



Article Environmental Determinants of the Distribution of Halophila beccarii Ascherson in Hainan Island, China

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Abstract: This study presents the first record of the overall distribution of the seagrass *Halophila beccarii* Ascherson on the island of Hainan. Statistical and ecological methods were used to analyze the distribution of the species and the influence of environmental factors. *Halophila beccarii* was mainly distributed in the northwest and southeast of Hainan, in lagoons with a total area of 20.981 km², including the largest *H. beccarii* area in China covering approximately 9.58 km² in Xiaohai, Wanning; there were also 4.89 km² in Xinying Bay, Danzhou, approximately 2.20 km² in Huachang Bay, Chengmai, 1.88 km² in Dongzhai Port, Haikou, 0.95 km² in Xinying Port, Lingao, approximately 0.668 km² in Laoyehai, Wanning, approximately 0.363 km² in Hongpai, approximately 0.23 km² in Maniao, and approximately 0.22 km² in Huanglong Port, Lingao. The average coverage of *H. beccarii* measured at 7.08–56.33%, the density of stem and branch was 487.47–20,167.1 ind/m², and the biomass measured at 1.57–112.94 gDW/m². The growth distribution was mainly influenced by habitat type and, to a lesser extent, by tidal branching channels, heavy metal content (Cu, Pb, Cr, Zn) in the marine environment, and human activities in adjacent coastal areas.

Keywords: Halophila beccarii; geographical distribution; influencing factors; Hainan Island

1. Introduction

Halophila beccarii Ascherson belongs to the Hydrocharitaceae family and is one of the oldest seagrass lineages with high taxonomic status [1]. This seagrass is a submerged marine plant found in the tropics to subtropics [2]; it is small, fast-growing, and monoecious, with pistillate prematurity, low genetic diversity, and coexisting annual and perennial life histories [3,4]. It grows only in intertidal areas and is highly influenced by anthropogenic activities. Its habitat is usually muddy or muddy-sandy in narrow areas with a mean depth ≤ 1.7 m [4]. According to the International Union for the Conservation of Nature, this seagrass has a global distribution of ≤ 2000 km² and is declining. It was listed as vulnerable in 2012 and is currently one of the ten seagrass species at high risk of extinction [5]. Few international studies on *H. beccarii* have focused on the distribution of the seagrass in the tropics [6–13] or on reproductive phenological observations [14–16]. In contrast, most studies on *H. beccarii* in China have focused on species distribution [17–20] and morphological structure [21,22], followed by population dynamics, soil seed banks [23–26], and genetic variation [27–29].

Hainan is the province with the largest number of seagrass species, covering the largest area in China, accounting for approximately 64% of the total seagrass area in the country [30]. Although the sea area of Hainan Island is rich in seagrasses, the distribution status of *H. beccarii* has been poorly reported. The earliest report on the distribution of seagrass in Hainan was published in 1979 [17]. In 2012, the distribution of seagrass in Huachang Bay, Chengmai, Hainan was reported, but the exact area was unknown [18]; subsequently, the distribution of seagrass in Dongzhai Port was reported [20,24]. Recently,



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Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). researchers have systematically studied the distribution of seagrass in Hainan based on long-term monitoring data around the island and found that it is distributed in harbors and lagoons in Wanning and Lingao, but the distribution area has not been reported in detail [31]. Therefore, based on comprehensive survey data of seagrass in coastal Hainan from 2018 to 2021, this study systematically reports its overall distribution status and influencing factors in Hainan, and explores the main environmental factors affecting its growth and reproduction by investigating its distribution area, cover, stem and branch density, biomass, and habitat. It also proposes conservation recommendations, aiming to provide a better understanding of this endangered species and basic data for the sustainable development and utilization of lagoon resources.

2. Materials and Methods

2.1. Study Area

Hainan has an area of 33,900 km², and the seagrass beds cover 48.64 km² [31]. The island has a maritime tropical monsoon climate, with an average annual temperature of 22–26 °C and average annual precipitation of >1600 mm. The unique geographical location and climate greatly enrich seagrass beds around Hainan. We conducted a comprehensive survey of the lagoon and the harbor surrounding Hainan Island in a total of 24 survey areas, including Dongzhai Port, Xiaohai, Huachang Bay, Laoyehai, Xincun Port, Lian Port, Xinying Bay, Hongpai, Maniao Port, Xinying Port, Huanglong Port, Tielu Port, Huxin Port, Tongguling, Yelin Bay in the eastern suburbs, Gaolong Bay, Changpi Port, Fengjiawan Port, Qingge Port, LongBay Port, Tanmen Port, Xiaodonghai, Deep Bay, and Luhuitou. Among these monitoring areas, *Halophila beccarii* was primarily distributed in Dongzhai Port, Haikou, Xiaohai, and Laoyehai in Wanning, Huachang Bay in Chengmai, Xinying Bay in Danzhou, Hongpai Port, Maniao Port, Xinying Port, and Huanglong Port in Lingao (Figure 1).



Figure 1. Distribution of Halophila beccarii Ascherson on Hainan.

Xiaohai is a well-developed sand bar lagoon system in the coastal area of China, and it is also the largest lagoon in the Hainan Province [32]. Xiaohai and Laoyehai are typical lagoons that are mainly farmed with *Epinephelus* spp., *Rachycentron, Penaeus orientalis,* and *Scylla paramamosain* [33]. Large-scale mariculture, mostly near the entrance of the tidal channel near the impact of tidal current velocity, and mariculture wastewater discharge also have a significant impact on the lagoon environment. Dongzhai Port, Huachang Bay, and Xinying Bay have become tourist attractions due to the mangrove resources in the lagoons. In addition, Dongzhai Port is one of the most important beach breeding bases in the Hainan Province mainly for the species *Meretrix lusoria, Ostreidae,* and *Tegillarca granosa*. After low tide, local fishers dredge for snails and mollusks in the distribution area of seagrass beds [20].

2.2. Research Methodology

2.2.1. Layout of Seagrass Survey Sections

In each survey area, 14–20 survey stations were evenly distributed according to the type and distribution of the seagrass, seabed topography, coastal environment, and hydrology. After the initial determination of the seagrass distribution within a 50.0 m radius around each station, the survey was carried out by setting up transects and quadrats. Three to five 20 or 50 m long transects were set per section, according to the distribution and type of seagrass. Each transect stretched through the seagrass bed from the intertidal zone to the subtidal zone, perpendicular to the coastline; therefore, the survey included the upper and lower limits and the center of the seagrass habitat. The sections were spaced >100 m apart in parallel. A 50 m long tape measure was laid on a relatively flat section, and an underwater digital camera was used to capture pictures and videos along each transect. The latitude and longitude coordinates at each end of the transect were recorded using a GPS device. Footage was interpreted upon returning to the laboratory, and the area of the seagrass bed was calculated.

2.2.2. Seagrass Survey and Analysis Methods

Nine quadrats (50×50 cm) were randomly placed at each survey station in each survey area, and the seagrass species within were identified [34] to investigate their cover and the densities of stems and branches. The surveys were carried out according to the Technical Regulations for Ecological Monitoring of Seagrass Beds (HY/T083-2005) [35], Technical Regulations for Ecological Survey of Marine Organisms (HY/T085-2005) [36], and Special Technical Procedures for Integrated Survey and Evaluation of China's Offshore Marine Areas [37]. All seagrass leaves, stems, and roots in the quadrat were placed into sample bags, numbered, and brought back to the laboratory to count the number of plants, calculate the density of stems and branches per unit area, wash and clean the surface adhering materials and sediments, and dry in an electric blast drying oven (XT5118-OV140) at 60–70 °C for 48–36 h, and determine the dry weight of the seagrass per unit area (gDW/m²).

2.2.3. Survey of Environmental Factors

Water quality and sediment samples were collected, pretreated, transported, and measured in accordance with the Marine Monitoring Code (GB17378-2007) [38] and Marine Survey Code (GB12763-2007) [39]. The analysis indicators included water depth, salinity (SAL), turbidity (TUR), pH, suspended solids (SS), dissolved oxygen (DO), chemical oxygen demand (COD), inorganic nitrogen (DIN), reactive phosphate (SRP), total phosphorus (TP), total nitrogen (TN), total organic carbon (TOC), sulfide (S), Pb, Cu, Zn, Cd, Cr, Hg, and As.

2.3. Data Analysis

ArcGIS 10.8 was used to map spatial distribution, Excel 2019 was used for data processing, SPSS 26.0 for statistical analysis, and R software was used for bivariate Pearson's correlation coefficient analysis of seagrass parameters and environmental factors. Data are expressed as the mean \pm standard error.

(1) Pearson correlation coefficient. In statistics, the Pearson correlation coefficient is used to measure the linear correlation between two variables, and the closer the absolute value of the coefficient is to 0, the smaller the linear correlation between the two variables; the closer the absolute value of the coefficient is to 1, the higher the linear correlation between the two variables [40]. In this study, water quality and sediment survey data were used as quantitative indicators for the correlation analysis.

$$r = \frac{\sum_{i=1}^{n} x_i y_i - \left(\sum_{i=1}^{n} x_i\right) \left(\sum_{i=1}^{n} y_i\right) / n}{\sqrt{\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2 / n} \sqrt{\sum_{i=1}^{n} y_i^2 - \left(\sum_{i=1}^{n} y_i^2\right)^2 / n}}$$

where *r* is the coefficient of correlation between two variables *x* and *y*, *x*_{*i*} and *y*_{*i*} are the first pairs of observations of *x* and *y*, respectively, and *n* is the number of pairs of observations.

(2) Factor analysis. Factor analysis finds a small number of prominent "Factors" to replace a large number of environmental variables. The KMO and Bartlett's sphericity tests were used to judge whether the variables were suitable for factor analysis. The method of factor extraction was principal component analysis. Principal component analysis (PCA), first proposed by Hotelling in 1933, uses the idea of dimensionality reduction to convert multiple indicators into several comprehensive indicators without losing much information [41]. Using SPSS software to carry out the principal component analysis of the selected index, the principal component characteristic value and contribution rate were obtained, and the number of principal components was selected. The principal component scores were then calculated using standardized values and eigenvalues. The mathematical model for factor analysis is as follows:

$$X_1 = \alpha_{11}F_1 + \alpha_{12}F_2 + \ldots + \alpha_{1m}F_m + \alpha_1\varepsilon_1 \tag{1}$$

$$X_2 = \alpha_{21}F_1 + \alpha_{22}F_2 + \ldots + \alpha_{2m}F_m + \alpha_2\varepsilon_2$$
⁽²⁾

$$X_1 = \alpha_{p1}F_1 + \alpha_{p2}F_2 + \ldots + \alpha_{pm}F_m + \alpha_p\varepsilon_p$$
(3)

3. Results and Discussion

3.1. Halophila beccarii Distribution and Area

The survey of Hainan's harbors, lagoons, and offshore islands showed that *H. beccarii* is mainly distributed in Dongzhai Port, Haikou; Xinying Bay, Danzhou; Huachang Bay, Chengmai; Xiaohai and Laoyehai, Wanning; and Xinying Port, Hongpai, Maniao, and Huanglong Port, Lingao, with a total area of approximately 20.981 km². The local distribution of *H. beccarii* around the island is shown in Figure 2. It has become the dominant species in Xiaohai, Laoyehai, Xinying Port, Hongpai, Maniao, and Huanglong Port. Xiaohai has the largest total area of *H. Beccarii* in Hainan at 9.58 km², which is mainly distributed in the southern (4.09 km^2) and northern (5.49 km^2) coastal sediment areas of lagoons, with a plant height of 2.41 \pm 0.96 cm. The area of *H. beccarii* in Xinying Bay is second only to that of Xiaohai, which covers approximately 4.89 km², has a plant height of 1.24 cm, and is mainly distributed in mangrove coastal waters such as Nanan village, Beijiangmen, and Harue Bridge. The seagrass in Huachang Bay covers approximately 2.2 km², ranking third on Hainan, with a plant height of 2.02 ± 0.18 cm. It is concentrated in the middle of the lagoon and is particularly abundant among mangrove habitats. It is mostly a monoculture, with a few areas mixed with Halophila ovalis and Halophila minor. The seagrass in Dongzhai Port covers an area of approximately 1.88 km² with short plants, mainly in the lagoons near the villages of Beixiang, Yanxi, Yanzhong, Bianhai, and Yanhai, as well as the mudflats along the riverbanks near Sanjiang. A small amount of seagrass grows in oyster and clam culture areas, recently planted mangroves, and alongside Halophila ovalis and Halodule uninervis. In addition, there are small areas in the lagoons of Laoyehai,



Wanning (0.668 km²), Xinying Port, Lingao (0.95 km²), Maniao (0.23 km²) and Huanglong Port (0.22 km²) in Hongpai (Table 1).

Figure 2. The distribution of *Halophila beccarii.* (**a**) Dongzhai Port; (**b**) Xiaohai; (**c**) Laoyehai; (**d**) Huachang Bay; (**e**) Xinying Bay; (**f**) Hongpai Port; (**g**) Maniao Port; (**h**) Xinying Port and Huanglong Port.

Survey Area	Area (km²)	Cover Rate (%)	Shoot Density (ind./m ²)	Total Biomass (gDW/m ²)
Xiaohai, Wanning	9.58	16.45 ± 28.72	1959.2 ± 3230.47	5.41 ± 8.93
Xingying Bay, Danzhou	4.89	8.46 ± 10.05	2327.98 ± 2852.28	1.57 ± 1.93
Huachang Bay, Chengmai	2.20	27.5 ± 32.63	3048.07 ± 5765.18	24.84 ± 46.98
Dongzhai Port, Haikou	1.88	20.97 ± 22.18	3592.89 ± 4778.72	16.90 ± 21.96
Laoyehai, Wanning	0.668	15 ± 15.28	3560 ± 4031.45	39.14 ± 41.87
Xinying Port, Lingao	0.95	7.08 ± 16.61	487.47 ± 1024.36	16.79 ± 56.91
Hongpai Port, Lingao	0.363	56.33 ± 14.04	$20,\!167.1 \pm 14,\!316.31$	112.94 ± 80.17
Maniao Port, Lingao	0.23	33.44 ± 21.61	9765.33 ± 3292.07	54.69 ± 18.44
Huanglong Port, Lingao	0.22	3.38 ± 7.08	396.31 ± 980.95	18.02 ± 61.26

Table 1. Basic traits of the Halophila beccarii population in Hainan Island.

Compared with other regions of China, the total area of *H. beccarii* in Hainan is much larger than those in Guangxi (approximately 0.863 km²) [2], Guangdong [2,42–44], Hong Kong [45], and Taiwan [19] (which has the largest area of seagrass in China). The area of *H. beccarii* in Xiaohai is much larger than that in Pearl Bay in Guangxi (0.214 km²), which is the largest *H. beccarii* area in China [23]. The specialized habitat of this seagrass and its limited distribution area, very small morphology, and frequent burial by sediment can hinder field surveys. Nonetheless, there is a large area and a well-preserved population in Hainan, which is arguably of high conservation value.

3.2. Biological Characteristics of Halophila beccarii

The average cover of *H. beccarii* seagrass on Hainan ranged from 7.08–56.33%, density of stem and branch from 487.47-20,167.10 ind/m², and biomass from 1.57-112.94 gDW/m². The average cover, density of stem and branch, and biomass were relatively high in Hongpai Port and Maniao, Lingao, with an average cover of 56.33 ± 14.04 and $33.44 \pm 21.61\%$, density of stem and branch of 20,167.11 \pm 14,316.3 and 9765.33 \pm 3292.07 ind/m², and biomass of 112.94 ± 80.17 and 54.68 ± 18.44 gDW/m², respectively. However, the average cover, density of stems and branches, and biomass in Xiaohai, Xinying Bay, and Huachang Bay, which have larger distribution areas, were relatively low, with average covers of 16.45 \pm 28.72, 8.46 \pm 10.05, and 27.5 \pm 32.63%, densities of stem and branch of 1959.2 ± 3230.47 , 2327.98 ± 2852.28 , and 3048.07 ± 5765.18 ind/m², and biomasses of 5.41 ± 8.93 , 1.57 ± 1.93 , and 24.84 ± 46.98 gDW/m², respectively. Compared with the populations elsewhere in China, the average cover of Hongpai Port (56.33 \pm 14.04%) was higher than that of Pearl Bay, Fangcheng Port City, Guangxi (55%), and Tangjia Bay, Zhuhai, Guangdong (53.33%) [23,44]. In contrast, the average covers of Xinying Port and Xinying Bay were relatively low, at 7.08 \pm 16.61 and 8.46 \pm 10.05%, respectively, which were lower than the average cover in most regions of China [2,23,42,44]. In terms of stem and branch density, Huachang Bay, Dongzhai Port, Xiaohai, Laoyehai, Xinying Bay, and Xinying Port had medium to low densities of stems and branches relative to other Chinese H. beccarii populations [24,44,46]. As it is a small seagrass, the populations of *H. beccarii* renew quickly and are mostly annual or perennial [14,15]. Most *H. beccarii* in China are one year old, and their biomass, erect density of stems and branches, and reproductive organ numbers are characterized by an "N"-shaped growth pattern [23], which first increases and then decreases. Examining population growth at one time is too reductive for estimating the growth and reproductive rate of seagrass. Therefore, further studies are needed to understand the relationship between the growth and reproduction of this seagrass and the variability of populations in different regions. More frequent ecological monitoring is recommended; for example, once a month to complete one growth cycle.

3.3. Analysis of Influencing Factors

Halophila beccarii serves as a habitat, nursery, and foraging site for many organisms [4]. Since its plants are relatively small and their stems and leaves are relatively tender, it is a direct and indirect food source for many marine organisms (Figure 3). However, as a typical intertidal seagrass, its growth and distribution are vulnerable to habitat type, tidal action, the marine environment, and human activities, and it is vulnerable to destruction.



Figure 3. Seagrass beds (a), plants (b), and habitats (c) of Halophila beccarii Ascherson on Hainan.

3.3.1. Effects of Habitat Type

The coastal harbors and lagoons of Hainan were examined and found to be dominated by coral reef shores and supplemented by mangroves, whereas mangroves dominated in lagoons. Different coastal habitats have different substrate types, and Zhiren Ke [19] concluded that the distribution of seagrasses in tropical and subtropical areas is related to substrate type. Halophila beccarii was found only in lagoons in Hainan, mostly in silt or muddy-sandy mangrove mudflats, or salt and freshwater marsh habitats. This shows that a protected, relatively undisturbed environment of closed or semi-closed waters is required for growth. Halophila beccarii was not found in Huxin Harbor, Gaolong Bay, or Fengjia Bay, where the substrates were coral debris or coral sand; this observation is consistent with the report by Cai [47]. The distribution of seagrass was not only influenced by substrate type but was also strongly related to different ecosystems. Dongzhai Harbor, Huachang Bay, and Xinying Bay were dominated by mangrove ecosystems; H. beccarii was mostly distributed in mangrove mudflats, and the substrates were mostly chalky sand with clayey texture or fine sand with silt. Mangrove habitats accelerate the siltation of lagoon substrates with shallow water, gentle winds and waves, and stable hydrodynamic conditions [20]. This is conducive to the growth and integrity of plants and is suitable for the growth of poorly resistant seagrasses such as halophiles. Xiaohai and Laoyehai are lagoons influenced by coastal aquaculture and inland currents; the salinity in the lagoons is highly variable, with ample nutrient salts and excellent water quality, and the substrate at the lagoon lining is mostly silt (84%), while the substrate at the mouth is mostly mud and sand. Halophila beccarii grows mostly in monoculture, and its area of cover at the lagoon edge is larger than that at the mouth. Compared with the lagoons, the coastal areas of bays

such as Gaolong Bay, Changpu Harbor, Long Bay, and Houhai Bay, have wide sea areas, wide reef pads, clear water, more coral reef debris, no obvious siltation, and the substrates are mainly medium and fine sand. The most common seagrass species in such coastal areas are *Thalassia hemprichii* and *Enhalus acoroides*, as these locations are distinct from the areas which favor low-height mud-loving species with small photosynthetic areas, such as *H. beccarii* [47].

3.3.2. Impacts of Tidal Branching Channels

H. beccarii grows in nearly enclosed or semi-enclosed natural lagoons (Figure 2), such as Xiaohai, Xinying Bay, Huachang Bay, Dongzhai Port, and Laoyehai, where water exchange is often influenced by tidal channels, and the dynamic conditions are mostly wave-tidal mixed energy [48]. The intertidal zone of the muddy-sandy beach in the inner areas of such lagoons is wide and flat (e.g., Huachang Bay). Although the tidal difference is large, the tide is slow, and the waves cause limited scouring and washing of the substrate; therefore, seagrass can achieve stability in the soil after germination. The tidal channel in the northeastern part of the lagoon is the only channel that connects Xiaohai to the outer sea and is the main navigation channel [49]. The Dongzhai Harbor is similar to Xiaohai in that it is connected to the outer sea by only one tidal branching channel; its inner tidal channel experiences an irregular semidiurnal tide, which has a standing wave nature; the tide time and velocity are asymmetric, and there is clockwise circulation throughout the harbor water [20]. Laoyehai is an 11 km-long narrow closed body of water [50], which has long been affected by land-sourced sediment, external tidal input, and wind-sand drop silt seabeds. Now that an eastern barrage has been built and the tidal channel has been dredged and deepened, water quality has improved. In addition, the tidal channel and outlet gate are the only channels for flooding in the watershed and for the entry of external tidal water into the lagoon, with a large tidal difference and a strong water exchange capacity. However, the strong hydrodynamic force is not conducive to the germination of *H. beccarii* seeds or the rooting of seedlings in the substrate; therefore, there is a significant difference in the area of seagrass in the lagoon and at the outlet. Overall, this suggests that tidal action influences the regional distribution of *H. beccarii* in the lagoons in Hainan.

3.3.3. Impacts of Temperature

The water temperature in the study area was 25.2–32.6 °C, which is ideal for *H. beccarii*, although there are no reports of temperature control experiments on this species. Halophila beccarii grows from the southernmost tip of the Malay Peninsula in Singapore to Jiayi County in Taiwan, with a latitudinal range of 0–24 °N; it is pantropical-subtropical in nature. The species can survive at surface temperatures as high as 40 °C [3]. It is evident that *H. beccarii* is tolerant to high temperatures but has relatively little tolerance at low temperatures. Wei [25] found that excessively high or low temperatures inhibited seed germination at an optimum temperature of 25 °C. Zakaria [15] showed that flowering and fruiting of *H. beccarii* in Kemaman, Malaysia, were not related to total monthly rainfall, mean sunshine hours, global mean daily radiation, pH, salinity, or water temperature, but were negatively correlated with mean temperature; the lower atmospheric temperatures from December to February were ideal for peak flowering and fruiting. However, Qiu [23] found that peak flowering and fruiting of seagrass in Pearl Bay, Guangxi, China, occurred in August and October when the temperature was higher, whereas no reproductive organs were observed from February to March when the temperature was lower. These opposing results suggested that *H. beccarii* reproduction is influenced by factors other than temperature.

3.3.4. Water Environment

Pearson's correlation analysis (Figure 4) shows that in Xiaohai, Xinying Bay, and Huachang Bay, where there were large areas of seagrass, (1) the seagrass cover was highly significantly positively correlated with density of stem and branch and biomass ($t_A = 0.83$, $t_B = 0.98$, $t_C = 0.94$, p < 0.01); (2) small seagrass cover was significantly positively correlated

with DO ($t_A = 0.55$, p < 0.05); seagrass cover in Xinying Bay was highly significantly positively correlated with turbidity ($t_B = 0.92$, p < 0.01) and with suspended matter ($t_B = 0.87$, p < 0.05); (3) water depth, salinity, PH, COD, SRP, DIN, Pb, Cu, Zn, Cr, and Cd were not significantly correlated with seagrass cover, biomass, density of stem and branch, nor plant height, where water depth, salinity, SRP, DIN, and heavy metal ions were negatively correlated with seagrass cover. Seagrass is mostly found in the low tidal zone, 0.9–1.5 m above sea level [14], with maximum depths of 1 m and 1.7 m on the west and east coasts of India, respectively [4]. It has a wide salinity tolerance, survives, and continues to reproduce at salinities of 0–45 [14,51–53]. In contrast, this study found that the water depth of the H. beccarii habitat in Hainan was 0.3-2.3 m, while no seagrass was found deeper than 2.6 m. The salinity range of 9.6–33.96 was consistent with the salinity of seagrass habitat in general, i.e., 16–35 [7]. These observations, combined with the correlations between water quality factors and seagrass parameters, indicated that water depth and salinity had little effect on the distribution of *H. beccarii* in Hainan. In addition, the water quality of the seagrass habitat was low in N, P, and heavy metals, and was mostly in a depleted state, which did not correlate significantly with seagrass parameters. This means that although there were some fluctuations in water quality in each survey area, these changes in concentration did not significantly affect the growth distribution of seagrass.



Figure 4. Pearson's correlation analysis of water quality factors. ((**A**) Xiaohai; (**B**) Xinying Bay; (**C**) Huachang Bay). "**" indicates highly significant correlation (p < 0.01), "*" indicates significant correlation (p < 0.05); effective number of cases n = 20. SPH, seagrass plant height; SC, seagrass coverage; SD, density of stems and branches; SB, seagrass biomass; DTW, depth to water; SAL, salinity).

To better explain the relationship between the distribution of *H. beccarii* and the surrounding environment, a factor analysis was conducted on the surface water quality indicators in Xiaohai, Xinying Bay, and Huachang Bay. The initial factor load was determined using principal component analysis. The sampling fitness of each KMO was greater than 0.6, and the significance of Bartlett's test of sphericity was 0. Salinity, COD, SRP, Pb, Cr, and other water quality factors were explained to the highest degree, and the extraction values were all above 0.8. The total variance interpretation of the factor analysis showed that the characteristic roots of the first four factors were all greater than 1, the cumulative contribution rate of variance was 73.57%, and the contribution rate of principal factor 1 was the highest, including salinity, Cd, Cr, Zn, and water depth. Except for Cd and Pb, the extraction values of the other water quality factors in Xinying Bay were all above 0.9. The total variance interpretation of the factor analysis showed that the characteristic roots of the first four factors were all above 1, and the cumulative contribution rate of variance was 95.39%; the contribution rate of main factor 1 was the highest, including DIN, COD, turbidity, suspended matter, and Pb. The total variance explained by factor analysis showed that the cumulative contribution rate of the first four factors was 93.11%, and the contribution rate of main factor 1, which mainly contained salinity, DO, DIN, COD, and other factors, was the highest (Figure 5). In summary, by combining information from the main factor score and Pearson correlation analysis, it was found that water quality factors, such as water depth, salinity, nutrients, and heavy metals, had little effect on the growth of H. *beccarii* during the survey period.



Figure 5. Rotation space factor diagram of water quality ((A) Xiaohai; (B) Xinying Bay; (C) Huachang Bay).

3.3.5. Deposition Environment

Pearson's correlation analysis (Figure 6) of the surface sediments of Xiaohai, Xinying Bay, and Huachang Bay showed that: (1) seagrass plant height in Xiaohai was highly significantly negatively correlated with Cu and Pb ($t_A = 0.59$, $t_A = 0.63$, p < 0.01), and with Zn and Cr ($t_A = 0.50$, $t_A = 0.54$, p < 0.05); seagrass cover was significantly negatively correlated with Cu, Pb, and Cr ($t_A = -0.49$, $t_A = -0.45$, $t_A = -0.53$, p < 0.05), and seagrass biomass and density of stem and branch were significantly negatively correlated with Pb ($t_A = -0.57$, $t_A = -0.57$, p < 0.01); (2) *Halophila beccarii* cover, density of stem and branch, and biomass in Huachang Bay were negatively correlated with Pb, Zn, Cd, and Hg; (3) TOC, TP, TN, sulfide, and water content were not significantly correlated with seagrass cover, biomass, nor plant height. Studies have confirmed significant positive linear correlations between heavy metals in seagrasses and sediments [53,54]. Heavy metals entering *H. beccarii* plants disrupt chloroplast structure, inhibit enzyme activity and photosynthetic phosphorylation, interfere with pigment synthesis, and limit the efficiency of CO₂ fixation, thus affecting photosynthesis [55–57]. In summary, the heavy metal content of the sediment may limit the growth and distribution of *H. beccarii*.



Figure 6. Pearson's correlation analysis of sediment factors. ((A) Xiaohai; (B) Xinying Bay; (C) Huachang Bay). "**" indicates highly significant correlation (p < 0.01), "*" indicates significant correlation (p < 0.05), effective number of cases n = 20. SPH, seagrass plant height; SC, seagrass coverage; SD, density of stems and branches; SB, seagrass biomass; WAF, water-accommodated fraction).

The sediment monitoring indices of Xiaohai, Xinying Bay, and Huachang Bay were selected for factor analysis. The extraction values of the deposition factors of Xiaohai were all greater than 0.75. The total variance interpretation of the factor analysis showed that the characteristic roots of the first two factors were all greater than one, and the cumulative contribution rate of variance was 78.29%. The contribution rate of principal factor 1 was the largest, and it mainly included Cd, Zn, TN, Cr, TP, Pb, and other factors. Except for Pb and moisture content, the extraction values of sedimentation factors in Xinying Bay were all above 0.92. The total variance interpretation of factor analysis showed that the characteristic roots of the first two factors were all above 1, and the cumulative contribution rate of variance was 87.61%, and main Factor 1 had the largest contribution, including Cd, Zn, Cr, Cu, and TN. Except for S, As, and Cu, the extraction values of the deposition factor analysis showed that the characteristic roots of the characteristic roots of the first two factors were all above 0.88. The total variance interpretation of factor series analysis showed that the characteristic roots of the first two factors of the first three factors were all above 1, and the cumulative contribution rate of variance was 87.61% of the characteristic roots of the first three factors were all above 1, and the cumulative contribution factor analysis showed that the characteristic roots of the first three factors were all above 1, and the cumulative contribution rate of variance was 81.60%. The main factor 1 had the



largest contribution rate and mainly contained heavy metal factors such as Pb, Zn, Hg, and Cu (Figure 7).

Figure 7. Rotation space factor diagram of Sediment ((A) Xiaohai; (B) Xinying Bay; (C) Huachang Bay).

The main factor scores and Pearson correlation analysis showed that the coverage and density of seagrass were significantly lower in stations dominated by metal ions. It can be inferred that heavy metals such as Cu, Pb, Cr, Zn, and Cd in the sediments may be one of the factors affecting the growth and distribution of *Halophila beccarii*.

3.3.6. Anthropogenic Impacts

The seagrass in Hainan mostly overlapped with mangrove ecological niches and was distributed in intertidal mudflats under intensive anthropogenic influence. Therefore, extensive aquaculture, as well as domestic and industrial wastewater discharge, can degrade seagrass beds by affecting the water and substrates of seagrass habitats. Furthermore, human activities such as destructive fishing, mangrove deforestation, coastal construction, and channel excavation can directly threaten seagrass survival [1]. For example, in Xiaohai, the total estimated area of aquaculture in 2020 was 2101.53 hm; there were 712 fish-farming households, and the total number of nets was 24,594. Dongzhai Port is an important beach farming base in Hainan Province, with a planned 4.24 km² seawater enrichment area. Several aquaculture species are farmed in the area, including oysters, clams, and blood ark clams. There are approximately 143 oyster farms in the lagoon, pigs are farmed nearby, and 325 small boats $(6.00 \times 2.20 \text{ m}^2)$ pass through or dock there [20]. Aquacultural discharge near the farms is likely to cause relatively high heavy metal content in *H. beccarii*, which will directly affect the growth of the seagrass. In addition, Wei et al. [26] found that >90% of *H. beccarii* seeds were distributed in the surface soil (0–8 cm deep), which means that frequent stirring of seagrass bed sediments by anthropogenic activities, such as dredging, would result in a high rate of seed loss [23].

4. Conclusions

This study found that *H. beccarii* was mostly distributed in the northwestern and southeastern lagoon areas of Hainan, covering a total area of 20.981 km² and a total area of 9 *H. beccarii* seagrass beds. Of this, Xiaohai, Wanning constitutes approximately 9.58 km², which is the largest area of seagrass in China; Xinying Bay, seagrass covers approximately 4.89 km²; Huachang Bay approximately 2.20 km²; Dongzhai Port approximately 1.88 km²; Xinying Port approximately 0.95 km²; Laoyehai approximately 0.668 km²; Hongpai approximately 0.363 km²; Maniao approximately 0.23 km², and Huanglong Port approximately 0.22 km². The average seagrass coverage was 7.08–56.33%, the density of stem and branch was 487.47–20,167.1 ind/m², and the biomass was 1.57–112.94 gDW/m2. On Hainan, *H. beccarii* prefers a muddy or sandy habitat, mostly overlapping with mangrove ecological niches, with water temperatures of 25.2–32.6 °C, a depth of 0.3–2.3 m, and a salinity of 9.6–33.96. Based on the results of field investigation and multivariate statistical analysis of environmental factors, it is inferred that the distribution of seagrass *H. beccarii* may be mainly influenced by the type of substrate. Second, it is affected by tide, heavy metal (Cu,

Pb, Cr, Zn, etc.) content in the marine environment, water depth, temperature, salinity, and other environmental conditions.

- (1) This study presents the first record of the overall distribution of *H. beccarii* along the coast of Hainan Lagoon in China, and we hope that this study will draw attention to the species. Although it has a rapid rate of rhizome elongation and a high seed yield to help with rapid recovery from disturbance, it is a pioneer species in mangrove formation, acting as a substrate stabilizer during the succession of mangroves [51]. However, it is only distributed in the intertidal zone where there is intensive man-made influence, so there is simply no way to deal with human activities such as aquaculture, destructive fishing, mangrove deforestation, agricultural, urban, and industrial wastewater discharges, oil spills, coastal construction, and waterway opening [2,20,23,24,31]. Globally, the distribution area is gradually declining [5].
- (2) To protect the *H. beccarii* resources of the lagoon, we propose the treatment of the aquaculture and domestic sewage discharged from the surrounding areas, control the sources of pollution, and protect the environment. Different areas of the farmed lagoons, such as Xiaohai, Dongzhai Port, and Laoyehai, should be zoned according to the distribution of seaweed. In areas where seagrass is more widespread, farming and human activities (such as coastal shrimp farming, snail and shellfish dredging, and artificial island construction) should be restricted, discouraged, or prohibited in adjacent areas. Other areas with less seagrass provide adequate fisheries to sustain the livelihoods of the local population and sustainable fishing should be established through area-based management for Resource Conservation and sustainable use. Second, we propose to accord priority as a protected species in mangrove nature reserves to the *H*. *beccarii* species in mangrove shoals such as Dongzhai Port, Huachang Bay and Xinying Bay, to achieve resource coexistence and stable coexistence of different ecosystems. We propose that *H. beccarii* grown in artificial culture areas or artificial mangroves in Dongzhai Port be relocated and protected as soon as possible. Third, we will carry out science popularization activities related to the protection of seaweed resources, and conduct publicity activities on the types, ecological functions, and protection needs of seaweed and promote these through the press and radio. Awareness of the value of protecting seaweed resources should be raised among residents, the public, and tourists, so that all may protect seaweed resources spontaneously.

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