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Population Status of the Endangered Semi-Mangrove *Dolichandrone spathacea* on Hainan Island, China

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Abstract: In China, *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. Despite conservation concerns, the population status of *D. spathacea* has received little scientific attention. In this study, we evaluated the current status of *D. spathacea* on Hainan Island, China, in order to propose sustainable conservation strategies for future ecological restoration of its natural population. *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 *D. spathacea* population on Hainan Island is declining. Furthermore, instead of temporal structure, we used 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 suggest that the *D. spathacea* population in the Bamen Gulf (Wenchang) and Qingmei Harbor (Sanya) 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 competition and anthropogenic interferences, which might be 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

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1. Introduction

Globally, mangrove forests are special coastal ecosystems dominating around 1.7×10^5 km^2 along the intertidal estuaries and coasts of tropical and subtropical areas, and they can function as one of the vital regions for major biological activities [1–4]. Mangrove forests possess multiple properties, including a 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]. Finally, 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]. 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 sparsely naturally distributed in areas of China including Zhanjiang City, Guangdong Province, and the east coast of Hainan Island [17]. *D. spathacea* is an evergreen tree, 5–20 m tall, with gray to dark brown bark; its twigs are thick and strong. It possesses odd-pinnate compound leaves opposite, with 2–3 (-4) paired leaflets, and its leaves are 5–16 cm long and 3–7 cm wide [17]. In the natural habitat, 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 [18]. As an excellent coastal shelterbelt mangrove species, *D. spathacea* possesses various medicinal, economic, and ecological values [18]. 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 [19]; their juice can also cure oral thrush, flatulence, and bronchitis [20,21]. Its bark can be used as laxative and for treatment of allergies [22]. In addition, its fruits are edible, and its timber can be used for wood products and construction materials [19]. Furthermore, this mangrove tree also plays a vital part in muddy sand (sediment) stabilization [19]. However, due to the severe destruction of its habitat in China, *D. spathacea* was added to the List of Key Protected Wild Plants from Hainan Island in 2006 [18,23]. 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 terms of the rare and endangered semi-mangrove species *D. spathacea* on Hainan Island, China, we hypothesize that, due to the natural and anthropogenic destruction, it must be well-protected in the future. Based on our previous experience in the investigation of *Laguncularia racemosa* (L.) C. F. Gaertn. [24], we evaluated the population status of the rare and endangered mangrove species *D. spathacea* across Hainan Island, China, using research methods of population ecology. We also summarize a sequence of reasonable conservation policies for rare *D. spathacea* resources in China. We hope that this study, as a typical case, can provide theoretical references for the conservation and restoration of rare and endangered mangrove species in the future.

2. Materials and Methods

2.1. Study Area

This research was conducted along the entire 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 it 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 2000–2400 mm yearly [25]. 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 it 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 [26].

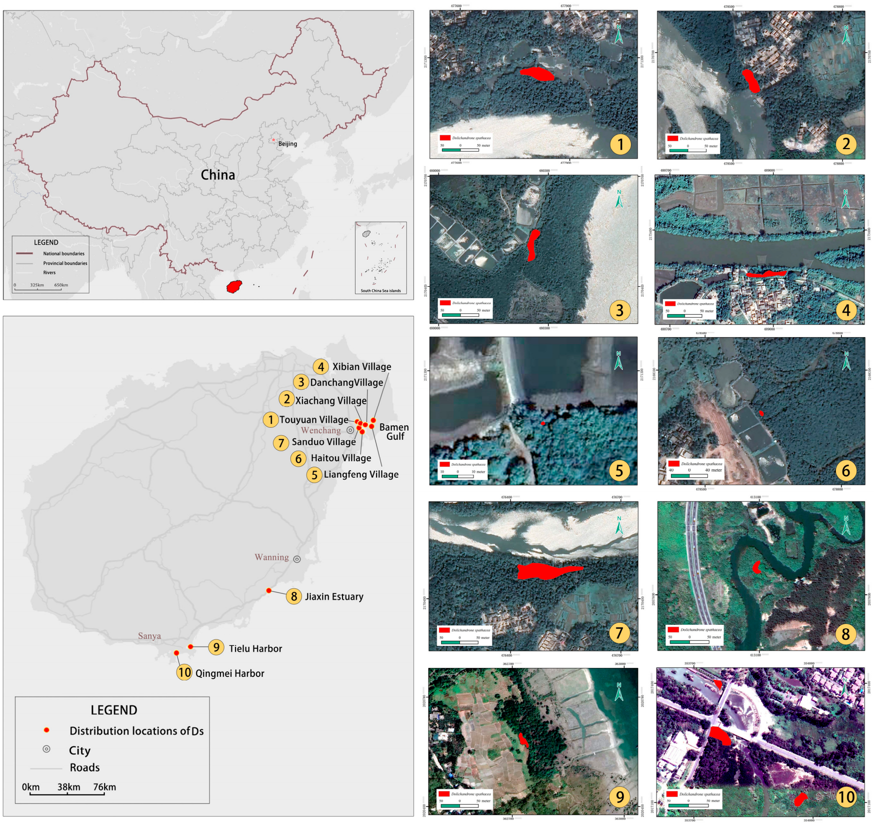

Figure 1. The geographical research area of the forests of *D. spathacea* Hainan Island, China. ① Touyuan Village; ② Xiachang Village; ③ Danchang Village; ④ Xibian Village; ⑤ Liangfeng Village; ⑥ Haitou Village; ⑦ Sanduo Village; ⑧ Jiaxin Estuary; ⑨ Qingmei Harbor; ⑩ Tielu Harbor.

In the present study, we explored all the regions on Hainan Island for evaluating the population status of *D. spathacea*, and the specific information of the geographical research area is exhibited in Figure 1.

2.2. Survey Design

We chose sample quadrats for evaluation of the endangered mangrove species following the basic criteria of large plain space, absence of animal interference (like wild boar, etc.), and dominance of *D. spathacea* (*D. spathacea* can occupy the majority of proportions or areas) [27]. A large enough size of 20 × 20 m^2 was chosen for each sample plot, due to the sparse distribution of *D. spathacea* trees, and 8 quadrat surveys in 10 regions from 3 cities on Hainan Island were established, in order to ensure the accuracy and representativeness of this investigation. The survey was carried out mainly based on the diameter at breast height (DBH) of trees in all quadrats. Apart from the DBH, the following specific information was also noted during the investigation for every quadrat:

(1) Plant species, dominant species, height, number (all individuals), and canopy density;
(2) City, distribution point, longitude, latitude, sediment type, tide situation, and interference condition.

2.3. Representations of D. spathacea Population Dynamic Characteristics

2.3.1. Population Structure

In the present work, the population structure of *D. spathacea* trees was analyzed by means of DBH, instead of temporal structure due to their low numbers [28]. We divided the age class (called DBH class below) of *D. spathacea* into 7 levels based on its DBH (Table 1). Additionally, the 7 levels of DBH 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 [29].

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

DBH Range	Level
DBH ≤ 2.5 cm	I
2.5 cm < DBH ≤ 7.5 cm	II
7.5 cm < DBH ≤ 12.5 cm	III
12.5 cm < DBH ≤ 17.5 cm	IV
17.5 cm < DBH ≤ 22.5 cm	V
22.5 cm < DBH ≤ 27.5 cm	VI
DBH > 27.5 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) [30]. The series of formulas were as follows:

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

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

$$P_{max} = \frac{1}{kmin(S_1, S_2, \ldots, S_k)} \quad (3)$$

$$V'_{pi} = V_{pi} \times P_{max} = \frac{\sum_{x=1}^{k-1} S_x V_x}{min(S_1, S_2, \ldots, S_k) k \sum_{x=1}^{k-1} S_x} \quad (4)$$

where V_x is the dynamic index of the number of individuals in the *D. spathacea* population from the xth to the x + 1th DBH class; S_x and S_{x+1} are the numbers of *D. spathacea* individuals within the xth and the x + 1th DBH classes, respectively; V_{pi} is the dynamic index of the entire *D. spathacea* population structure; k is the number of DBH classes in the *D. spathacea* population; P_{max} is the risk probability of *D. spathacea* population with respect to external random disturbances; and V'_{pi} is the dynamic index of the entire *D. spathacea* population structure considering external disturbances. In addition, $V_x \in$ (*belonging to)* $[-1, 1]$, 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 DBH 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 significances only when the 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 it reflects the causes of death and change factors of different DBH classes of a population [31,32]. As the target mangrove species in this research belonged to a natural population, it was inevitable that the mortality rate would be negative due to systematic sampling error, which is inconsistent with the mathematical hypothesis using the number of individuals with different DBH 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 DBH class and the number of surviving *D. spathacea* were used as the independent and dependent variables to fit the equation, respectively [31]. The series of formulas were as follows:

$$l_x = (a_x/a_0) \times 1000 \tag{5}$$

$$d_x = l_x - l_{x+1} \tag{6}$$

$$q_x = (d_x/l_x) \times 100(\%) \tag{7}$$

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

$$T_x = L_x + L_{x+1} + L_{x+2} + \ldots + L_{x+n} \tag{9}$$

$$e_x = T_x/l_x \tag{10}$$

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

$$P_x = \left(\frac{l_{x+1}}{l_x}\right) \times 100(\%) \tag{12}$$

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

2.3.4. Drawing of Survival Curve

The survival curve, which is drawn with the DBH 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 $N_x = N_0\ e^{-bx}$ 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 [33].

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 ($f_{(t)}$), and the hazard rate function ($\lambda_{(t)}$) were used for analysis of its survival status [34]. The associated formulas are as follows:

$$S_{(i)} = P_1 P_2 \ldots P_x \tag{13}$$

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

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

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

where P_x is the survival rate of the xth DBH class, S_x is the number of *D. spathacea* individuals within the xth DBH class, and h_x is the length of the interval for DBH 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 distributed in the cities of Wenchang, Wanning, and Sanya (Table 2). 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 *Areca catechu* L., *B. sexangula*, *Ceriops tagal* (Perr.) C. B. Rob., *Cocos nucifera* L., *D. spathacea*, *Heritiera littoralis* Dryand., *Lumnitzera racemosa* Willd., *N. fruticans*, *Rhizophora apiculata* Bl., *Rhizophora stylosa* Griff., *Sonneratia caseolaris* (L.) Engler, *Sonneratia alba* Sm. in Ress, *Sonneratia paracaseolaris* Ko, E. Y. Chen et W. Y. Chen, *Talipariti tiliaceum* (L.) Fryxell, and *Xylocarpus granatum* J. Koenig (Table 2). Except for *D. spathacea*, 3–4 species of other dominant trees above were also found in the community (Table 2). The sediment type characterizing the habitat of *D. spathacea* was simply composed of sandy and silty, while the disturbance types were complex, including aquaculture, dam, roadblock, and deforestation (Table 2).

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

3.2. DBH Class Structure Analysis of D. spathacea Population

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 the 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).

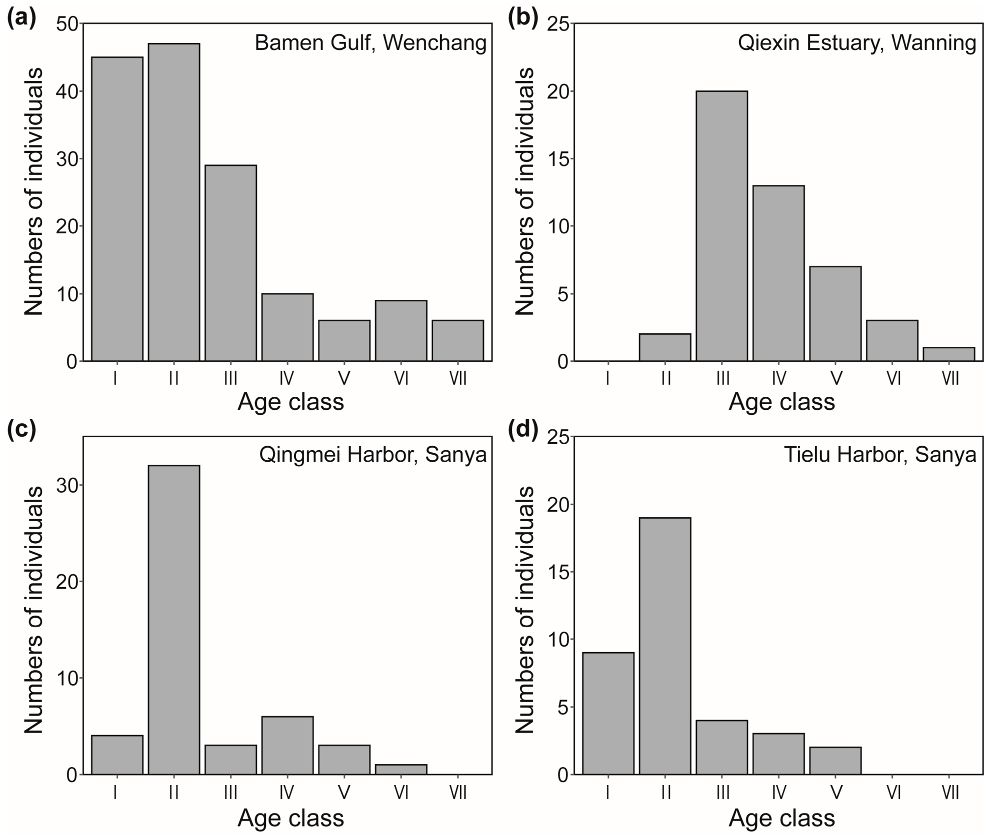

Figure 2. DBH class structures of *D. spathacea* populations in (**a**): Bamen Gulf (Wenchang), (**b**): Qiexin Estuary (Wanning), (**c**): Qingmei Harbor (Sanya), and (**d**): Tielu Harbor (Sanya) on Hainan Island, China.

3.3. Quantitative Population Dynamic Analysis of D. spathacea Population

As shown in Table 3, the data ranges of $V1$ to $V7$ 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 DBH classes in the process of population development (Table 3). Furthermore, the $V1$ values for the four *D. spathacea* populations were all negative, suggesting that all four of the *D. spathacea* populations exhibited a decline in DBH 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 $V5$ of the Bamen Gulf (Wenchang) population and $V2$ of the Qiexin Estuary (Wanning) population, indicating that the *D. spathacea* populations in these stages also might exhibit similar decreasing trends (Table 3).

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

Distribution Point	Variation Index of *D. spathacea* 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 xth to the x + 1th DBH 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.

Furthermore, the values of V_{pi} for the four *D. spathacea* populations in the areas of the 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 might show sensitivity to external random disturbances, which could thus have serious impacts on the *D. spathacea* population (Table 3).

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 fluctuation (Table 4). In particular, after standardized smoothing treatment, the number of surviving individuals (l_x) gradually slowed down and leveled off with an increase in the DBH class. The peak values of the mortality rate (q_x) and vanishing rate (K_x) were all observed in the highest DBH classes in the areas of the 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	DBH 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	–	–	–	–	–	–	–

Table 4. *Cont.*

Distribution Point	DBH Class	a_x	l_x	lga_x	d_x	q_x (%)	L_x	T_x	e_x	K_x	P_x (%)
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 xth DBH class after smoothing treatment, l_x is the standardized number of surviving individuals in the xth DBH class, d_x is the standardized number of dead individuals between two adjacent DBH classes, q_x is the mortality rate for the xth DBH class, L_x is the average number of surviving individuals from the xth to the x + 1th DBH class, T_x is the total number of surviving individuals from the xth to the higher DBH classes, e_x is the life expectancy of an individual in the xth DBH class, K_x is the vanishing rate for the xth DBH class, and P_x is the survival rate for the xth DBH class.

3.5. Survival Curve Analysis of D. spathacea Population

The survival curve of the *D. spathacea* population on Hainan Island was drawn with the DBH class as the horizontal coordinate and $lg(l_x)$ as the vertical coordinate, and the results of fitting equations and their 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 (depending on R^2) than those of the power function equations (Table 5), indicating that the mortality rates of *D. spathacea* populations in these regions were generally stable across the DBH classes.

Table 5. Survival curves (N_x) and their verification models (R^2) 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 indices 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 DBH class of the four *D. spathacea* populations (Figure 3).

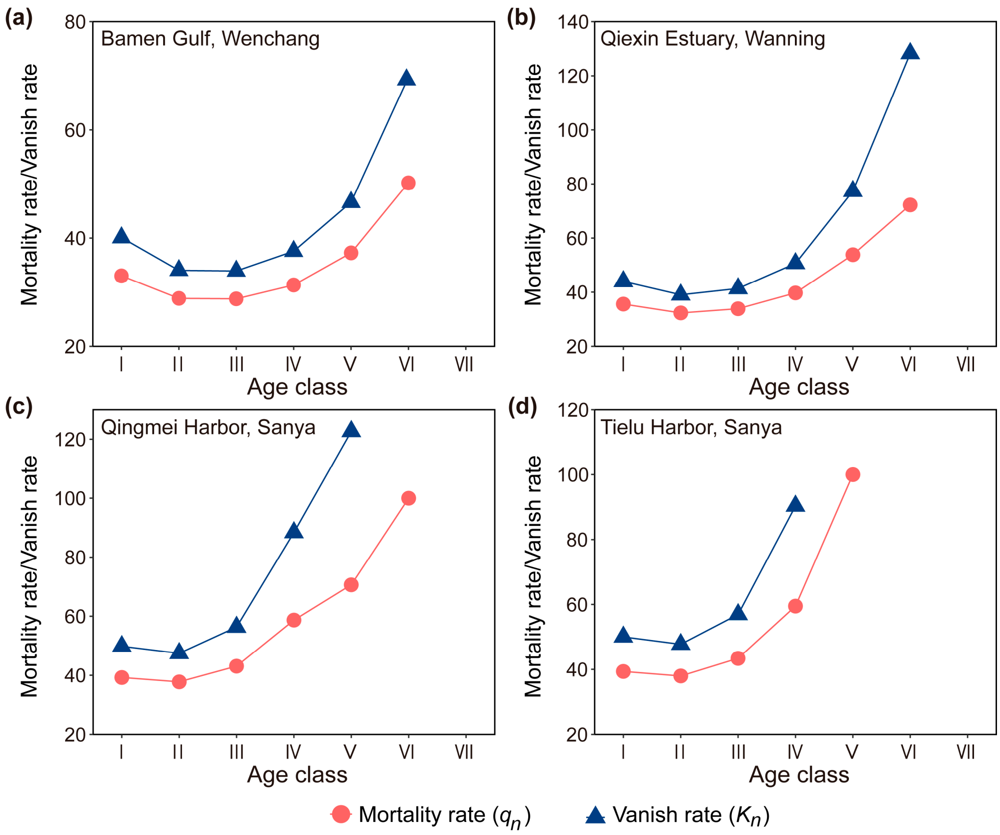

Figure 3. Curves of the mortality and vanishing rates of *D. spathacea* population on Hainan Island, China. The the mortality and vanishing rates of *D. spathacea* population in (**a**): Bamen Gulf (Wenchang), (**b**): Qiexin Estuary (Wanning), (**c**): Qingmei Harbor (Sanya), and (**d**): Tielu Harbor (Sanya) 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 the 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 DBH classes (Figure 4). The intersection point of these two curves appeared around DBH class II and, interestingly, the values at the intersections for all four of the *D. spathacea* populations were 50% (Figure 4).

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 the 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 might exist fluctuation in the young age, with a significant number of individuals dying; however, as they grew older, the mortality risk gradually declined.

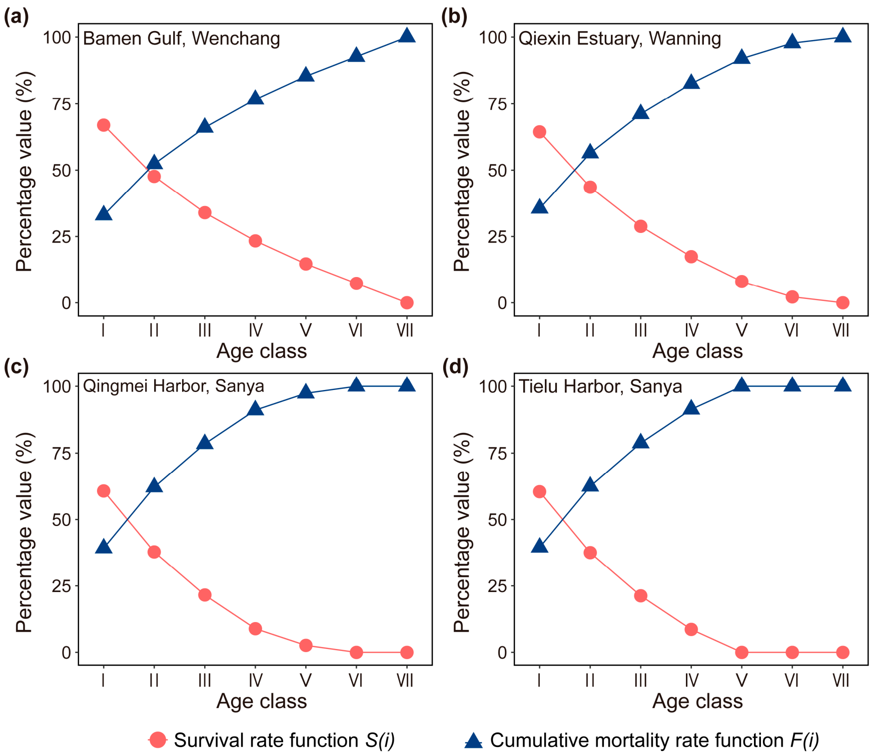

Figure 4. Curves of the survival rate function and the cumulative mortality rate function of *D. spathacea* population on Hainan Island, China. The survival rate function and the cumulative mortality rate function of *D. spathacea* population in (**a**): Bamen Gulf (Wenchang), (**b**): Qiexin Estuary (Wanning), (**c**): Qingmei Harbor (Sanya), and (**d**): Tielu Harbor (Sanya) on Hainan Island, China.

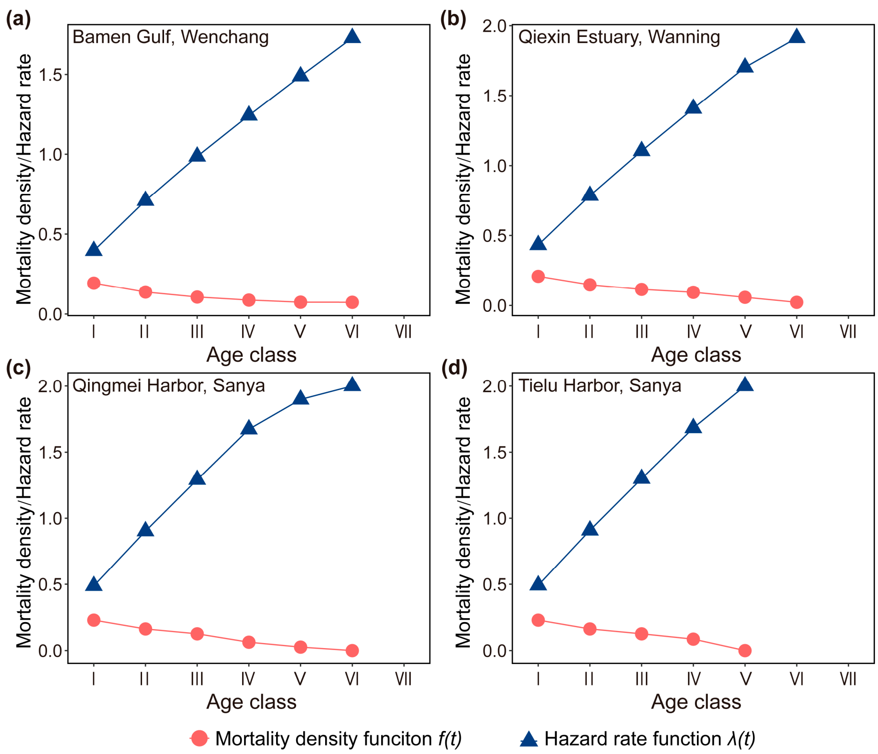

Figure 5. Curves of the mortality density function and the hazard rate function of *D. spathacea* population on Hainan Island, China. The mortality density function and the hazard rate function of *D. spathacea* population in (**a**): Bamen Gulf (Wenchang), (**b**): Qiexin Estuary (Wanning), (**c**): Qingmei Harbor (Sanya), and (**d**): Tielu Harbor (Sanya) on Hainan Island, China.

4. Discussion

4.1. Analysis of D. spathacea Population Structure

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 [35]. In the present study, we first found the number of seedlings was significantly higher than that in the old individuals; furthermore, the *D. spathacea* population structure was mainly composed of young and middle individuals in DBH classes I, II, and III (0 cm $\leq$ DBH $\leq$ 12.5 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 [36]. Additionally, all 4 of the *D. spathacea* populations possessed a large number of young individuals and 3–4 species of other dominant trees in the community, which might imply 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 [37]. In this work, the higher *D. spathacea* population mortality rate in the early DBH class may be a result of the enhanced intraspecific and interspecific competition. Based on these results, 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 the *D. spathacea* population in its initial DBH class made it insufficient to provide enough young individuals to supplement the older DBH classes, thus affecting the renewal and development of its population. Moreover, the small population was found to be likely sensitive to changes in the external environment, making it unable to maintain long-term stability and, so, the *D. spathacea* population might stay low [38]. As for the older DBH 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 DBH 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 DBH classes in the process of population development. These results were broadly similar to those of two previous studies on *T. cuspidata* [36,39]. 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 result can be summarized according to two main evidential aspects. On one hand, all the survival curves for the DBH classes of the four *D. spathacea* populations displayed a standard Deevey II type, characterized by an exponential curve, implying that their mortality rates might be stable throughout the process of population development, even in the last DBH class. This indicated that external (natural or anthropogenic) factors could affect the population development of *D. spathacea* [36]. On the other hand, the irregular initial number of *D. spathacea* trees might correspond to our hypothesis of unsustainable deforestation.

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 rare and endangered semi-mangrove species in China: (1) Prohibiting human deforestation: the unscrupulous logging activities would only result in the destruction of mature and old *D. spathacea* trees which held higher values to become more rare and endangered [40]. (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. [41] reported that the detrimental influences of serious habitat fragmentation can be partially offset by frequent gene exchange between internal populations. (2) Preserving ex situ 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 [42]. In addition, especially the in situ conservation of coastal species and habitats must be considered the best strategy for the natural genetic exchange process, as suggested by several botanists [43]. (3) Rehabilitating the habitats to promote provenance restoration: We observed various external disturbances, such as aquaculture (fishpond construction), 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. (5) 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 [18].

5. Conclusions

In this research, our findings indicated only four *D. spathacea* populations, distributed in the areas of the Bamen Gulf (Wenchang), Qiexin Estuary (Wanning), Qingmei Harbor (Sanya), and Tielu Harbor (Sanya), on Hainan Island, China. These populations existed in geographical isolation. The DBH class distribution of the *D. spathacea* population on Hainan Island belongs to a decline type. In addition, the analysis of population dynamic characteristics indirectly indicated that the *D. spathacea* population in Bamen Gulf (Wenchang) and Qingmei Harbor (Sanya) on Hainan Island might be sensitive to external disturbances and possessed two main increases in mortality rate—namely, in the juvenile and mature stages. 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 restoration 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.

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