequently, two intervals $[X_{(1)},\ X_{(n)}]$ and $[X - 3\sigma,\ \ X + \sigma]$ were obtained. Clearly, the domain U contained the interval $[X_{(1)},\ X_{(n)}]$. In addition,

$$x_2 = \bar{x} \tag{16}$$

$$x_1 = \bar{x} - \frac{3\sigma}{\sqrt{n}} \tag{17}$$

and

$$x_3 = \bar{x} + \frac{3\sigma}{\sqrt{n}} \tag{18}$$

Combined with Figure 2, the membership function is established as follows.

$$u_{v1} = \begin{cases} 1 & x_{xi} < x_1 \\ \frac{x_{ij}-x_2}{x_1-x_2} & x_1 \le x_{ij} < x_2 \end{cases} \tag{19}$$

$$u_{v2} = \begin{cases} \frac{x_{ij}-x_3}{x_2-x_3} & x_2 \le x_{ij} < x_3 \\ \frac{x_{ij}-x_1}{x_2-x_1} & x_1 \le x_{ij} < x_2 \end{cases} \tag{20}$$

$$u_{v3} = \begin{cases} \frac{x_{ij}-x_2}{x_3-x_2} & x_2 \le x_{ij} < x_3 \\ 1 & x_3 \le x_{ij} \end{cases} \tag{21}$$

The weight vector of the hierarchy index is established. The expressions of the weight vector of hierarchical indicators are as follows: the index layer weight vector:

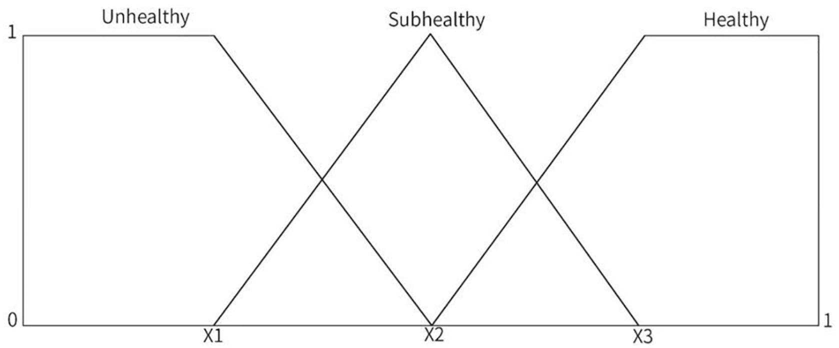

FIGURE 2
Index membership function diagram.

$$C_{ij} = (c_{ij1},\ c_{ij2}, \cdots \cdots c_{ijk}) \tag{22}$$

state layer weight vector:

$$B_{ij} = (b_{ij1},\ b_{ij2}, \cdots \cdots b_{ij}) \tag{23}$$

and system layer weight vector:

$$A = (a_1,\ a_2,\ a_3) \tag{24}$$

A fuzzy relationship between the assessment index and the review set was established. According to the membership function, it is obtained that C_{ijk} belongs to the single factor evaluation set

$$C_{ijk} = (\,C_{ikj(unhealthy)}\ \ C_{ijk(sub-healthy)}\ \ C_{ikj(healthy)}\,) \tag{25}$$

Thus, the fuzzy relation R from the factor set C to assessment set V can be determined for each assessment indicator, which is a matrix:

$$R_{ij} = \begin{pmatrix} C_{ij1(unhealthy)} & C_{ij1(sub-healthy)} & C_{ij1(\text{healthy})} \\ \vdots & \ddots & \vdots \\ C_{ijk(unhealthy)} & C_{ijk(sub-healthy)} & C_{ijk(\text{healthy})} \end{pmatrix} \tag{26}$$

The fuzzy evaluation set of the previous layer is

$$P_{ij(vm)} = c_{ij} \times R_{ij} \tag{27}$$

If $\sum P_{ij(vm)} \neq 1$, the normalization process is performed with

$$Q_{ij(vm)} = \frac{P_{ij(vm)}}{\sum P_{ij(vm)}} \tag{28}$$

The normalized matrix can be obtained as follows.

$$P_{i(vm)} = \begin{pmatrix} Q_{i1(Unhealthy)} & Q_{i1(Subhealthy)} & Q_{i1(\text{Healthy})} \\ \vdots & \ddots & \vdots \\ Q_{ik(Unhealthy)} & Q_{ik(Subhealthy)} & Q_{ik(\text{Healthy})} \end{pmatrix} \tag{29}$$

The fuzzy evaluation set of the state layer is

$$S_{ij(vm)} = B_i \times P_{i(vm)} \tag{30}$$

If $\sum Q_{ij(vm)} \neq 1$, the normalization process is carried out with

$$T_{ij(vm)} = \frac{Q_{ij(vm)}}{\sum Q_{ij(vm)}} \tag{31}$$

The normalized matrix can be obtained as follows:

$$S_{i(vm)} = \begin{pmatrix} T_{i1(unhealthy)} & T_{i1(sub-healthy)} & T_{i1(\text{healthy})} \\ \vdots & \ddots & \vdots \\ T_{ik(unhealthy)} & T_{ik(sub-healthy)} & T_{ik(\text{healthy})} \end{pmatrix} \tag{32}$$

The fuzzy evaluation set of the system layer is $V = A \times S_{i(vm)}$. (33)

The health status of the mangrove ecosystem in natural protected areas was determined according to the principle of maximum membership degree.

3 Results

3.1 Bird diversity

Overall, the level of bird diversity in protected areas is relatively low, and bird diversity varied across different protected areas (Table 2).

3.2 Mangrove community

Table 3 shows that mangrove communities in natural protected areas exhibit certain differences.

3.3 Mangrove habitat pattern

The mangrove habitat pattern varied in each natural protection area, with differences in the proportions of mangrove area, tidal flat area, aquaculture pool area, and open water area (Table 4).

TABLE 2 Bird diversity of mangrove ecosystems in natural protected areas, Guangdong Province.

Mangrove protected area	Species number	Individual number	Shannon-Wiener index	Evenness index	Rarity index
1	138	46235	3.1697	0.6433	16
2	42	3520	2.0486	0.5481	2
3	27	494	2.3096	0.7007	0
4	34	1028	2.6783	0.7595	1
5	44	1966	2.8034	0.7408	1
6	43	1493	2.7952	0.7432	2
7	42	1096	2.1914	0.5863	1
8	42	716	2.1750	0.7806	4
9	34	271	2.8155	0.7984	1
10	26	2764	0.8724	0.2677	2
11	54	8860	2.3233	0.5824	3
12	59	9162	2.2478	0.5513	6
13	45	382	3.2174	0.8452	2
14	55	13246	1.9716	0.4920	4
15	33	280	2.2714	0.6496	4
16	27	1168	2.0726	0.6288	2
17	31	1730	1.6305	0.4748	5
18	40	2539	1.3021	0.3529	3
19	65	10784	2.5314	0.6064	10
20	40	4938	2.1325	0.5781	3

1- Zhanjiang Mangrove National Nature Reserve, 2- Zhanjiang Jiulongshan Mangrove National Wetland Park, 3- Maoming Maogang Mangrove County Nature Reserve, 4- Maoming Dianbai Mangrove County Nature Reserve, 5- Yangxi Haoguang Mangrove County Nature Reserve, 6- Yangjiang Hailingdao Mangrove National Wetland Park, 7- Yangdong Shouchanghe Mangrove National Wetland Park, 8- Jiangmen Taishan Zhenhai Mangrove National Wetland Park, 9- Zhuhai Hengqin National Wetland Park, 10- Zhongshan Cuiheng National Wetland Park, 11- Guangzhou Nansha Wetland Park, 12- Zhuhai Qi'ao-Dang'gan Island Provincial Nature Reserve, 13- Shenzhen Overseas Chinese Town National Wetland Park, 14- Shenzhen Futian-Neilingding National Nature Reserve, 15- Shenzhen Dapeng Peninsula Municipal Nature Reserve, 16- Huizhou Daya Bay Mangrove Urban Wetland Park, 17- Huizhou Huidong Mangrove Municipal Nature Reserve, 18- Huidong Yanzhou Island Mangrove County Wetland Park,19- Shanwei Haifeng Bird Provincial Nature Reserve, 20- Shantou Wetland Municipal Nature Reserve.

TABLE 3 Mangrove communities in natural protected areas, Guangdong Province.

Mangrove protected area	Crown width (cm)	Crown height (cm)	Tree height (cm)	Diameter at breast height (ground diameter) (cm)	Number of mangrove species	Proportion of native mangrove species
1	275.3 ± 289.1	292.4 ± 271.4	330.3 ± 301.7	33.4 ± 23.8	7	85.71
2	153.3 ± 66.2	292.6 ± 130.9	321.2 ± 135.6	29.4 ± 12.9	3	33.33
3	945.9 ± 106.9	1059.7 ± 158.6	1185.4 ± 167.9	116.1 ± 84.6	5	60.00
4	218.8 ± 105.4	167.9 ± 67.5	200.5 ± 66.7	22.9 ± 11.0	2	100.00
5	139.3 ± 55.3	208.5 ± 86.6	222.2 ± 97.0	19.9 ± 5.9	6	83.33
6	227.2 ± 75.6	210.7 ± 52.6	228.5 ± 58.5	23.7 ± 3.97	3	100.00
7	346.6 ± 277.0	343.7 ± 281.8	384.5 ± 306.7	33.2 ± 6.7	3	33.33
8	513.9 ± 371.3	652.8 ± 377.1	724.4 ± 408.6	49.9 ± 31.5	2	50.00
9	922.27 ± 105.3	955.3 ± 116.1	1042.2 ± 129.5	97.0 ± 11.1	5	80.00
10	428.5 ± 134.3	599.6 ± 191.6	639.6 ± 191.4	34.2 ± 10.2	1	0.00

(Continued)

TABLE 3 Continued

Mangrove protected area	Crown width (cm)	Crown height (cm)	Tree height (cm)	Diameter at breast height (ground diameter) (cm)	Number of mangrove species	Proportion of native mangrove species
11	507.1 ± 39.5	885.2 ± 126.5	989.1 ± 146.5	76.5 ± 5.5	4	75.00
12	969.6 ± 129.7	1039.9 ± 153.6	1129.6 ± 158.9	99.3 ± 11.9	6	83.33
13	152.3 ± 52.7	429.7 ± 281.7	457.1 ± 284.3	30.7 ± 5.2	4	75.00
14	273.4 ± 132.4	559.2 ± 267.1	595.4 ± 275.2	38.8 ± 15.6	3	100.00
15	325.8 ± 120.9	581.5 ± 207.7	623.1 ± 212.1	34.8 ± 10.9	3	67.67
16	672.2 ± 209.9	640.9 ± 203.9	73.9 ± 222.4	65.5 ± 14.5	1	0.00
17	538.8 ± 107.3	490.8 ± 86.5	572.9 ± 93.2	54.9 ± 9.0	8	75.00
18	637.3 ± 204.2	611.8 ± 194.9	698.4 ± 212.6	63.3 ± 14.2	1	100.00
19	370.5 ± 71.0	698.4 ± 121.5	741.6 ± 117.4	43.7 ± 10.6	5	60.00
20	482.9 ± 73.1	872.9 ± 170.8	934.9 ± 185.4	72.3 ± 12.3	2	50.00

1- Zhanjiang Mangrove National Nature Reserve, 2- Zhanjiang Jiulongshan Mangrove National Wetland Park, 3- Maoming Maogang Mangrove County Nature Reserve, 4- Maoming Dianbai Mangrove County Nature Reserve, 5- Yangxi Haoguang Mangrove County Nature Reserve, 6- Yangjiang Hailingdao Mangrove National Wetland Park, 7- Yangdong Shouchanghe Mangrove National Wetland Park, 8- Jiangmen Taishan Zhenhai Mangrove National Wetland Park, 9- Zhuhai Hengqin National Wetland Park, 10- Zhongshan Cuiheng National Wetland Park, 11- Guangzhou Nansha Wetland Park, 12- Zhuhai Qi'ao-Dang'gan Island Provincial Nature Reserve, 13- Shenzhen Overseas Chinese Town National Wetland Park, 14- Shenzhen Futian-Neilingding National Nature Reserve, 15- Shenzhen Dapeng Peninsula Municipal Nature Reserve, 16- Huizhou Daya Bay Mangrove Urban Wetland Park, 17- Huizhou Huidong Mangrove Municipal Nature Reserve, 18- Huidong Yanzhou Island Mangrove County Wetland Park,19- Shanwei Haifeng Bird Provincial Nature Reserve, 20- Shantou Wetland Municipal Nature Reserve.

3.4 Water and sedimentary environment

As shown in Tables 5, 6, the water and sedimentary environmental factors varied among the natural protected areas.

3.5 Weight coefficient

According to Equations 3–11, the weight coefficient of each index can be obtained. Table 7 illustrates the health assessment system for mangrove ecosystems in the protected areas of Guangdong Province, which constitutes an ecological protection framework centered on mangrove habitat patterns to maintain biodiversity and realize ecosystem service values. Further details are provided below.

(1) Mangrove habitat pattern emerged as the primary factor influencing the health of the mangrove ecosystem (47.95%), reflecting both habitat competition and the ecosystem's self-adjustment process. Different habitat types contributed differently to the health status of mangrove ecosystems. Notably, the mangrove area played a pivotal role in fostering the ecosystem's healthy development (15.34%), followed by the presence of aquaculture ponds(14.99%), tidal flat areas (8.84%), and open water areas (8.78%).

(2) Bird diversity (20.97%) and mangrove community (14.31%) emerged as pivotal factors affecting the health status of the mangrove ecosystem and were significant indicators of its biodiversity. Regarding bird diversity, individuals (9.67%) and the number of species (4.47%) directly reflected the health status of the mangrove ecosystem. A higher bird species diversity indicated a healthier mangrove ecosystem. A robust mangrove community, characterized by tall, dense vegetation, played a vital role in maintaining ecosystem health. Moreover, the diversity of mangrove species and the presence of indigenous mangrove forests significantly contributed to resisting the invasion of alien species.

(3) The water environment (11.76%) and soil sedimentary environment (5.01%) were significant factors affecting the health status of the mangrove ecosystem. They could directly demonstrate its ability to purify water quality and sequester harmful substances. The minimal variance in weight values across indices suggested that each index is equally important for sustaining the health of the mangrove ecosystem.

3.6 Fuzzy matrix

Based on the data processing method (Equations 12–33), we presented a fuzzy matrix for the overall evaluation of all nature protected areas. The matrix of each evaluation index was as follows: bird diversity matrix (P_1), mangrove community matrix (P_2), mangrove habitat pattern matrix (P_3), water environment matrix (P_4), and sedimentary environment matrix (P_5). The matrix of the system layer was S_1.

$$P_1 = \begin{pmatrix} 0.4050 & 0.4029 & 0.1921 \\ 0.4344 & 0.3773 & 0.1883 \\ 0.2977 & 0.3585 & 0.3438 \\ 0.1189 & 0.4999 & 0.3812 \\ 0.4538 & 0.3422 & 0.2040 \end{pmatrix} \quad P_2 = \begin{pmatrix} 0.3483 & 0.2475 & 0.4043 \\ 0.2762 & 0.1681 & 0.5557 \\ 0.2771 & 0.1659 & 0.5570 \\ 0.4110 & 0.2125 & 0.3765 \\ 0.4319 & 0.1985 & 0.3696 \\ 0.3070 & 0.2409 & 0.4523 \end{pmatrix}$$

TABLE 4 Habitat patterns of mangrove ecosystems in natural protected areas, Guangdong Province.

Mangrove protected area	Mangrove area (ha)	Tidal flat area (ha)	Aquaculture pond area (ha)	Open water area (ha)
1	4240.75	5054.68	6603.90	4821.72
2	119.51	429.77	266.83	451.70
3	182.25	166.36	65.02	166.36
4	115.10	663.82	63.79	1018.20
5	202.37	393.88	257.60	150.21
6	32.22	92.53	30.47	34.49
7	108.05	17.85	0.00	202.10
8	147.94	991.83	58.23	779.10
9	10.62	11.41	0.00	40.38
10	10.34	1.29	0.00	1.29
11	79.93	148.30	323.80	404.80
12	68.02	49.49	154.20	283.15
13	7.32	14.72	17.51	316.21
14	114.68	987.00	50.80	80.54
15	4.12	14.33	0.00	19.63
16	61.07	3.43	27.99	346.23
17	493.46	2530.00	12.03	1944.00
18	1.00	119.40	95.56	33.43
19	51.75	1758.00	3293.00	947.50
20	20.71	3465.70	775.80	5170.90

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$$P_3 = \begin{pmatrix} 0.3381 & 0.5963 & 0.0656 \\ 0.5429 & 0.2410 & 0.2161 \\ 0.4261 & 0.4657 & 0.1082 \\ 0.4775 & 0.3600 & 0.1625 \end{pmatrix} \quad P_4 = \begin{pmatrix} 0.2779 & 0.3240 & 0.3981 \\ 0.3820 & 0.2554 & 0.3626 \\ 0.4665 & 0.2812 & 0.2523 \\ 0.4323 & 0.1785 & 0.3892 \\ 0.4462 & 0.2031 & 0.3507 \\ 0.3998 & 0.4454 & 0.1548 \\ 0.3675 & 0.5124 & 0.1201 \\ 0.4347 & 0.3723 & 0.1931 \\ 0.4182 & 0.1764 & 0.4054 \\ 0.4426 & 0.3592 & 0.1983 \end{pmatrix}$$

$$P_5 = \begin{pmatrix} 0.3973 & 0.3431 & 0.2596 \\ 0.3530 & 0.3034 & 0.3436 \\ 0.3757 & 0.5118 & 0.1124 \\ 0.3812 & 0.1766 & 0.4422 \end{pmatrix} \quad S_1 = \begin{pmatrix} 0.4020 & 0.3801 & 0.2179 \\ 0.3452 & 0.2048 & 0.4500 \\ 0.4289 & 0.4466 & 0.1245 \\ 0.3724 & 0.2925 & 0.3350 \\ 0.3832 & 0.3954 & 0.3114 \end{pmatrix}$$

3.7 Comprehensive evaluation of mangrove ecosystem health status in natural protected areas of Guangdong Province

Table 8 indicates that following the principle of maximum membership, the overall health status of mangrove ecosystems in the natural protected areas of Guangdong Province can be predominantly unhealthy. Specifically, there were four healthy protected areas, constituting 20.00% of the total area, including the Zhanjiang Mangrove National Nature Reserve and the Shanwei Haifeng Bird Provincial Nature Reserve, et al. Additionally, four areas were deemed sub-healthy, accounting for 20.00% of the total, including Guangzhou Nansha Wetland Park, Shenzhen Futian-Neilingding National Nature Reserve, and Huizhou Huidong Municipal Mangrove Nature Reserve, et al. Furthermore, 12 areas were classified as unhealthy, accounting for 60% of the total, including Zhuhai Hengqin National Wetland Park, and Huizhou Daya Bay Mangrove Urban Wetland Park, et al.

TABLE 5 Water environment of mangrove ecosystems in natural protected areas, Guangdong Province.

Mangrove protected area	pH	Water temperature (°C)	Salinity (%)	Dissolved oxygen (mg/L)	Soil salinity (%FS)	Chemical oxygen demand (mg/L)	Sulfide (mg/L)	Nitrite (mg/L)	Nitrate (mg/L)	Ammonia (mg/L)
1	7.87 ± 0.52	23.51 ± 2.95	1.33 ± 0.33	36.18 ± 9.94	11.99 ± 7.50	394.22 ± 457.30	0.02 ± 0.01	0.05 ± 0.03	4.40 ± 1.87	1.34 ± 0.57
2	7.76 ± 1.41	23.75 ± 2.49	0.52 ± 0.53	34.20 ± 5.82	3.77 ± 4.07	99.24 ± 100.15	0.05 ± 0.05	0.05 ± 0.05	7.72 ± 4.36	1.27 ± 0.49
3	7.97 ± 0.09	23.93 ± 3.43	2.27 ± 0.28	36.33 ± 10.33	10.72 ± 9.66	91.41 ± 24.26	0.07 ± 0.05	0.04 ± 0.03	2.65 ± 1.73	2.04 ± 0.85
4	7.76 ± 0.26	23.19 ± 2.58	1.80 ± 0.61	34.12 ± 11.24	6.35 ± 7.56	88.89 ± 56.89	0.04 ± 0.04	0.04 ± 0.03	8.40 ± 8.24	2.66 ± 2.73
5	8.10 ± 0.25	23.55 ± 6.37	0.88 ± 0.56	48.83 ± 25.60	4.39 ± 4.49	137.40 ± 111.08	0.06 ± 0.05	0.05 ± 0.03	10.10 ± 6.87	0.97 ± 1.28
6	8.34 ± 0.35	23.46 ± 5.74	1.01 ± 0.58	45.45 ± 22.69	8.62 ± 5.61	148.78 ± 79.94	0.05 ± 0.04	0.09 ± 0.13	6.01 ± 2.32	0.76 ± 0.45
7	7.74 ± 0.32	21.17 ± 3.27	0.97 ± 0.73	45.45 ± 20.18	6.44 ± 7.48	96.93 ± 90.19	0.29 ± 0.41	0.08 ± 0.05	7.17 ± 4.50	6.48 ± 6.76
8	9.94 ± 0.06	23.36 ± 4.82	0.79 ± 0.53	41.26 ± 21.37	1.68 ± 1.64	132.98 ± 105.21	0.01 ± 0.01	0.04 ± 0.02	5.14 ± 0.96	0.50 ± 0.34
9	8.06 ± 0.33	24.66 ± 6.97	0.77 ± 0.55	39.55 ± 23.00	2.59 ± 2.20	141.47 ± 135.43	0.02 ± 0.01	0.04 ± 0.02	3.84 ± 1.73	0.32 ± 0.23
10	8.39 ± 0.09	26.34 ± 4.58	0.20 ± 0.17	47.42 ± 29.66	0.71 ± 0.66	55.91 ± 34.92	0.05 ± 0.04	0.07 ± 0.03	6.67 ± 2.64	0.40 ± 0.16
11	8.11 ± 0.23	24.78 ± 3.19	0.43 ± 0.07	31.31 ± 23.67	1.46 ± 0.48	103.09 ± 24.10	0.05 ± 0.03	0.03 ± 0.01	2.37 ± 0.03	1.31 ± 0.47
12	7.63 ± 0.27	25.01 ± 6.47	0.53 ± 0.45	40.62 ± 19.84	3.08 ± 2.08	127.01 ± 77.43	0.05 ± 0.07	0.03 ± 0.02	5.81 ± 5.36	0.51 ± 0.23
13	7.62 ± 0.48	25.30 ± 4.25	0.32 ± 0.33	31.00 ± 10.93	4.75 ± 5.96	114.29 ± 113.06	0.02 ± 0.02	0.02 ± 0.01	7.64 ± 3.46	1.86 ± 0.79
14	7.75 ± 0.59	26.75 ± 6.28	0.58 ± 0.37	31.20 ± 15.12	8.69 ± 10.77	152.54 ± 120.19	0.07 ± 0.06	0.06 ± 0.06	1.55 ± 1.42	1.49 ± 0.53
15	8.30 ± 0.1	26.07 ± 3.75	2.93 ± 4.14	26.71 ± 6.52	10.52 ± 9.20	91.73 ± 71.74	0.05 ± 0.04	0.03 ± 0.03	3.40 ± 1.48	2.05 ± 0.89
16	7.73 ± 0.07	24.81 ± 2.71	0.59 ± 0.55	47.22 ± 25.34	0.86 ± 0.90	109.95 ± 99.83	0.03 ± 0.02	0.22 ± 0.19	9.46 ± 7.43	0.94 ± 1.16
17	8.31 ± 0.31	25.08 ± 3.10	1.05 ± 0.59	53.91 ± 23.00	3.53 ± 3.55	218.97 ± 94.75	0.04 ± 0.03	0.06 ± 0.04	7.83 ± 6.56	1.06 ± 0.70
18	8.14 ± 0.36	24.76 ± 3.52	1.61 ± 1.10	53.83 ± 22.99	7.52 ± 8.93	128.01 ± 60.14	0.04 ± 0.03	0.06 ± 0.05	4.86 ± 1.25	1.50 ± 1.02
19	7.74 ± 0.42	24.92 ± 1.18	0.18 ± 0.25	24.46 ± 9.99	5.59 ± 9.09	86.83 ± 79.37	0.11 ± 0.06	0.05 ± 0.01	3.63 ± 2.06	4.60 ± 2.49
20	8.53 ± 0.52	24.91 ± 3.96	0.60 ± 0.22	30.62 ± 11.17	3.81 ± 4.81	131.31 ± 91.48	0.05 ± 0.04	0.12 ± 0.12	2.30 ± 1.64	1.35 ± 0.81

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TABLE 6 Sedimentary environment of mangrove ecosystems in natural protected areas, Guangdong Province.

Mangrove protected area	Organic carbon (%)	Suspended matter (%)	Inorganic phosphorus (mg/L)	Active silicate (mg/L)
1	0.83 ± 0.09	37.72 ± 25.17	0.03 ± 0.02	3.06 ± 1.80
2	1.86 ± 0.16	20.71 ± 14.30	0.01 ± 0.01	4.30 ± 0.33
3	0.75 ± 0.05	20.84 ± 17.30	0.03 ± 0.02	1.00 ± 0.76
4	1.09 ± 0.10	13.36 ± 8.38	0.07 ± 0.05	1.10 ± 0.45
5	0.80 ± 0.12	49.91 ± 17.30	0.30 ± 0.28	4.27 ± 0.46
6	0.55 ± 0.17	59.83 ± 67.73	0.33 ± 0.29	4.22 ± 1.38
7	0.89 ± 0.25	59.79 ± 19.84	0.47 ± 0.41	4.17 ± 1.73
8	1.26 ± 0.22	64.34 ± 96.03	0.35 ± 0.32	4.65 ± 0.60
9	0.87 ± 0.62	52.11 ± 46.57	0.43 ± 0.39	4.98 ± 1.38
10	0.68 ± 0.03	93.57 ± 58.94	0.25 ± 0.21	4.83 ± 0.24
11	0.73 ± 0.35	60.72 ± 34.82	0.04 ± 0.21	2.78 ± 0.88
12	2.36 ± 0.04	128.04 ± 115.00	0.46 ± 0.39	5.96 ± 1.36
13	1.66 ± 0.01	18.69 ± 19.25	0.11 ± 0.07	2.18 ± 0.06
14	0.92 ± 0.40	56.23 ± 40.32	0.08 ± 0.02	1.31 ± 0.41
15	0.81 ± 0.09	7.60 ± 2.47	0.11 ± 0.09	1.76 ± 0.22
16	1.02 ± 0.04	28.91 ± 12.84	2.90 ± 2.41	3.02 ± 2.88
17	1.22 ± 0.06	73.05 ± 56.43	0.55 ± 0.45	4.06 ± 0.98
18	0.24 ± 0.03	58.97 ± 66.27	0.24 ± 0.21	3.35 ± 1.07
19	0.42 ± 0.48	68.45 ± 26.47	0.10 ± 0.03	2.78 ± 0.01
20	0.22 ± 0.04	44.97 ± 27.72	0.17 ± 0.12	2.00 ± 0.09

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4 Discussion

The health of the world's mangrove ecosystems is under a serious threat. Sheikh et al. (2023) shown that the deltaic Sundarbans mangrove ecosystem is currently in moderate to an acceptable condition, with low or non-significant pollution levels and fair water quality. Our results indicate that the health status of mangrove ecosystems in Guangdong is at an unhealthy level. This presents an opportunity to measure mangrove ecosystem health more accurately and improve strategies for their protection.

4.1 Assessment index system of mangrove ecosystem health status

Based on existing research findings, and considering the mangrove ecosystem structure in the natural protected areas of Guangdong Province, an indicator system was developed to assess the health status of the mangrove ecosystem. This system encompassed bird diversity, mangrove communities, habitat patterns, and water and sedimentary environments (Table 1). Based on the mangrove habitat pattern, this assessment system served as an ecological protection framework, with objectives centered on preserving biodiversity and harnessing ecosystem service value, specifically as follows.

4.1.1 Mangrove habitat pattern is the main factor affecting mangrove ecosystem health

Mangrove habitat patterns resulted from competition among diverse habitats and served as a direct reflection of the ecosystem's self-adjustment process. The contribution of different habitat types to the maintenance of mangrove ecosystem health varied, with a weight of 47.95%.

(1) Mangrove area is a primary indicator of mangrove ecosystem health, with a weight of 15.34%. Previous studies have confirmed that larger mangrove areas provide greater potential for providing valuable ecosystem

TABLE 7 Weight coefficients for health assessment index of mangrove ecosystems in natural protected areas, Guangdong Province.

Target level	System level	Weight coefficient (%)	Indicator level	Weight coefficient (%)
Health assessment of mangrove ecosystem in Guangdong Province	Bird diversity	20.97	Species number	4.47
			Individual number	9.67
			Shannon-Wiener index	2.42
			Evenness index	0.91
			Rarity index	3.50
	Mangrove community	14.31	Crown width	3.21
			Crown height	2.36
			Tree height	2.54
			Diameter at breast height (ground diameter)	1.93
			Number of mangrove species	2.89
			Proportion of native mangrove species	1.38
	Mangrove habitat pattern	47.95	Mangrove area	15.34
			Tidal flat area	8.84
			Aquaculture pond area	14.99
			Open water area	8.78
	Water environment	11.76	pH	4.16
			Water temperature	0.86
			Salinity	0.89
			Dissolved oxygen	0.20
			Soil salinity	1.48
			Chemical oxygen demand	0.55
			Sulfide	0.51
			Nitrite	0.57
			Nitrate	1.87
			Ammonia	0.67
	Sedimentary environment	5.01	Organic carbon	2.24
			Suspended matter	0.84
			Inorganic phosphorus	0.49
			Active silicate	1.44

services, including biodiversity preservation (Jackson et al., 2021; Mancini et al., 2018; Yang et al., 2021), carbon sink capacity (Gu et al., 2021; Tri et al., 2024), serving as a habitat for flagship species (Thompson and Rog, 2019), and mitigating natural disaster risks (Menéndez et al., 2018). Hence, efforts are underway to expand the mangrove area within protected areas such as Zhanjiang Mangrove National Nature Reserve through mangrove planting initiatives (Saenger, 1987; Tri et al., 1998; Ren, 2009; Leung, 2015; Kodikara et al., 2017; Mancini et al., 2018; Syahid et al., 2023) to enhance the complexity of both internal and external mangrove structures (Li et al., 2013), thereby promoting the health of the mangrove ecosystem.

(2) Aquaculture ponds, with a weight of 14.99%, are a significant indicator for preserving mangrove ecosystem health and safeguarding biodiversity (Yang et al., 2022). Research demonstrates that dike-ponds within mangrove forests contribute to enhancing biological richness, such as fish and shrimp populations (Ahmed et al., 2023; Wanjiru et al., 2023), while also offering ample food resources for avian species residing in mangrove habitats. Furthermore, these ponds serve as alternative or supplementary feeding

TABLE 8 Health assessment of mangrove ecosystem of natural protected areas in Guangdong Province.

Mangrove protected area	Evaluation set	Assessment result
Zhanjiang Mangrove National Nature Reserve	(0.1767, 0.1113, 0.67121)	Healthy
Zhuhai Qi'ao-Dang'gan Island Provincial Nature Reserve	(0.3246, 0.3107, 0.3647)	Healthy
Huizhou Huidong Mangrove Municipal Nature Reserve	(0.1547, 0.3055, 0.5398)	Healthy
Shanwei Haifeng Bird Provincial Nature Reserve	(0.1604, 0.3194, 0.5205)	Healthy
Guangzhou Nansha Wetland Park	(0.2720, 0.4785, 0.2496)	Sub-healthy
Shenzhen Futian-Neilingding National Nature Reserve	(0.3346, 0.4494, 0.2159)	Sub-healthy
Jiangmen Taishan Zhenhai Mangrove National Wetland Park	(0.2964, 0.4855, 0.2181)	Sub-healthy
Shantou Wetland Municipal Nature Reserve	(0.2420, 0.3963, 0.3617)	Sub-healthy
Zhanjiang Jiulongshan Mangrove National Wetland Park	(0.4854, 0.4643, 0.0505)	Unhealthy
Maoming Maogang Mangrove County Nature Reserve	(0.4090, 0.3338, 0.2554)	Unhealthy
Maoming Dianbai Mangrove County Nature Reserve	(0.5322, 0.4016, 0.0668)	Unhealthy
Yangxi Haoguang Mangrove County Nature Reserve	(0.4812, 0.4175, 0.1013)	Unhealthy
Yangjiang Hailingdao Mangrove National Wetland Park	(0.5623, 0.3044, 0, 1332)	Unhealthy
Yangdong Shouchanghe Mangrove National Wetland Park	(0.4736, 0.4066, 0.1197)	Unhealthy
Zhuhai Hengqin National Wetland Park	(0.4954, 0.2372, 0.2674)	Unhealthy
Zhongshan Cuiheng National Wetland Park	(0.5667, 0.3118, 0.1215)	Unhealthy
Shenzhen Overseas Chinese Town National Wetland Park	(0.4777, 0.3146, 0.2125)	Unhealthy
Shenzhen Dapeng Peninsula Municipal Nature Reserve	(0.5132, 0.3578, 0.1290)	Unhealthy
Huizhou Daya Bay Mangrove Urban Wetland Park	(0.5102, 0.2996, 0.1902)	Unhealthy
Huidong Yanzhou Island Mangrove County Wetland Park	(0.4407, 0.3403, 0.2189)	Unhealthy
Overall situation	(0.3972, 0.3578, 0.2449)	Unhealthy

According to the principle of maximum membership, the comments corresponding to the highest value in the review set are the evaluation results.

grounds for declining migratory waterbird populations globally during various life stages (Walton et al., 2015; Wang et al., 2020). Different from other aquaculture models primarily aimed at economic profit, preserving dike ponds for conservation purposes is pivotal for maintaining species diversity. To diversify mangrove ecosystem habitat types, Guangdong Province has restored the biodiversity within mangrove ecosystems and ensure their health. This includes withdrawing aquaculture farmers, preserving the original form of the base enclosure, and regulating water levels within the Guangzhou Nansha Wetland and the Shanwei Haifeng Avian Natural Reserve.

(3) The tidal flat area is another crucial indicator of the mangrove ecosystem health. Among benthic organisms, tidal flats are vital foraging grounds for predators. Larger tidal flat areas correspond to more abundant benthic organisms, enabling them to resist the decrease in density caused by predator foraging (Yang et al., 2021, 2022). Consequently, natural reserves such as Zhuhai Qi'ao-Dang'gan Island Provincial Nature Reserve, Shanwei Haifeng Avian Natural Reserve, and Shenzhen Futian–Neilingding National Nature Reserve have preserved extensive tidal flat areas during mangrove planting initiatives.

(4) Open water areas also play a significant role in maintaining ecosystem health. In the coastal regions of Guangdong, there is higher rainfall in the summer and lower rainfall in the winter, which promotes nutrient enrichment and exposure. As summer transitions to winter, expansive shallow water areas gradually form in certain waters, exposing nutrient-rich sediments and facilitating predator foraging (Yang et al., 2022). Parks such as the Zhuhai Hengqin National Wetland Park, Shenzhen Overseas Chinese Town National Wetland Park, and Zhongshan Cuiheng National Wetland Park promote species diversity by preserving extensive water areas.

4.1.2 Bird diversity is a direct indicator of the health of mangrove ecosystems

Birds occupy a significant position in the nutrient web and contribute substantially to ecosystem energy dynamics (Ogden et al., 2014), playing essential ecological roles in mangrove ecosystem dynamics (Mancini et al., 2018). Simultaneously, it demonstrates exceptional athletic prowess in challenging circumstances and opportunities while also being relatively straightforward to quantify in terms of both spatial and temporal dimensions. Our research confirmed that bird diversity was a direct indicator of mangrove ecosystem health, with a weight of 20.97%. Healthy mangrove ecosystems exhibit resilience to external pollution and enhance benthic richness within mangrove forests (Leung, 2015; Fusi et al., 2016). Furthermore, they offer diverse habitat types, meeting the needs of various bird species and fostering mangrove bird diversity (Chen et al., 2016; Mancini et al., 2018). Moreover, given Guangdong Province's location along the East Asian-Australasian Flyway, mangroves serve as crucial resting spots for migratory birds. Consequently, bird diversity also serves as an intuitive reflection of birds preferences for healthy mangroves.

4.1.3 Mangrove community is a key factor affecting the health of mangrove ecosystems

The heterogeneity of the mangrove community structure contributes to the complexity of the mangrove ecosystem and is a key factor affecting its health, with a weight of 14.31%. Varied mangrove communities, comprising different species and sizes, have caused area and isolation effects, localized interactions (competition) for limited resources, vegetation diversity, and structural heterogeneity, along with species availability in regional species banks (Azlan and Michael, 2011). These complex three-dimensional habitats enhance microhabitats and accommodate more ecological niches, thereby leading to niche heterogeneity. This supports the breeding and habitat needs of diverse organisms while also enhancing the mangroves' resilience against risks (Chen et al., 2016; Mancini et al., 2018).

Although the weight values of mangrove species diversity and the proportion of native species in assessing mangrove ecosystem quality are lower than those of community structure, they remain significant indicators of health status. Greater mangrove species abundance contributes to resistance to ecosystem simplification caused by single-species dominance (Barnuevo et al., 2017). However, mangrove ecosystems dominated by the alien species *Sonneratia apetala* are deemed unhealthy because invasive species have resulted in significant changes in local ecosystems, including alterations in habitat structure and ecosystem productivity, ultimately undermining ecological functions (Ren, 2009; Chen et al., 2016). For instance, the healthy status of ecosystems in Zhongshan Cuiheng National Wetland Park is unhealthy attributed to *Sonneratia apetala* dominance within the mangrove ecosystem.

4.1.4 Water environment and soil sedimentary environment are important factors affecting the health of mangrove ecosystems

Mangrove ecosystems are fragile and are significantly affected by human activities. Pollution in mangrove areas can result in biodiversity loss and decline in health, hampering normal functioning (Caussy, 2009). Our findings indicated that although the water environment (weight 11.76%) and soil sedimentary environment (weight 5.01%) were relatively less emphasized in the mangrove health assessment index system, they remained pivotal factors affecting mangrove ecosystem health. Extensive research has highlighted how the physical and chemical properties of these environments not only shape the growth and development of mangrove plant communities but also influence benthic communities within mangrove forests, subsequently driving mangrove biodiversity levels (Leung and Cheung, 2017; Fusi et al., 2016; Peterson et al., 2006; Cannicci et al., 2008; Leung and Tam, 2013), thereby affecting ecosystem health. Notably, the natural protected areas in Guangzhou, Zhuhai, and Shenzhen within the Pearl River Delta are particularly vulnerable to external pollution because of their higher levels of social and economic development than other regions. Consequently, the water and soil sedimentary environments exerted a more pronounced impact on the health of mangrove ecosystems in these protected areas.

4.2 Factors restricting the health of mangrove ecosystem natural protected areas in Guangdong

Overall, the health of the mangrove ecosystem in the protected areas of Guangdong Province is deemed unhealthy. At the individual protected area level, only a minority exhibited healthy or sub-healthy conditions, with the majority classified as unhealthy (Table 8). This trend may be attributed to the following factors.

(1) A decline in habitat diversity within mangrove ecosystems significantly affects their health. Despite the Chinese government's initiative to restore and expand mangroves by 18,800 ha by 2025 (Yang et al., 2021), this expansion has encroached on tidal flats, retained aquaculture ponds, and open water areas within protected zones. Consequently, habitat diversity has decreased, limiting utilization space for certain species, notably birds (Leung, 2015; Yang et al., 2021). This has fundamentally affected the abundance and distribution of various species (Ma et al., 2019), thereby hindering the overall health of mangrove ecosystems.

(2) The homogenization of mangrove plants and the increase in invasive alien species are the main factors affecting mangrove ecosystem health. Despite the crucial role of habitat heterogeneity in sustaining mangrove ecosystems, species composition within protected areas tends to be uniform (Table 9). Given the relative fragility of mangrove ecosystems, restoration efforts face challenges as once destroyed, mangroves are difficult to fully recover (Ren, 2009). China has experienced mangrove destruction, protection, and restoration. However, restoration practices in recent decades have predominantly involved either gradual reintroduction of native mangrove species by reserve managers or expedited restoration using alien species, such as *Sonneratia apetala*. Regrettably, over 80%

TABLE 9 Overview of mangrove ecosystems in natural protected areas, Guangdong Province.

Number	Name of the natural protected areas	Mangrove species
1	Zhanjiang Mangrove National Nature Reserve	*Avicennia marina, Rhizophora stylosa, Bruguiera gymnorhiza, Aegiceras corniculatum, Kandelia obovata, Acanthus ilicifolius, Sonneratia apetala*
2	Zhanjiang Jiulongshan Mangrove National Wetland Park	*Avicennia marina, Rhizophora stylosa, Sonneratia apetala*
3	Maoming Maogang Mangrove County Nature Reserve	*Laguncularia racemosa, Sonneratia apetala, Avicennia marina*
4	Maoming Dianbai Mangrove County Nature Reserve	*Laguncularia racemosa, Avicennia marina, Kandelia obovata, Aegiceras corniculatum, Sonneratia apetala*
5	Yangxi Haoguang Mangrove County Nature Reserve	*Kandelia obovata, Aegiceras corniculatum*
6	Yangjiang Hailingdao Mangrove National Wetland Park	*Kandelia obovata, Aegiceras corniculatum, Avicennia marina*
7	Yangdong Shouchanghe Mangrove National Wetland Park	*Avicennia marina, Acanthus ilicifolius, Aegiceras corniculatum, Kandelia obovata, Acrostichum aureum, Sonneratia apetala*
8	Jiangmen Taishan Zhenhai Mangrove National Wetland Park	*Kandelia obovata, Sonneratia apetala*
9	Zhuhai Hengqin National Wetland Park	*Avicennia marina, Rhizophora stylosa, Sonneratia apetala, Kandelia obovata, Bruguiera gymnorhiza*
10	Zhongshan Cuiheng National Wetland Park	*Sonneratia apetala*
11	Guangzhou Nansha Wetland Park	*Sonneratia apetala, Bruguiera gymnorhiza, Pongamia pinnata, Kandelia obovata*
12	Zhuhai Qi'ao-Dang'gan Island Provincial Nature Reserve	*Sonneratia apetala, Avicennia marina, Kandelia obovata, Bruguiera gymnorhiza, Rhizophora stylosa, Aegiceras corniculatum*
13	Shenzhen Overseas Chinese Town National Wetland Park	*Heritiera littoralis, Avicennia marina, Kandelia obovata, Aegiceras corniculatum*
14	Shenzhen Futian-Neilingding National Nature Reserve	*Kandelia obovata, Aegiceras corniculatum, Avicennia marina*
15	Shenzhen Dapeng Peninsula Municipal Nature Reserve	*Sonneratia apetala, Kandelia obovata, Bruguiera gymnorhiza*
16	Huizhou Daya Bay Mangrove Urban Wetland Park	*Sonneratia apetala*
17	Huizhou Huidong Mangrove Municipal Nature Reserve	*Sonneratia apetala, Acanthus ilicifolius, Bruguiera gymnorhiza, Aegiceras corniculatum, Kandelia obovata, Pongamia pinnata, Heritiera littoralis, Talipariti tiliaceum*
18	Huidong Yanzhou Island Mangrove County Wetland Park	*Kandelia obovata*
19	Shanwei Haifeng Bird Provincial Nature Reserve	*Sonneratia apetala, Laguncularia racemosa, Avicennia marina, Aegiceras corniculatum, Kandelia obovata*
20	Shantou Wetland Municipal Nature Reserve	*Sonneratia apetala, Aegiceras corniculatum*

(Continued)

TABLE 9 Continued

of these restoration attempts have resulted in degraded secondary forests. For example, in Huizhou Daya Bay Mangrove Urban Wetland Park and Zhongshan Cuiheng Wetland Park (Table 9), *Sonneratia apetala*, an invasive species, was selected for mangrove planting. This not only contributes to mangrove vegetation homogenization but also alters habitat structure and ecosystem productivity, thereby disrupting the ecological functions of local mangrove ecosystems (Ren, 2009; Chen et al., 2016). Consequently, this practice is a significant factor driving the unhealthy state of mangrove ecosystems (Table 8).

(3) Exogenous pollution significantly affects mangrove ecosystems. Existing study results have proved that mangroves can be critical in purifying exogenous pollutants and resisting environmental pollution. However, when the pollutant exceed the self-purification capacity of mangrove ecosystems, it can be detrimental to the health status. Mangroves have long suffered from the adverse impact of inorganic and organic pollutant discharge. It not only weakens the physiological and biochemical processes including photosynthesis and transpiration of mangrove plants, but also amplifies the effect through being enriched inside the mangrove food web. Furthermore, it affects the benthic communities in mangrove forests and the mangrove biodiversity level (Leung and Cheung, 2017; Fusi et al., 2016; Peterson et al., 2006; Cannicci et al., 2008; Leung and Tam, 2013). As pollution levels escalate, mangroves may transition from pollutant sinks to sources, particularly in naturally protected areas such as Nansha, Qi'ao island, and Shenzhen in the Pearl River Delta.

4.3 Suggestions on healthy development of mangrove ecosystems of natural protected areas in Guangdong

Our research findings demonstrated the multifaceted and complex nature of factors affecting the health of mangrove ecosystems in the protected areas of Guangdong Province. The heterogeneity of mangrove habitat structure, mangrove communities, and their pollutant purification capacity are key determinants of ecosystem health. To promote the robust development of mangrove ecosystems, optimizing their structure in accordance with these factors is imperative for enhancing the overall ecosystem health.

(1) To optimize mangrove habitat patterns and enhance habitat heterogeneity, it is crucial to scientifically manage protected areas. This involves selecting diverse native tree species to increase mangrove species diversity while reducing the planting of alien species, such as *Sonneratia apetala*. Concurrently, maintaining a balanced ratio of mangrove planting area to tidal flat area at 1:4 is essential (Yang et al., 2021). Managing aquaculture ponds in mangrove regions is necessary. This includes regulating artificial water levels and planting aquatic vegetation to enhance habitat complexity and contribute to the overall optimization of the mangrove ecosystem structure and function.

(2) Establishing source control as the foundation and enhancing overall environmental quality can be effective. Guangdong's mangrove ecosystem has experienced exogenous pollution for a long time, exceeding its self-purification capacity. To enhance the overall environmental quality, encompassing water and sediment, effective control of exogenous pollution at its source is crucial. Specific measures include establishing a marine ecological environment monitoring system for real-time surveillance utilizing a multidimensional network comprising ocean stations, satellite remote sensing, monitoring ships, and buoys, with a particular focus on sensitive areas such as coastal wetlands (mangroves). Furthermore, constructing a marine environmental information database facilitates data sharing among land and sea regulatory agencies, enabling comprehensive monitoring, evaluation, and pollution source tracing efforts. Additionally, initiatives such as garbage classification, sludge recycling in water plants, and scientific crop fertilization should be enforced.

5 Conclusion

In this study, the health status of mangrove ecosystems in nature reserves in Guangdong Province was assessed, and the results of each index was consistent with each other. Overall, the mangrove ecosystems in the protected areas of Guangdong Province were in an unhealthy state. Among the individual protected areas, only a few were classified as healthy or sub-healthy, whereas most were classified as unhealthy. Factors such as mangrove habitat pattern, bird diversity, mangrove community, water environment, and sedimentary environment all affected the health of the mangrove ecosystem, with the mangrove habitat pattern playing a particularly significant role.

To effectively protect the mangrove ecosystem, the Chinese government is strengthening conservation efforts. Measures such as planting native mangroves, removing exotic tree species, and controlling water pollution sources are being implemented to gradually restore the structure and function of mangrove ecosystems and improve their service functions.

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

XY: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. RW: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. MQ: Methodology, Writing – review & editing. CZ: Data curation, Writing – review & editing. JL: Formal analysis, Methodology, Writing – review & editing. WZ: Methodology, Software, Writing – review & editing. TJ: Software, Writing – review & editing. XHL: Methodology, Writing – review & editing. XKL: Data curation, Methodology, Writing – review & editing.

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Conflict of interest

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

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