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Posted Date: 3 April 2024

doi: 10.20944/preprints202404.0279.v1

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Article

Current Resource Status and Evaluation of Population Dynamic Characteristics of the Endangered Semi-Mangrove Species *Dolichandrone spathacea* for Its Conservation on Hainan Island, China

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Abstract: *Dolichandrone spathacea* is a rare and endangered semi-mangrove plant species with an extremely small population, naturally distributed only in Zhanjiang City and the east coast of Hainan Island, China. Regrettably, the present situation of the *D. spathacea* population in China has not yet been carefully investigated. In this study, we aim to evaluate the current resource status and population dynamic characteristics of *D. spathacea* on Hainan Island, China, in order to propose sustainable conservation and management strategies for future ecological restoration of its natural population. Our results show that *D. spathacea* on Hainan Island can be divided into four populations. All the *D. spathacea* populations present a state of overall dispersion, local concentration, and occasionally sporadic existence, and they exist in geographical isolation. The young, middle, and old *D. spathacea* plants account for 20.42%, 66.20%, and 13.38%, respectively, indicating that the overall age class of the *D. spathacea* population on Hainan Island belongs to a declining type. Furthermore, instead of temporal structure, we chose diameter at breast height (DBH) to establish a static life table, draw a population survival curve, and quantify the future development trend through population dynamic analysis and time-series prediction. These results directly point out that the *D. spathacea* population on Hainan Island is sensitive to external disturbances and possesses two main increases in mortality rate—namely, in its juvenile and mature stages—due to weak vitality, competition, and anthropogenic interferences, which are the most important reasons for its endangered status. Depending on the current conditions of the *D. spathacea* population, we should conserve and expand mature trees in situ, preserve their germplasm resources, rehabilitate their habitats to promote provenance restoration, and conduct artificial cultivation and spreading planting in order to realize the sustainable conservation and management of *D. spathacea*.

Keywords: Mangrove; *Dolichandrone spathacea*; population dynamic characteristics; natural population; diameter at breast height; static life table

1. Introduction

Mangrove forests are special vegetated and coastal ecosystems, globally dominating around 1.7×10^5 km² along the intertidal estuaries and coasts of tropical and subtropical areas and functioning as one of the vital regions for major biological activities [1–3]. Mangrove wetland ecosystems are considered as a transitional zone between terrestrial and marine environments, and they comprise approximately 75% of the acreage of coastlines worldwide [4]. Mangrove forests possess multiple properties, including high productivity, high decomposition rate, high restitution rate, and high stress resistance [5]. Meanwhile, mangrove ecosystems can supply large-scale ecological value to local communities, thereby continually stabilizing the intertidal regions [1,4–6]. In particular, they can purify the ocean through phytoremediation, offer detritus and superior refuges for aquatic animals, produce biomass energy resources for local residents, maintain climatic stability through their huge sequestration and storage abilities, and preserve coastal buffer zones against natural disasters such as sea waves, tides, and storm events due to their large coverage and strong root systems [1,4–6].

Unfortunately, because of their special ecological niche between the land and ocean, mangrove forests are extremely susceptible to both anthropogenic and natural destruction in a global context. First, mangrove forests are frequently exposed to the effects of climate changes, such as extreme temperature and precipitation, sea level rise, biotic and abiotic stresses, and sediment property changes in terms of natural factors [7–9]. Furthermore, with the rapid development of industrialization and urbanization, aquaculture activity, seawall construction, metal smelting, and industrial wastewater discharge have consequently followed in recent decades [7–9]. In addition, due to the highly valuable wood of mangrove trees, coastal dwellers persistently carry out unsustainable land clearing, illegal logging, and over-exploitation [10]. As a result, mangrove forests are among one of the fastest disappearing ecosystems, with a decline rate of 1–2% per year globally, which is equal to (or even greater than) decreases in tropical rainforests and their adjacent coral reefs [11]. Consequently, around 16% of mangrove species are on the verge of extinction on Earth [12]. In terms of Chinese mangroves, the mangrove resource investigation conducted by the National Investigation of Forest Resource in 1956 reported that their initial acreage approximately covered 2.5×10^5 ha; however, they dramatically dropped to 4.2×10^4 ha [13]. The worse news is that China's mangrove area sharply plunged to 2.1×10^4 ha and 1.5×10^4 ha from 1970 to 1980, respectively, due to land reclamation by seaside residents [13]. In a word, the reserve of Chinese mangrove forests has declined by around a half from 1950 to 2001 due to a series of anthropogenic and natural factors [13]. Hence, preventing the continued loss of natural mangrove resources and protecting endangered mangrove species requires more attention by humans.

Dolichandrone spathacea (L.f.) K. Schum. (also named mangrove trumpet tree) is a semi-mangrove species belonging to the genus *Dolichandrone* of the Bignoniaceae, which can wildly grow on land without tide effects as well as in waterlogged beaches and estuaries [14]. It is naturally found in regions of southern India, Sri Lanka, and New Caledonia (island) [15,16] and is also sparsely naturally distributed in areas of China including Zhanjiang City, Guangdong Province, and the east coast of Hainan Island [17]. In the natural world, its common companion species are *Nypa fruticans* Wurmb, *Bruguiera gymnorhiza* (L.) Savigny, *Bruguiera sexangula* (Lour.) Poir., *Pongamia pinnata* (L.) Pierre, *Cerbera manghas* L., and so on [17]. As an excellent coastal shelterbelt mangrove species, *D. spathacea* possesses various medicinal, economic, and ecological values [17]. For example, the leaves of this traditional medicinal plant have been widely used as a tonic, as well as an emmenagogue for post-partum females [18]; their juice can also cure oral thrush, flatulence, and bronchitis [19,20]. Its bark can be used as laxative and for treatment of allergies [21]. In addition, its fruits and timber are edible and can be used for wood products and construction materials, respectively [18]. Furthermore, this mangrove tree also plays a vital part in muddy sand (sediment) stabilization [18]. However, due to severe destruction of its habitat in China, *D. spathacea* was added to the List of Key Protected Wild Plants from Hainan Island in 2006. Unfortunately, to the best of our knowledge, there have been scarce contributions in the existing literature regarding the conservation and management of *D. spathacea* in Hainan Province.

Therefore, in this work, based on our latest experiences gained through field investigation of *Laguncularia racemosa* (L.) C. F. Gaertn. over the whole of Hainan Island [22], we aimed to evaluate the current population resource status and dynamic characteristics of the endangered mangrove species *D. spathacea* across Hainan Island, China in detail through a genecological analysis. We also

summarize a sequence of reasonable conservation and management policies for *D. spathacea* resources, based on our obtained results. We cordially hope that this study, as a typical case, can provide theoretical references for the conservation, management, restoration, and rehabilitation of endangered mangrove species in the future.

2. Materials and Methods

2.1. Study Area

This research was conducted along the entire circular coastline of Hainan Island, China, spanning from 108°36' E to 111°30' E and from 18°80' N to 20°10' N (Figure 1), during July and August of 2022. Hainan Island (officially called Hainan Province in China) is located in the southernmost part of the country and neighbors Guangdong Province to the north across the Qiongzhou Strait. As the second-largest island in China, Hainan Island covers an area of approximately 3.39×10^6 ha, and is characterized by a typical tropical monsoon climate. The vast majority of the coastline terrain of Hainan Island is low and flat, but the central insular area contains large-scale mountains. Due to this special landform, the western part of the island experiences an annual average rainfall of 1600 mm, while the eastern part has an average precipitation of $2.0\text{--}2.4 \times 10^3$ mm yearly [23]. Combining the suitable annual average precipitation and temperature (around 25 °C), Hainan Island possesses extremely rich tropical and subtropical forest resources, with a stable forest cover of over 60%, and boasts one of the most impressive ecotopes in China. The 1823 km long coastline of Hainan Island is dotted with plentiful rivers and creeks that run into the ocean, creating a complicated network of estuary deltas which offers an ideal living circumstance for the existence and procreation of mangrove forests. As a consequence, Hainan Island has one of the widest distributions of mangroves in China, with the greatest species variety and the richest biodiversity [24].

In the present study, all the four cities on Hainan Island were discovered to harbor our target endangered species, *D. spathacea*, after our overall investigation, and the specific information of the geographical research area is exhibited in Figure 1.

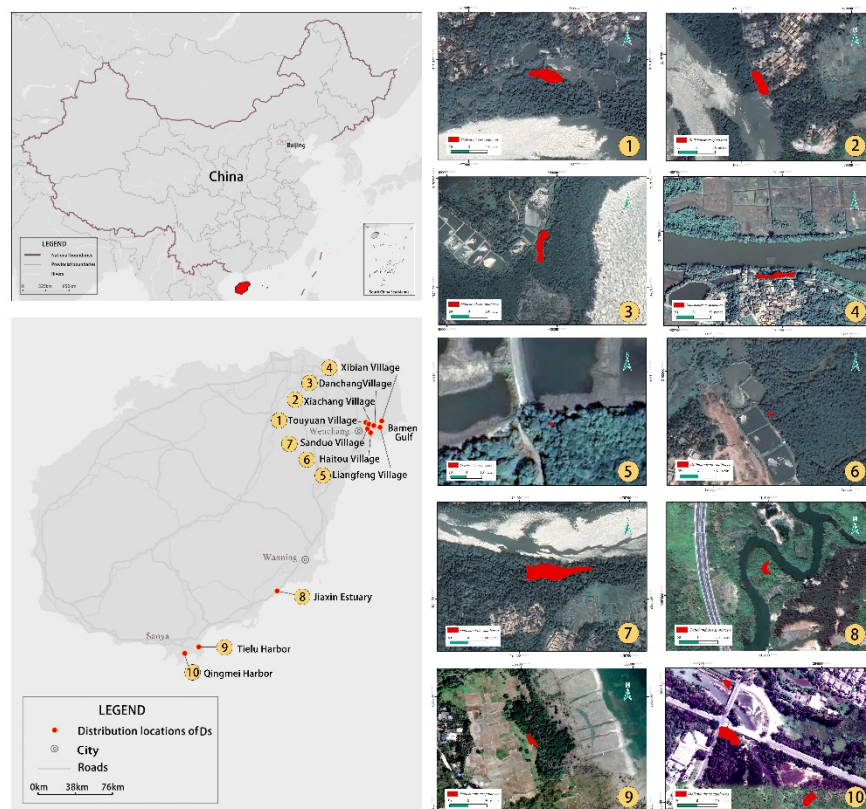


Figure 1. A combination figure showing the geographical research area of the forests of *D. spathacea* Hainan Island, China. ① Distribution of *D. spathacea* in Touyuan Village; ② distribution of *D. spathacea* in Xiachang Village; ③ distribution of *D. spathacea* in Danchang Village; ④ distribution of

D. spathacea in Xibian Village; ⑤ distribution of *D. spathacea* in Liangfeng Village; ⑥ distribution of *D. spathacea* in Haitou Village; ⑦ distribution of *D. spathacea* in Sanduo Village; ⑧ distribution of *D. spathacea* in Jiaxin Estuary; ⑨ distribution of *D. spathacea* in Qingmei Harbor; ⑩ distribution of *D. spathacea* in Tielu Harbor.

2.2. Experimental Design

We chose sample quadrats for evaluation of the endangered mangrove species following the basic criteria of large space, absence of animal interference, and dominance of *D. spathacea* [25]. A large enough size of $20 \times 20 \text{ m}^2$ was chosen for each sample plot, due to the sparse distribution of *D. spathacea* trees, and 8 quadrat surveys in 12 regions of 4 cities on Hainan Island were established, in order to ensure the accuracy and universality of this investigation. The survey was carried out mainly based on the Diameter at Breast Height (DBH) of trees in all quadrats. Apart from DBH, the following specific ecological information was also noted during the investigation for every quadrat:

- (1) Plant species, dominant species, height, number, and canopy density;
- (2) City, specific distribution point, longitude, latitude, sediment type, intertidal zone condition, and interference condition.

2.3. Representations of *D. spathacea* Population Dynamic Characteristics

2.3.1 Population Structure

Due to the low number of the endangered *D. spathacea* trees on Hainan Island, it is difficult to obtain their ages accurately. Therefore, their population structure was analyzed by means of DBH, instead of temporal structure [26]. In the present work, we divided the age class of *D. spathacea* into 7 levels based on its DBH (Table 1). Additionally, according to Frost and Rydin (2000), the 7 levels of age classes were divided into 3 stages for the convenience of this study, among which the level I plants were considered as young individuals, levels II to IV indicated middle individuals, and levels V and above were identified as old individuals [27].

Table 1. Definition of age class levels of *D. spathacea* based on its DBH on Hainan Island, China.

DBH range	Level
$\text{DBH} \leq 2.5 \text{ cm}$	I
$2.5 \text{ cm} < \text{DBH} \leq 7.5 \text{ cm}$	II
$7.5 \text{ cm} < \text{DBH} \leq 12.5 \text{ cm}$	III
$12.5 \text{ cm} < \text{DBH} \leq 17.5 \text{ cm}$	IV
$17.5 \text{ cm} < \text{DBH} \leq 22.5 \text{ cm}$	V
$22.5 \text{ cm} < \text{DBH} \leq 27.5 \text{ cm}$	VI
$\text{DBH} > 27.5 \text{ cm}$	VII

2.3.2 Analysis of Quantitative Population Dynamics

The analysis of quantitative *D. spathacea* population dynamics was conducted according to Shen et al. (2008) [28]. The series of formulas were as follows:

$$V_x = \frac{S_x - S_{x+1}}{\max(x, S_{x+1})} \times 100\% \quad (1)$$

$$V_{pi} = \left(\frac{1}{\sum_{x=1}^{k-1} S_x} \right) \times \sum_{x=1}^{k-1} (S_x V_x) \quad (2)$$

$$V'_{pi} = \frac{\sum_{x=1}^{k-1} S_x V_x}{\min(S_1, S_2, \dots, S_k) k \sum_{x=1}^{k-1} S_x} \quad (3)$$

$$P_{max} = \frac{1}{k \min(S_1, S_2, \dots, S_k)} \quad (4)$$

where V_x is the dynamic index of the number of individuals in the *D. spathacea* population from the x^{th} to the $x+1^{\text{th}}$ age class; S_x and S_{x+1} are the numbers of *D. spathacea* individuals within the x^{th} and the $x+1^{\text{th}}$ age classes, respectively; V_{pi} is the dynamic index of the entire *D. spathacea* population structure;

k is the number of age classes in the *D. spathacea* population; V'_{pi} is the dynamic index of the entire *D. spathacea* population structure considering external disturbances; and P_{max} is the risk probability of *D. spathacea* population with respect to external random disturbances. In addition, $V_x \in [-1, 1]$, where positive, negative, and 0 values of V_x reflect the dynamic relationships of growth, decline, and stability in the number of individuals between two adjacent age classes (or the age structure of the whole population), respectively. Either V_{pi} or V'_{pi} reflects a consistent dynamic relationship with V_x . V_{pi} is considered to have the greatest effects only when P value reaches its maximum.

2.3.3 Compilation of Static Life Table

A static life table can describe the static state of a plant population, and reflects the causes of death and change factors of different age classes of population [29]. As the target mangrove species in this research belonged to a natural population, it was inevitable that the mortality rate will be negative due to systematic sampling error, which is inconsistent with the mathematical hypothesis using the number of individuals with different age class structures to study the population dynamics within a specific time period. Therefore, many scholars use the smoothing slip technique to process the statistical data. In this study, the method of equation fitting was used to smooth the result, and the age class and the number of surviving *D. spathacea* were used as the independent and dependent variables to fit the equation, respectively [29]. The series of formulas were as follows:

$$l_x = (a_x/a_0) \times 1000 \quad (5)$$

$$d_x = l_x - l_{x+1} \quad (6)$$

$$q_x = (d_x/l_x) \times 100\% \quad (7)$$

$$L_x = (l_x + l_{x+1})/2 \quad (8)$$

$$T_x = L_x + L_{x+1} + L_{x+2} + \dots + L_{x+n} \quad (9)$$

$$e_x = T_x/l_x \quad (10)$$

$$K_x = (\ln l_x - \ln l_{x+1}) \times 100\% \quad (11)$$

$$P_x = (l_{x+1}/l_x) \times 100\% \quad (12)$$

where a_0 is the actual number of survivors in the x^{th} age class, a_x is the current number of surviving individuals in the x^{th} age class after smoothing, l_x is the standardized number of surviving individuals in the x^{th} age class, d_x is the standardized number of dead individuals between two adjacent age classes, q_x is the mortality rate for the x^{th} age class, L_x is the average number of surviving individuals from the x^{th} to the $x+1^{\text{th}}$ age class, T_x is the total number of surviving individuals from the x^{th} to the higher x^{th} age class, e_x is the life expectancy of an individual in the x^{th} age class, K_x is the vanishing rate for the x^{th} age class, and P_x is the survival rate for the x^{th} age class.

2.3.4 Drawing of Survival Curve

The survival curve, which is drawn with the age class as the horizontal coordinate and the pair value ($\ln a_n$) of surviving individuals as the vertical coordinate, can describe the death rate at different age stages according to the number of deaths of individual organisms, and can directly indicate the survival state and the changing trend of population dynamics [30]. In this study, the equations $N_x = N_0 e^{-bx}$ (where N_x is the value of $\ln l_x$, x is the diameter class, and N_0 and b are constants) and $N_x = N_0 x^{-b}$ (where N_x is the value of $\ln l_x$, x is diameter class, and N_0 and b are constants) were used to verify the type of survival curve of *D. spathacea*, according to Deevey's theory [31].

2.3.5 Compilation of Population Survival Analysis Functions

In order to visually display the dynamic characteristics of the *D. spathacea* population, the survival rate function ($S_{(i)}$), the cumulative mortality rate function ($F_{(i)}$), the mortality density function ($f_{(i)}$), and the hazard rate function ($\lambda_{(i)}$) were used for analysis of its survival status [32]. The associated formulas are as follows:

$$S_{(i)} = P_1 P_2 \cdots P_x \quad (13)$$

$$F_{(i)} = 1 - S_{(i)} \quad (14)$$

$$F_{(t)} = \frac{P_{x-1} - P_x}{h_x} \quad (15)$$

$$\lambda_{(t)} = \frac{2(1 - P_x)}{h_x(1 + P_x)} \quad (16)$$

where P_x is the survival rate of the x^{th} age class, S_x is the number of *D. spathacea* individuals within the x^{th} age class, and h_x is the length of the interval.

2.3.6 Analysis of Time-Series

In order to understand the future change trend of each age class of the *D. spathacea* population, the survival numbers after 2, 4, and 6 age classes were predicted using the one-time moving average method [28]. The formula is as follows:

$$M_n = \frac{1}{n} \sum_{k=x-n+1}^x D_x \quad (17)$$

where M_n is the moving average of the n^{th} cycle, which is the number of individuals in the x^{th} age class group after n age classes; n is the age classes that need to be predicted; x is the age class; and D_x is the population size of the x^{th} age class.

2.4. Description of Statistical Analysis

All the obtained data were treated using Excel (version 2016), and all the figures in this work were created using Origin (version 2020). All the DBH data were calculated for at least three replicates.

3. Results

3.1. Basic Information and Current Distribution Status of *D. spathacea* on Hainan Island, China

After the detailed investigation of wild *D. spathacea* across Hainan Island, we found that it was only discovered in the cities of Wenchang, Wanning, and Sanya (Table 2). *D. spathacea* presented a state of overall dispersion, local concentration, and occasionally sporadic existence on Hainan Island. In addition, we also discovered that it was mainly distributed at the edge of mangrove forests, in land areas that could be flooded or completely unaffected by tides during high tides (Table 2). The altitude for *D. spathacea* survival on Hainan Island was 2.5–10.2 m (Table 2). The number and canopy density of *D. spathacea* on Hainan Island were 284 (in total) and 0.5–0.9 (Table 2), and its largest DBH and height were 48 cm and 13 m, respectively. The dominant tree species in the *D. spathacea* community on Hainan Island included *D. spathacea*, *Heritiera littoralis* Dryand., *Cocos nucifera* L., *Rhizophora stylosa* Griff., *B. sexangula*, *Sonneratia caseolaris* (L.) Engler, *Rhizophora apiculata* Bl., *Ceriops tagal* (Perr.) C. B. Rob., *Sonneratia paracaseolaris* Ko, E. Y. Chen et W. Y. Chen, *Xylocarpus granatum* J. Koenig, *Talipariti tiliaceum* (L.) Fryxell, *Areca catechu* L., *N. fruticans*, *Lumnitzera racemosa* Willd., and *Sonneratia alba* Sm. in Ress (Table 2). The sediment type characterizing the habitat of *D. spathacea* was simply composed of sandy and silty, while the disturbance types were complicated, including aquaculture, dam, roadblock, and deforestation (Table 2).

Moreover, *D. spathacea* on Hainan Island could be divided into four populations. Specifically, the population in Wenchang City was located along the west coast of Bamen Gulf, between its mangroves and seven surrounding villages (Table 2); the population in Wanning City was located in Qiexin Estuary; and the two populations in Sanya City were located in the Qingmei Harbor

Mangrove Reserve and Tielu Harbor Mangrove Reserve, respectively. Notably, these two latter *D. spathacea* populations were geographically isolated.

Table 2. Basic information and current distribution status of *D. spathacea* on Hainan Island, China.

City	Distribution Point	Longitude	Latitude	Altitude (m)	Quantity	Canopy Density	Dominant Tree Species	Tide Situation	Sediment Type	Disturbance Type
Wenchang	Touyuan Village	110°47'19"E	19°37'42"N	2.5	13	0.9	<i>S. caseolaris</i> , <i>B. sexangula</i>	Spring Tides	Silty	Dam
	Xiachang Village	110°47'43"E	19°37'22"N	6.5	24	0.7	<i>S. caseolaris</i> , <i>B. sexangula</i> , <i>S. paracaseolaris</i>	Spring Tides	Sandy and Silty	Roadblock
	Danchang Village	110°48'42"E	19°37'18"N	3.2	36	0.8	<i>R. stylosa</i> , <i>B. sexangula</i>	Spring Tides	Silty	Dam
	Bamen Gulf Xibian Village	110°53'40"E	19°38'50"N	10.2	17	0.7	<i>C. nucifera</i> , <i>S. caseolaris</i> , <i>H. tiliaceus</i>	No Tides	Silty	Aquaculture
	Liangfeng Village	110°51'34"E	19°37'43"N	3.5	1	0.5	<i>R. apiculata</i> , <i>C. tagal</i>	No Tides	Sandy and Silty	Dam
	Haitou Village	110°47'46"E	19°36'03"N	2.6	2	0.6	<i>R. stylosa</i> , <i>X. granatum</i>	No Tides	Sandy and Silty	Dam
	Sanduo Village	110°46'32"E	19°37'17"N	3.4	59	0.9	<i>H. littoralis</i> , <i>D. spathacea</i> , <i>C. nucifera</i>	Spring Tides	Silty	Aquaculture
Wanning	Jiaxin Estuary	110°10'36"E	18°36'02"N	3.5	46	0.9	<i>D. spathacea</i> , <i>A. catechu</i> , <i>N. fruticans</i>	No Tides	sandy and Silty	Desertification
Sanya	Tielu Harbor	109°42'07"E	18°15'47"N	4.2	37	0.7	<i>R. apiculata</i> , <i>S. alba</i> , <i>L. racemosa</i>	Spring Tides	Sandy	–
	Qingmei Harbor	109°37'03"E	18°13'57"N	5.2	49	0.6	<i>L. racemosa</i> , <i>C. tagal</i> , <i>R. apiculata</i>	Spring Tides	Sandy	Roadblock

3.2. Age Class Structure Analysis of *D. spathacea* Population

Among the investigated 284 *D. spathacea* trees on Hainan Island, their age classes were as follows: There were 58, 188, and 38 young, middle, and old individuals, accounting for 20.42%, 66.20%, and 13.38% of the population, respectively (Figure 2). Specifically, the numbers of young individuals in the *D. spathacea* populations of Bamen Gulf (Wenchang), Qiexin Estuary (Wanning), Qingmei Harbor (Sanya), and Tielu Harbor (Sanya) only accounted for 29.61% (45), 0% (0), 8.16% (4), and 24.32% (9), while the numbers of middle individuals accounted for up to 56.58% (86), 76.90% (35), 83.67% (41), and 70.27% (26) in the four above-mentioned populations (Figure 2). The numbers of old individuals in these *D. spathacea* populations were the fewest, occupying only a proportion of 13.82% (21), 23.91% (11), 8.16% (4), and 5.41% (2), respectively (Figure 2).

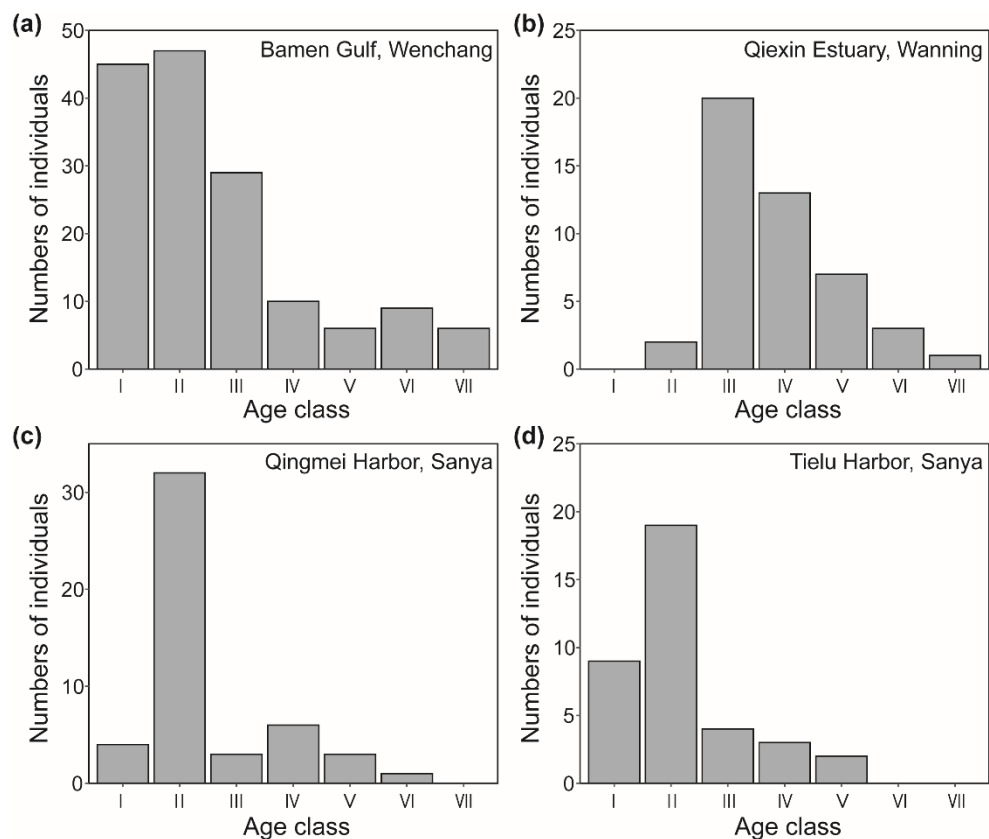


Figure 2. Age class structures of *D. spathacea* populations in Bamen Gulf (Wenchang), Qiexin Estuary (Wanning), Qingmei Harbor (Sanya), and Tielu Harbor (Sanya) on Hainan Island, China.

3.3. Quantitative Population Dynamic Analysis of *D. spathacea* Population

The dynamic index of the *D. spathacea* population was used to evaluate the variation characteristics of its different age classes on Hainan Island more accurately. As shown in Table 3, the data ranges of V_1 to V_7 for the four *D. spathacea* populations in the areas of Bamen Gulf (Wenchang), Qiexin Estuary (Wanning), Qingmei Harbor (Sanya), and Tielu Harbor (Sanya) on Hainan Island were irregular, suggesting that there were large fluctuations between age classes in the process of population development (Table 3). Furthermore, the V_1 values for the four *D. spathacea* populations were all negative, suggesting that all four of the *D. spathacea* populations exhibited a decline in age class I; namely, there was a large loss of *D. spathacea* seedlings at the initial stage (Table 3). In addition, negative values also appeared for V_5 of the Bamen Gulf (Wenchang) population and V_2 of the Qiexin Estuary (Wanning) population, indicating that the *D. spathacea* populations in these stages also exhibited similar decreasing trends (Table 3).

Furthermore, the values of V_{pi} for the four *D. spathacea* populations in the areas of Bamen Gulf (Wenchang), Qiexin Estuary (Wanning), Qingmei Harbor (Sanya), and Tielu Harbor (Sanya) on Hainan Island were 27.46%, 38.22%, 38.55%, and 38.55%, respectively. Considering the potential external random disturbances, the values of V'_{pi} accounted for 0.65%, 5.46%, 2.75%, and 2.75%, indicating that the growth of the *D. spathacea* populations was severely limited at these stages (Table 3). Fortunately, both V_{pi} and V'_{pi} presented positive values, suggesting that these four populations possessed an overall potential to grow (Table 3). The values of V'_{pi} were much lower than those of V_{pi} , and all the P_{max} values were positive, indicating that all four *D. spathacea* populations on Hainan Island showed sensitivity to external random disturbances, which could thus have serious impacts on the *D. spathacea* population (Table 3).

Table 3. Variation indices of *D. spathacea* population dynamics on Hainan Island, China.

Distribution Point	Variation Index of <i>D. spathacea</i> Population Dynamics (%)									
	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_{pi}	V'_{pi}	P_{max}

Bamen Gulf (Wenchang)	-4.26	38.30	65.52	40.00	-33.33	33.33	100.00	27.46	0.65	2.38
Qiexin Estuary (Wanning)	-100.00	-90.00	35.00	46.15	57.14	66.67	100.00	38.22	5.46	14.29
Qingmei Harbor (Sanya)	-52.63	78.95	25.00	33.33	100.00	100.00	100.00	38.55	2.75	7.14
Tielu Harbor (Sanya)	-52.63	78.95	25.00	33.33	100.00	100.00	100.00	38.55	2.75	7.14

Note: V_x is the dynamic index of the number of individuals in the population from the x^{th} to the $x+1^{th}$ age class, V_{pi} is the dynamic index of the entire population structure, V'_{pi} is the dynamic index of the entire population structure when external disturbances are taken into account, and P_{max} is the risk probability of the *D. spathacea* population with respect to external random disturbances.

3.4. Analysis of Static Life Table of *D. spathacea* Population

As can be seen from the static life table of *D. spathacea*, all four of the *D. spathacea* population structures exhibited significant fluctuation (Table 4). In particular, we discovered that, after standardized smoothing treatment, the number of surviving individuals (l_x) gradually slowed down and levelled off with an increase in the age class. In addition, we found the trend in the data for a_x was consistent with that of l_x . The peak values of the mortality rate (q_x) and vanishing rate (K_x) were all observed in the highest age classes in the areas of Bamen Gulf (Wenchang), Qiexin Estuary (Wanning), Qingmei Harbor (Sanya), and Tielu Harbor (Sanya). The two highest mortality rates (100.00%) of *D. spathacea* populations both occurred in Sanya City (Table 4). In addition, all individual life expectancy (e_x) values were relatively small in the four *D. spathacea* populations, suggesting that the population might be continually exposed to great fluctuations (Table 4).

Table 4. Static life table of *D. spathacea* population on Hainan Island, China.

Distribution Point	Age class	a_x	l_x	lga_x	d_x	q_x (%)	L_x	T_x	e_x	K_x (%)	P_x (%)
Bamen Gulf (Wenchang)	I	52	1000	3.946	330	33.0	835	2402	2.402	40.1	67.0
	II	35	670	3.545	193	28.8	573	1567	2.339	34.0	71.2
	III	25	477	3.205	137	28.8	408	994	2.085	33.9	71.2
	IV	18	339	2.866	106	31.3	286	586	1.725	37.6	68.7
	V	12	233	2.490	87	37.3	190	300	1.287	46.6	62.7
	VI	8	146	2.024	73	50.2	110	110	0.749	69.7	49.8
	VII	4	73	1.326	–	–	–	–	–	–	–
Qiexin Estuary (Wanning)	I	45	1000	3.806	356	35.6	718	1943	1.943	44.0	64.4
	II	29	644	3.366	208	32.3	540	1225	1.902	39.0	67.7
	III	20	436	2.976	148	33.9	305	685	1.572	41.4	66.1
	IV	13	288	2.562	115	39.7	231	380	1.319	50.6	60.3
	V	8	174	2.056	94	53.9	98	149	0.859	77.3	46.1
	VI	4	80	1.283	58	72.3	51	51	0.639	128.3	27.7
	VII	1	22	1.000	–	–	–	–	–	–	–
Qingmei Harbor (Sanya)	I	38	1000	3.647	392	39.2	804	1803	1.803	49.8	60.8
	II	23	608	3.149	230	37.8	493	999	1.644	47.7	62.2
	III	15	378	2.674	163	43.1	297	506	1.339	56.3	56.9
	IV	8	215	2.111	126	58.7	152	210	0.974	88.4	41.3
	V	3	89	1.227	63	70.7	57	57	0.647	122.7	29.3
	VI	1	26	0.000	26	100.0	13	13	0.500	–	0.0
	VII	0	0	–	–	–	–	–	–	–	–
Tielu Harbor (Sanya)	I	24	1000	3.184	394	39.4	803	1782	1.782	50.0	60.6
	II	15	606	2.683	230	38.0	491	979	1.614	47.7	62.0
	III	9	376	2.206	163	43.4	295	487	1.295	56.9	56.6
	IV	5	213	1.637	127	59.5	150	193	0.905	90.3	40.5
	V	2	86	0.734	86	100.0	43	43	0.500	–	29.3
	VI	0	0	–	0	–	0	0	–	–	–
	VII	0	0	–	–	–	–	–	–	–	–

Note: a_x is the current number of surviving individuals in the x^{th} age class after smoothing treatment, l_x is the standardized number of surviving individuals in the x^{th} age class, d_x is the standardized number of dead individuals between two adjacent age classes, q_x is the mortality rate for the x^{th} age class, L_x is the average number of surviving individuals from the x^{th} to the $x+1^{th}$ age class, T_x is the total number of surviving individuals from

the x^{th} to the higher age classes, e_x is the life expectancy of an individual in the x^{th} age class, K_x is the vanishing rate for the x^{th} age class, and P_x is the survival rate for the x^{th} age class.

3.5. Survival Curve Analysis of *D. spathacea* Population

The survival curve of *D. spathacea* population on Hainan Island was drawn with the age class as horizontal coordinate and lgl_x as the vertical coordinate, and the results of fitting equations and verifications (R^2) are shown in Table 5. All of the survival curves for the *D. spathacea* populations in the Bamen Gulf (Wenchang), Qiexin Estuary (Wanning), Qingmei Harbor (Sanya), and Tielu Harbor (Sanya) areas tended to the Deevey II pattern, as the fitting effects of exponential function equations for them were better than those of power function equations (Table 5), indicating that the mortality rates of *D. spathacea* populations in these regions were generally stable across the age classes.

Table 5. Survival curves and their verification models of *D. spathacea* population on Hainan Island, China.

Distribution Point	$N_x = N_0 e^{-bx}$	$N_x = N_0 x^{-b}$
Bamen Gulf (Wenchang)	$N_x = 5.0355e^{-0.16x}$, $R^2 = 0.9235$	$N_x = 4.6354x^{-0.457}$, $R^2 = 0.7586$
Qiexin Estuary (Wanning)	$N_x = 4.986e^{-0.19x}$, $R^2 = 0.9314$	$N_x = 4.3919x^{-0.491}$, $R^2 = 0.7819$
Qingmei Harbor (Sanya)	$N_x = 5.435e^{-0.281x}$, $R^2 = 0.887$	$N_x = 4.295x^{-0.633}$, $R^2 = 0.7297$
Tielu Harbor (Sanya)	$N_x = 5.3633e^{-0.357x}$, $R^2 = 0.8766$	$N_x = 3.9627x^{-0.301}$, $R^2 = 0.7149$

Moreover, the mortality and vanishing rates for the *D. spathacea* populations in the Bamen Gulf (Wenchang), Qiexin Estuary (Wanning), Qingmei Harbor (Sanya), and Tielu Harbor (Sanya) areas were basically consistent, showing a similar trend of first decreasing and then increasing, suggesting that *D. spathacea* populations were more susceptible to death at the young and old age stages (Figure 3), In addition, the vanishing rates were obviously higher than the mortality rates for each age class of the four *D. spathacea* populations (Figure 3).

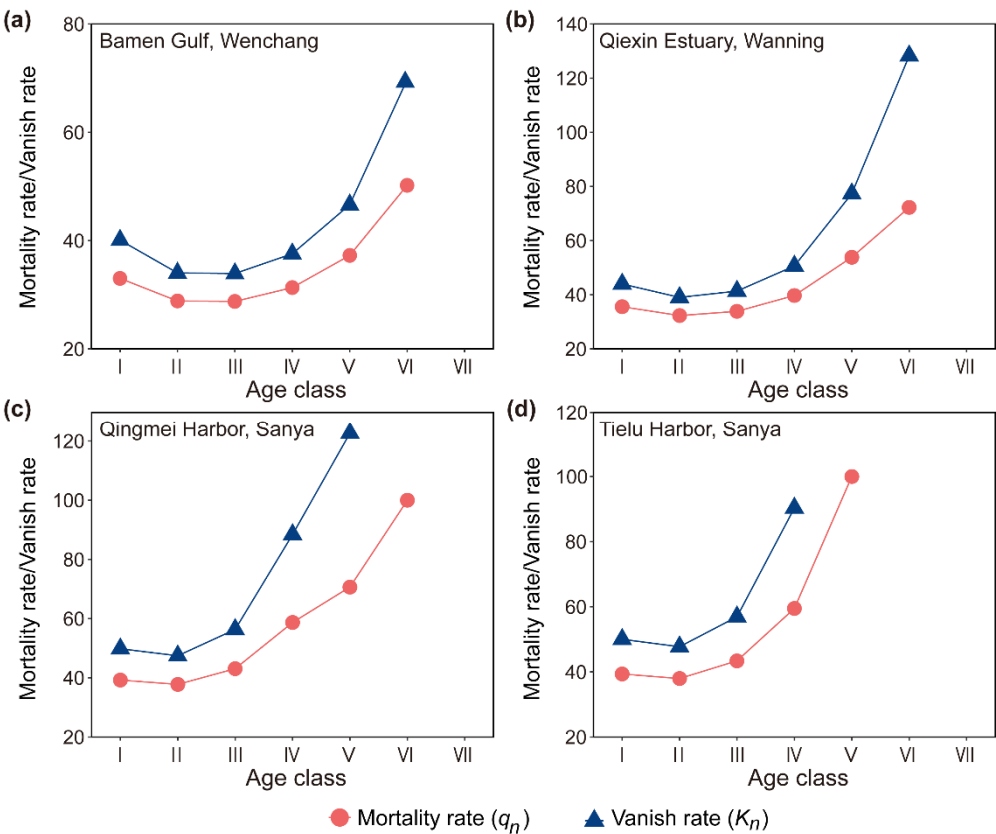


Figure 3. Curves of the mortality and vanishing rates of the *D. spathacea* populations on Hainan Island, China.

3.6. Population Survival Analysis of *D. spathacea* Population

In terms of the survival rate function and the cumulative mortality rate function of the *D. spathacea* populations on Hainan Island, they exhibited two exactly contradictory trends (Figure 4). In particular, the survival rate functions of the *D. spathacea* populations in the areas of Bamen Gulf (Wenchang), Qiexin Estuary (Wanning), Qingmei Harbor (Sanya), and Tielu Harbor (Sanya) were decreasing, while the cumulative mortality rate functions increased continuously with the growth of their age classes (Figure 4). The intersection point of these two curves appeared around age class II and, interestingly, the values at the intersections for all four of the *D. spathacea* populations were 50% (Figure 4).

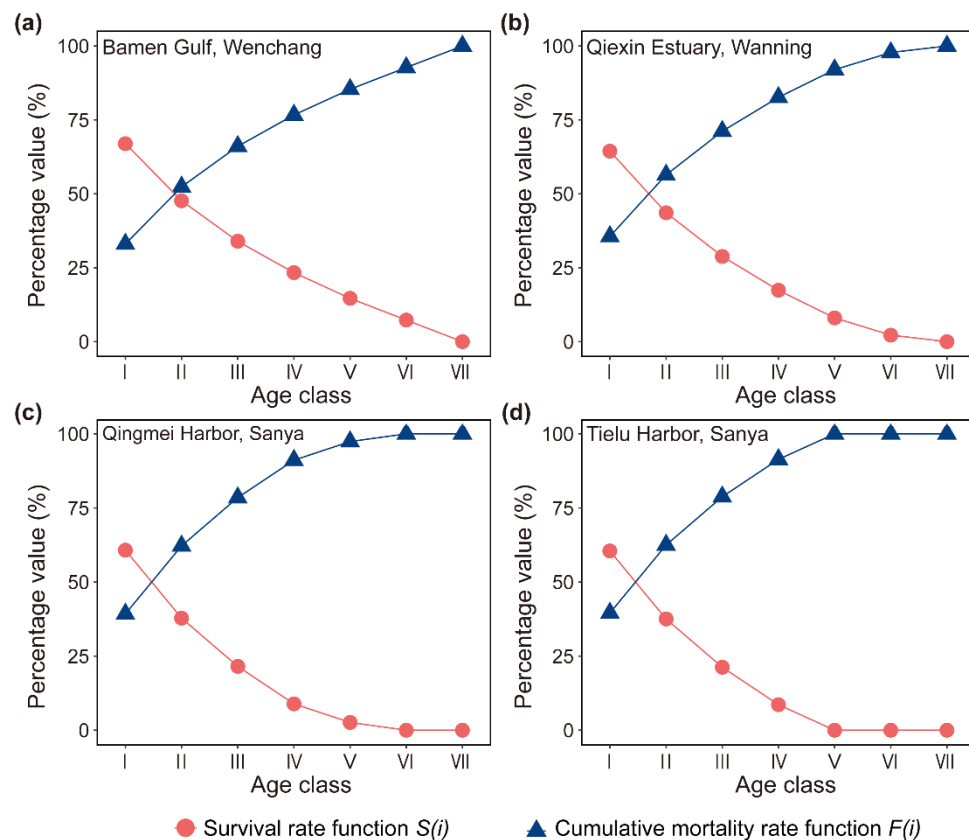


Figure 4. Curves of the survival rate function and the cumulative mortality rate function of *D. spathacea* population on Hainan Island, China.

The mortality density function and hazard rate function of the *D. spathacea* populations on Hainan Island were also explored. Similar to the survival rate function and the cumulative mortality rate function, these two curves in the areas of Bamen Gulf (Wenchang), Qiexin Estuary (Wanning), Qingmei Harbor (Sanya), and Tielu Harbor (Sanya) also presented an opposite trend, where the former decreased while the latter increased dramatically (Figure 5). It is worth mentioning that the early slopes of the two functions were higher than the late ones (Figure 5), indicating that the life state of the *D. spathacea* population was unstable in the young age, with a significant number of individuals dying; however, as they grew older, the mortality risk gradually declined.

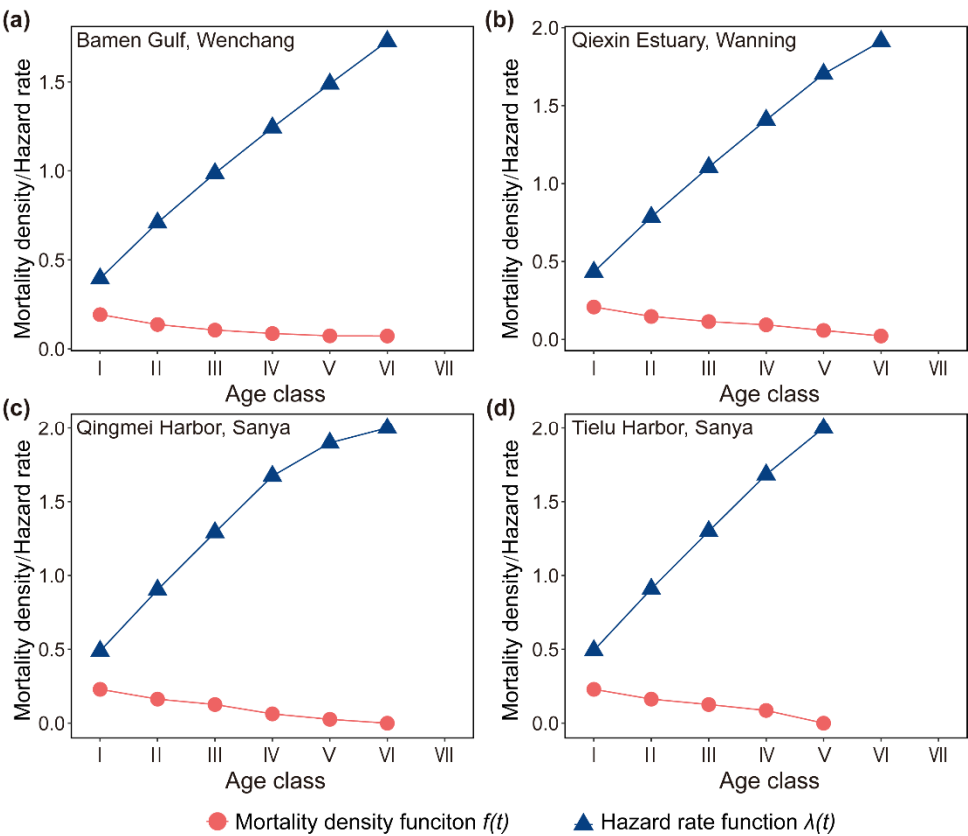


Figure 5. Curves of the mortality density function and the hazard rate function of *D. spathacea* population on Hainan Island, China.

3.7. Analysis of Age Class Time-Series of *D. spathacea* Population

For the age class time-series of the four *D. spathacea* populations, we observed that the initial numbers in the Bamen Gulf (Wenchang), Qiexin Estuary (Wanning), Qingmei Harbor (Sanya), and Tielu Harbor (Sanya) areas were visibly irregular (Table 5). After going through the next predicted 2, 4, and 6 age classes, the elderly individuals in the *D. spathacea* populations were supplemented, to a certain extent (Table 5); however, due to the lack of young individuals in the areas of Qiexin Estuary (Wanning), Qingmei Harbor (Sanya), and Tielu Harbor (Sanya), the number of middle-aged individuals decreased and the *D. spathacea* population renewal potential was insufficient. Eventually, this would lead to an obvious decline.

Table 5. Time-series prediction of *D. spathacea* population on Hainan Island, China.

Age class	Bamen Gulf (Wenchang)				Qiexin Estuary (Wanning)				Qingmei Harbor (Sanya)				Tielu Harbor (Sanya)			
	Initial Number	M2	M4	M6	Initial Number	M2	M4	M6	Initial Number	M2	M4	M6	Initial Number	M2	M4	M6
I	45	–	–	–	0	–	–	–	4	–	–	–	9	–	–	–
II	47	46	–	–	2	1	–	–	32	18	–	–	19	14	–	–
III	29	38	–	–	20	11	–	–	3	18	–	–	4	12	–	–
IV	10	20	33	–	13	17	9	–	6	5	11	–	3	4	9	–
V	6	8	23	–	7	10	11	–	3	5	11	–	2	3	7	–
VI	9	8	14	24	3	5	11	8	1	2	3	8	0	1	2	6
VII	6	8	8	18	1	2	6	8	0	1	3	8	0	0	1	5

Note: M2, M4, and M6 are number distributions in the predicted 2, 4, and 6-age classes of *D. spathacea* population.

4. Discussion

4.1. Analysis of *D. spathacea* Population Structure

It is generally accepted that mangroves play key roles in coastal wetland ecosystems in tropical and subtropical areas, such as coastal protection and maintenance of coastal ecosystem function [1]. However, due to human interference (e.g., urban development and aquaculture), mangrove deforestation has occurred in an endless stream, causing the acreage of mangrove forests in the world to decrease by 30–50% over the last century [11,12]. As a result, a large number of mangrove species are globally in the process of becoming endangered species, and they may even face extinction. In the present study, we tried to evaluate the current resource status and the population dynamic characteristics of an endangered semi-mangrove species, *D. spathacea*, on Hainan Island, China, in order to propose sustainable conservation and management strategies for future ecological restoration of its natural population. This research may allow us to better understand how to effectively protect, manage, and rehabilitate endangered mangrove species in the future.

The population structure can reflect the current situation and the development direction, which plays an important role in analyzing the history and predicting the future dynamics of a population [33]. In the present study, we first found the number of seedlings was significantly higher than that in the larger-age classes; furthermore, the *D. spathacea* population structure was mainly composed of young individuals in age classes I, II, and III ($0 \text{ cm} \leq \text{DBH} \leq 12.5 \text{ cm}$), which could survive in the understory of the forest community, suggesting that the seed germination and seedling growth of *D. spathacea* could be well-adaptively completed in a shaded situation. This result was particularly similar to that of another endangered terrestrial tree species—*Taxus cuspidata* Siebold et Zucc—in China reported by Liu et al. (2023) [34]. Additionally, all four of the *D. spathacea* populations possessed a large number of young individuals and 3–4 species of other dominant trees in the community, implying that competition for light, water, and nutrients might exist within and among the various species. Indeed, our previous study on the ecological patterns of three kinds of terrestrial medicinal plants in Altay Prefecture, China, also found that competition was one of the most important factors that crucially determined the ecological niche of a species [35]. In this work, the higher *D. spathacea* population mortality rate in the early age class may be a result of the enhanced intraspecific and interspecific competition. Based on these deductions, it was no wonder that the young seedlings could not grow into medium- and large-sized trees, leading to their ultimate death. Except for the effects of drastic competition, it was certainly the case that the higher mortality rate of *D. spathacea* population in its initial age class made it insufficient to provide enough young individuals to supplement the older age classes, thus affecting the renewal and development of its population. Moreover, the small plant population was found to be extremely sensitive to changes in the external environment, making it unable to maintain long-term stability and, so, the *D. spathacea* population might stay low [36]. As for the older age class, the populations of *D. spathacea* in the Bamen Gulf (Wenchang) and Qingmei Harbor (Sanya) areas presented fluctuations, indicating that there might be strong anthropogenic disturbances in these two regions which caused them to deviate from a stable population structure. During the period from the 1970s to 1980s, unlawful logging for construction and manufacturing were common, particularly targeting higher age class mangrove plants [13]. These behaviors had severely detrimental influences on the stand type and structure of mangrove forests.

4.2. Analysis of *D. spathacea* Population Dynamics

After analysis of the *D. spathacea* population dynamic index, we found that there were large fluctuations between age classes in the process of population development. Furthermore, the V_1 values for the four *D. spathacea* populations on Hainan Island were all negative, suggesting a large loss of *D. spathacea* seedlings at the initial stage, which was in keeping with our analysis of the mortality and vanishing rate curves. The values of V'_{pi} were much lower than those of V_{pi} , and all the P_{max} values were positive, indicating that all four *D. spathacea* populations on Hainan Island showed sensitivity to external random disturbances, which could have serious impacts on the *D. spathacea* population. These results were broadly similar to those of a previous study on *T. cuspidata* [34].

From the results of the static life table and other dynamic indices for the *D. spathacea* population, we discovered that the *D. spathacea* population experienced two fluctuations in its growth cycle: one in the juvenile stage and the other during the mature stage. The first fluctuation in the immature stage of the *D. spathacea* population may be mainly caused by their weak vitality and the intraspecific and interspecific competition for light, water, and nutrients. As for the second fluctuation, emerging in

the mature stage, we propose that it may be attributed to anthropogenic interferences with high probability. This speculation can be summarized according to two main evidential aspects. On one hand, all the survival curves for the age classes of the four *D. spathacea* populations displayed a standard Deevey II type, characterized by an exponential curve, implying that their mortality rates were significantly stable throughout the process of population development, even in the last age class. This indicated that external factors could obviously affect the population development of *D. spathacea* [34]. On the other hand, the reflection of the irregular initial number of *D. spathacea* trees could correspond to our hypothesis of unsustainable deforestation. In general, a healthy forest population would present a more balanced distribution of age classes, similar to the predicted time-series, with a gradual decrease in number with enhancement of the age class [34].

4.3. Recommendations of Conservation and Management for *D. spathacea* Population

Based on the above discussion, we propose some recommendations for the sustainable conservation and management of this endangered semi-mangrove species in China: (1) In situ conservation and expanding *D. spathacea* trees: We must make sure that there are enough viable seeds or seedlings being naturally produced. Considering the geographical isolation among the four *D. spathacea* populations on Hainan Island, so we should encourage endogenous gene exchange through sexual reproduction as much as possible, increase genetic diversity within the population and, thus, enhance population stability. Kramer et al. (2008) reported that the detrimental influences of serious habitat fragmentation can be partially offset by frequent gene exchange between internal populations [37]. (2) Preserving germplasm resources: A diverse range of genetic materials such as pollens, seeds, and tissues should be stored to form a source of genetic diversity that can serve the purpose of gene exchange in the future. (3) Rehabilitating the habitats to promote provenance restoration: We observed various external disturbances, such as aquaculture, dams, and roadblocks, affecting the *D. spathacea* populations on Hainan Island. There is no doubt that these disturbances impose serious restrictions on their development and, hence, we should return ponds to forests and reinforce habitat restoration to provide favorable conditions for their recovery and growth. (4) Artificial cultivation and spreading planting: Last, but not least, we should plant more of this species in its local land or other suitable planting regions in order to enlarge its population quantity, as there are no obstacles to the anthropogenic propagation and breeding of *D. spathacea* in China [17].

5. Conclusions

D. spathacea is a typical endangered semi-mangrove species in China that needs to be protected and managed urgently. In this research, our findings indicated only four main *D. spathacea* populations, distributed in the areas of Bamen Gulf (Wenchang), Qiexin Estuary (Wanning), Qingmei Harbor (Sanya), and Tielu Harbor (Sanya), on Hainan Island, China. These populations presented a state of overall dispersion, local concentration, and occasionally sporadic existence, and existed in geographical isolation. The number of young, middle, and old *D. spathacea* plants accounted for 20.42%, 66.20%, and 13.38% of the population, respectively, suggesting that the age class distribution of the *D. spathacea* population on Hainan Island belongs to a decline type. In addition, the analysis of *D. spathacea* population dynamic characteristics directly indicated that the *D. spathacea* population on Hainan Island was sensitive to external disturbances and possessed two main increases in mortality rate—namely, in the juvenile and mature stages—due to weak vitality, competition, and anthropogenic interferences, which are the most important reasons for its endangered status. Hence, in order to protect *D. spathacea* resources, we should conserve and expand the mature *D. spathacea* trees in situ, preserve its germplasm resources, rehabilitate its habitats to promote provenance restoration, and conduct artificial cultivation and spreading planting, in order to realize the sustainable conservation and management of *D. spathacea*.

Author Contributions: M.T., T.L. and H.Z. conceived of the original research project and selected methods. M.T., X.K., M.L., K.D., Y.Y., Z.F., C.Z., S.L. and Z.Z. performed most of the experiments. N.F.-y.T., T.L. and H.Z. supervised the experiments and provided technical assistance to M.T., X.K., M.L., K.D., Y.Y., Z.F., C.Z., S.L. and Z.Z. M.T. and T.L. wrote the article. H.Z. and N.F.-y.T. refined the project and revised the writing. All authors have read and agreed to the published version of the manuscript.

Funding: This research was jointly supported by the Hainan Province Science and technology Special Fund (ZDYF2021SHFZ259), the Foundation for the Scientific Research Base and Distinguished Talents in Guangxi (Guike AD22035015; Guike AC22080006), the National Natural Science Foundation of China (32101367), the

Guangdong Basic and Applied Basic Research Foundation (2022A1515010698), the Science, Technology, and Innovation Commission of Shenzhen Municipality (JCYJ20220818095601003; KCXFZ20230731092801002), and the Guangxi First-class Disciplines (Agricultural Resources and Environment, BSUFCD-KF202402).

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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