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Analyses of community stability and inter-specific associations between a plant species with extremely small populations (*Hopea hainanensis*) and its associated species

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Hopea hainanensis is a large evergreen tree belonging to the family Dipterocarpaceae. It is currently listed as an endangered species on the International Union for Conservation of Nature's (IUCN) Red List of Threatened Species. It is found primarily on China's Hainan Island and northern Vietnam. To protect the plant species with extremely small populations *Hopea hainanensis* and understand its community stability and the inter-specific associations between *Hopea hainanensis* and other occurring species, we set up 16 quadrats in the areas where wild *Hopea hainanensis* populations occurred on Hainan Island to investigate the composition of plant species in the quadrats. We used the M. Godron Community stability index to quantify community stability. Based on the two × two contingency tables, the statistic X^2 , association coefficient (AC), and Pearson correlation coefficient (PCC), percentage co-occurrence (PC), and OI index (OI) analyze the degree of association between *Hopea hainanensis* and the dominant species in each layer. The results showed that the relationship between *Hopea hainanensis* and the dominant species in the community was not significant. In addition, there were both positive and negative associations between *Hopea hainanensis* and other examined six tree species, positive associations with 13 shrub species, positive associations with two herbs, and negative associations with species of 7 species. The connection between *Hopea hainanensis* and herbs is more complex than that between trees, shrubs, and the dominant species. M. Godron's stability analysis showed that the community where *Hopea hainanensis* occurred is relatively unstable (36.84/63.16). The ecology is somewhat fragile, indicating that the community is still at the early or middle stage of competing with other species for resource utilization. The stability of community structure and function is a suitable environment for *Hopea*

hainanensis and finally achieve the purpose of adequate protection, we should choose species with strong positive associations for protecting and recovering *Hopea hainanensis*.

KEYWORDS

Hopea hainanensis, population associativity, associated species, community stability, inter-specific association

Introduction

Hopea hainanensis is one of the Red List of Threatened Species of the International Union for Conservation of Nature (IUCN), mainly distributed in Hainan Island of China and northern Vietnam, and is one of the representative tree species of tropical rain forests in China (Satiraphan, 2012; Ly et al., 2018). It is mainly distributed in mountain valleys, streams, and hillsides with an altitude of 400–800 m in tropical rainforest areas such as Jianfengling, Bawangling, and Diaoluo Mountain in Hainan Province, China (Chen et al., 2015). Despite the high quality of its wood, it has been severely harvested by humans, resulting in a rapid decline in its population. Due to the excessive felling of mature trees on *H. hainanensis*, the population has decreased by 50–70% in recent decades (Ly et al., 2018). The slow recovery of the *H. hainanensis* population in the wild state has transformed it from a representative tree species of tropical rainforest to a rare species (Wang et al., 2007; Mehmood et al., 2018). Due to the narrow distribution area of *H. hainanensis* and the small number of individuals, the sensitivity to the external environment has attracted many scholars at home and abroad to study them.

Rare and endangered plant species typically have few individuals that live in specific communities and ecosystems. The mass ratio hypothesis suggests that the community and ecosystem processes and functions are influenced mainly by the dominant (or sub-dominant, or both) species other than endangered species and their traits (Grime, 1998; Sonkoly et al., 2019). Because the dominant species are more important than the endangered species and their traits (Lohbeck et al., 2015). Rare species also play essential roles in ecosystems, especially species with unique characteristics and intraspecific variations (Powell and Rillig, 2018). The spread of their propagules is necessary for the preservation of biodiversity. They are identifying and measuring functional traits of endangered species that show how they respond to changes in the environment and how the ecosystem functions could help us understand the way these species become endangered or threatened (Turner et al., 2017; Álvarez -Yépez et al., 2019). They could help us better understand how these species become

endangered or threatened, especially under the uncertainty of climate changes in the future (Di Musciano et al., 2020).

The interspecific association is an essential structural feature of plant communities. Interspecific connectivity is the basis for classifying plant communities, community evolution, and community structuring (Miyadokoro et al., 2003; Schnitzler and Closset, 2003). For instance, interspecific association analyses can investigate the changes in interspecific relationships during the stabilizing and succession of a forest community (Chen et al., 2021). Studying the interspecific connectivity and community stability is essential for the evaluation of the coexistence mechanisms in the communities where the rare and endangered plants occur and thereby can provide the theoretical basis for conservation strategies (Zhang et al., 2022).

Currently, studies on the population characteristics of *H. hainanensis* mainly focus on the geographical distribution patterns, population development characteristics, habitat survey and prediction, the relationship between seedling distribution and parent tree, seedling classification, chloroplast genome characteristics, and phylogeny (Song et al., 2020; Mehmood et al., 2022). Likewise, research regarding the conservation of *H. hainanensis* mainly focuses on the ex-situ conservation and seedling breeding, etc. This study focuses on the distribution and habitat characteristics, population structure types, wild seed dispersal, seedling growth, and ex-situ conservation of *H. hainanensis* in Hainan. Environmental selection and seedling cultivation, and the phylogenetic relationship of Dipterocarpaceae. Ecological selection and seedling cultivation for ground protection, the phylogenetic relationship of Dipterocarpaceae plants, etc. However, few studies at the community level, inter-specific association, and community stability of *H. hainanensis*.

To protect the endangered species *H. hainanensis*, and understand its community stability and inter-specific associations, we set up 16 quadrats (20 m × 20 m) in the areas where wild *H. hainanensis* population occurs on Hainan Island to investigate the composition of plant species in the quadrats. Then we used the analysis method combining population connectivity and community stability to explore the connectivity of *H. hainanensis* and the associated species and their status in the community, to predict changes in

community structure and succession trends, and to provide scientific information for the restoration and reconstruction of *H. hainanensis*.

Study area

Hainan (E108°37'–111°03' N18°10'–20°10') is a tropical and continental island off the southern coast of the Chinese mainland (Zhang et al., 2022). It is the largest island city (Figure 1), covering 35,400 km².¹ Hainan Island has a tropical monsoon climate with a mild climate, long summers, and short winters, with an average annual temperature of 22–27°C and abundant rainfall. It is rich in forest resources and a vital distribution area of China's monsoon and tropical rain forests. The main forest vegetation types of Hainan Island include tropical rain forests, mangroves, tropical monsoon forests, evergreen broad-leaved forests, coniferous forests, artificial forests, etc. Plant components mostly have tropical, subtropical, and temperate properties (Zhang et al., 2022). Biodiversity is relatively rich in the central and southern mountainous areas, with more rare and endangered wild plants. At the same time, the northern and coastal regions have relatively low biodiversity and fewer rare and endangered species due to the greater intensity of human disturbance (Guo et al., 2006).

Materials and methods

Quadrat setup and investigation

A total of 16 quadrats (20 m × 20 m) were set up in the area of wild *H. hainanensis* and distributed in Hainan (Figure 1 and Table 1). The adjacent grid method is then divided

into 16 quadrats (5 m × 5 m). Each quadrat is 400 m², and the total of 16-quadrat area is 6,400 m². We investigate the plants in the quadrats by tree layer, shrub layer, and herb layer, respectively. Among them, the species name, height, diameter at breast height, crown width, etc., these species are recorded in the tree layer and the shrub layer, respectively. A small quadrat of (1 m × 1 m) in the herb layer is selected at the four corners of each quadrat, and the species name, height, coverage, number of plants, etc. At the same time, the GPS coordinates, altitude, slope, slope aspect, slope position, natural regeneration, stand growth, threatened status, and degree of human interference of each plot were recorded. Species within the plot were identified using the “An Illustrated Flora of Hainan” (Yang, 2015). In the survey, we found 366 species of 228 genera in 92 families.

The relationships between *Hopea hainanensis* and dominant species at all levels of the community

Community importance value calculation

Importance value (IV) = [(relative density (RA) + relative frequency (RF) + relative significance (RP)]/3.

Main populations in the community

The overall correlation between species reflects whether there is a significant correlation between multiple species that appear in a particular place, and the overall correlation is determined by the variance ratio method (VR). First, make the null hypothesis, that is, there is no significant correlation between the study species, and use the following formula to calculate the test statistic (Wang et al., 2021) as follows (1)–(3):

$$\delta_T^2 = \sum_{i=1}^s \frac{n_i}{N} \left(1 - \frac{n_i}{N}\right) \quad (1)$$

¹ <https://www.hainan.gov.cn>

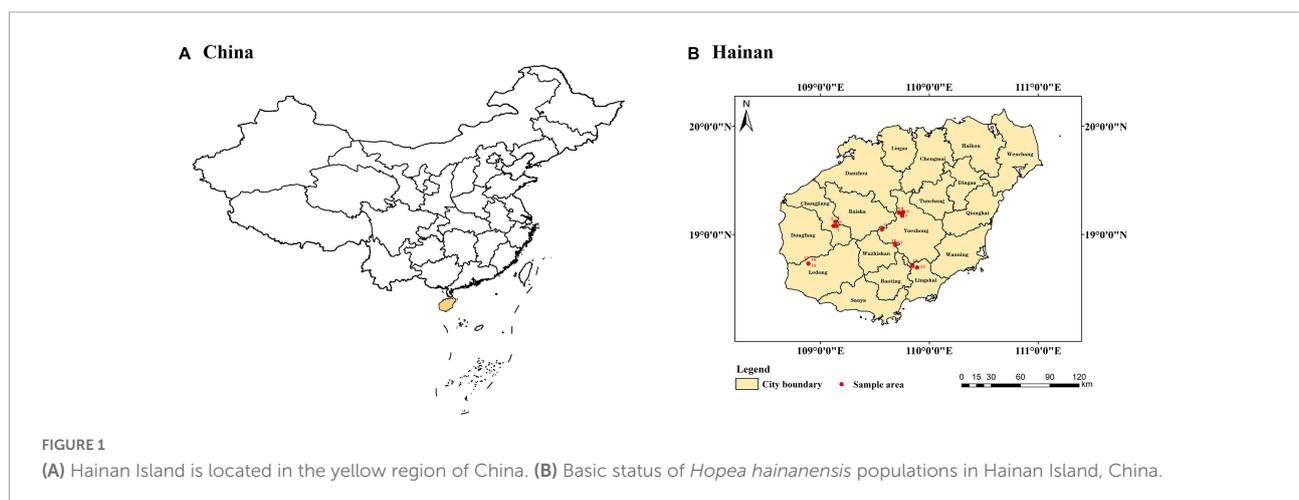


TABLE 1 Basic status of *Hopea hainanensis* populations in Hainan Island.

Quadrant number	City	Name of protected area	Longitude	Latitude	Altitude (m)
1	Changjiang	Bawanglin	109°07'38.1"	19°04'45.7"	609
2	Changjiang	Bawanglin	109°07'18.7"	19°04'49.6"	795
3	Changjiang	Bawanglin	109°08'45.4"	19°04'42.7"	731
4	Changjiang	Bawanglin	109°08'17.3"	19°07'07.1"	560
5	Changjiang	Yingelin	109°33'56.7"	19°02'52.2"	697
6	Qiongzong	Limushan	109°45'15.0"	19°12'07.9"	742
7	Qiongzong	Limushan	109°44'56.7"	19°11'45.1"	708
8	Qiongzong	Limushan	109°43'17.7"	19°12'03.9"	560
9	Qiongzong	Limushan	109°45'04.0"	19°10'31.0"	770
10	Wuzhishan	Wuzhishan	109°41'10.8"	18°54'15.8"	798
11	Wuzhishan	Wuzhishan	109°41'09.6"	18°54'14.4"	794
12	Linshui	Diaoluoshan	109°53'16.9"	18°41'39.0"	717
13	Linshui	Diaoluoshan	109°50'49.1"	18°42'39.9"	622
14	Ledong	Jianfenglin	108°53'34.0"	18°43'56.1"	848
15	Ledong	Jianfenglin	108°53'9.1"	18°43'55.0"	859
16	Ledong	Jianfenglin	108°53'15.2"	18°43'55.1"	887

$$S_T^2 = \frac{1}{N} \sum_{j=1}^N (T_j - t)^2 \tag{2}$$

$$VR = \frac{S_T^2}{\delta_T^2} \tag{3}$$

In the formula, *S* is the total number of species, *N* is the total number of the quadrat, *T_j* is the total number of species appearing in quadrat *j*, *n_i* is the quadrat number of species *i* occurring, and *t* is the average number of populations in the quadrat. The *VR* value is the overall connection index between plant species in the community. *VR* = 1, that is, there is no correlation among all species; *VR* > 1 means that the overall performance of the species is positive, and *VR* < 1 means that the overall performance of the species is negative.

The statistic *W* is used to test the significant degree of *VR* value deviation by 1, *W* = *N* × *VR*. If the interspecies correlation is not significant, the probability of *W* falling within the limit of $X^2_{0.95(N)} < W < X^2_{0.05(N)}$ has a 90% probability.

Interspecies association analysis

The *X²* statistic is often used to measure the deviation between the observed and expected values on a probabilistic basis. The connectivity of paired species was determined by *X²* according to a 2 × 2 contingency table, and calculated by using Yates's continuity correction formula as follows (4):

$$X^2 = \frac{N \left[|ad - bc| - \frac{1}{2}N \right]^2}{(a+b)(c+d)(a+c)(b+d)} \tag{4}$$

N represents the total number of squares, *a* is the number of squares with both species present. *b* is the number of squares with species B, but no species A. *c* is the number of squares with species A but no species B. *d* is no quadratic number for both species (the same below). If $X^2 < 3.841$ (*P* > 0.05),

it means that the species-pair connection is not significant; if $3.841 < X^2 < 6.635$ ($0.01 < P < 0.05$), it means that the species-pair connection is substantial; if $X^2 > 6.635$ (*P* < 0.01), then indicates that species pair linkages are incredibly significant. When *ad* > *bc*, it is determined to be a positive connection. Otherwise, it is a negative connection.

Interspecies relatedness measurement

The *X²* test can more accurately reflect whether the association between species is significant, but species pairs that are not significantly associated still have a particular association (Huang et al., 2015). To further determine the degree of association, point correlation coefficient (PCC), association coefficient (AC), Ochiai index (OI), and percent co-occurrence (PC) were used for analysis. The formula is as follows (5)–(9):

$$PCC = \frac{ad - bc}{\sqrt{(a+b)(a+c)(b+d)(c+d)}} \tag{5}$$

$$AC = \frac{ad - bc}{(a+b)(b+d)}, \text{ When } ad - bc \geq 0 \tag{6}$$

$$AC = \frac{ad - bc}{(a+b)(a+c)}, \text{ When } ad - bc < 0, \text{ and } d-a \geq 0 \tag{7}$$

$$AC = \frac{ad - bc}{(b+d)(c+d)}, \text{ When } ad - bc < 0, \text{ and } d-a < 0 \tag{8}$$

$$OI = \frac{a}{\sqrt{(a+b)(a+c)}} \tag{9}$$

$$PC = \frac{a}{a+b+c} \tag{10}$$

When calculating the connection coefficient AC, to avoid *a*, *b*, or *d* being 0 and causing AC = 1 or AC = -1 to be unable to compare the degree of correlation, weight *a*, *b*, *c*, *d* all 0–1.

Community stability analysis

The M. Godron stability measurement method uses the relationship between the relative frequency of each species in the plot and the number of species to determine stability. The relative frequencies of different species in the quadrat are gradually accumulated and added in order from large to small. Then we match them with the reciprocal percentage of species and establish a fuzzy scatter smooth curve model (11), and finally, the coordinates of the curve and straight-line intersection (12) are calculated (Zhang et al., 2022). The equation is as follows: (11)–(14):

Smooth Curve Simulation Model,

$$y = ax^2 + bx + c \quad (11)$$

Straight line equation,

$$y = 100 - x \quad (12)$$

The two equations are brought into the solution to obtain the following formula,

$$ax^2 + (b + 1)x + c - 100 = 0 \quad (13)$$

$$x = \frac{-(b + 1) \pm \sqrt{(b + 1)^2 - 4a(c - 100)}}{2a} \quad (14)$$

Results

Overall association of *Hopea hainanensis* community

All populations of *H. hainanensis* showed a net positive association. The degree of deviation of the VR value is tested by the statistic W. The value of W falls between $X^2_{(0.95,N)}$ and $X^2_{(0.05,N)}$, which means that there is 90% reliability that the deviation of VR from 1 is not significant. The community shows no significant positive associations, overall, reflecting the consistency of the populations in the community on habitat requirements. Still, the community succession was at the early stage with poor community maturity and stability. Therefore, the overall association degree of the community can also reflect the stability of the community (Table 2).

Connectivity measure of *Hopea hainanensis* and the associated species

Based on the overall association test of the community, based on the 2×2 contingency table, the statistic X^2 , association coefficient (AC) and Pearson correlation coefficient (PCC),

percentage co-occurrence (PC), and OI index (OI), we analyze the degree of association between *H. hainanensis* and dominant species in each layer.

Association of *Hopea hainanensis* with arbor dominant species

The association results between *H. hainanensis* and the twelve dominant species with tree layer importance value > 1 (Table 3). *H. hainanensis* and tree species pair statistics $X^2_t < 3.841$ ($P > 0.05$). The results show that *H. hainanensis* is not significantly associated with all dominant tree species. From the results of AC and PCC, six species are positively linked to *H. hainanensis*, and six species are negatively correlated. There are five species with $|AC| < 0.1$, and these species accounted for 41.77% of the total number of arbor plants. They are *Cyclobalanopsis patelliformis*, *Sarcosperma laurinum*, *Gironniera subaequalis*, *Hancea hookeriana*, and *Vatica mangachapoi*, which are positively connected with *H. hainanensis*. The OI index and PC value of the *Sarcosperma laurinum* are the largest, indicating *H. hainanensis* and *Sarcosperma laurinum* have a higher probability of co-occurring, and the connection between the *Sarcosperma laurinum* stronger among the 5 species pairs (Table 4). There were seven species with $0.1 < |AC| < 0.3$, accounting for 58.33% of the total number of arbor plants and *H. hainanensis* showed a positive association with *Sarcosperma laurinum* and showed a negative association with *Nephelium topengii*, *Polyalthia*

TABLE 2 Overall inter specific associations among dominant populations of *Hopea hainanensis* community.

Variance ratio (VR)	Weight (W)	X^2 threshold ($X^2_{0.95,N}$, $X^2_{0.05,N}$)	Results
1.41	22.51	(7.962, 26.296)	Overall positive association, but not significant

TABLE 3 Indices of inter-specific association between *Hopea hainanensis* and tree species.

Tree species	Association indices					
	(IV)	X^2	PCC	AC	OI	PC
<i>Schefflera heptaphylla</i>	3.6824	0.1778	0.4412	0.25	0.9354	0.875
<i>Cyclobalanopsis patelliformis</i>	3.169	0.225	0.125	0.0156	0.75	0.5625
<i>Sarcosperma laurinum</i>	2.7462	0.0278	0.0395	0.0625	0.8292	0.6875
<i>Gironniera subaequalis</i>	2.5754	0.225	0.0395	0.0156	0.75	0.5625
<i>Hancea hookeriana</i>	1.8616	0.225	0.0395	0.0156	0.75	0.5625
<i>Vatica mangachapoi</i>	1.8318	0.225	0.0395	0.0156	0.6614	0.4375
<i>Nephelium topengii</i>	1.8269	0.225	-0.0395	-0.1	0.75	0.5625
<i>Polyalthia laui</i>	1.3873	0.1039	-0.0806	-0.1818	0.6124	0.375
<i>Walsura robusta</i>	1.1789	0.1039	-0.0806	-0.1818	0.6124	0.375
<i>Engelhardia roxburghiana</i>	1.1103	0.1039	-0.0806	-0.1818	0.6124	0.375
<i>Cryptocarya chinensis</i>	1.0406	0.0278	-0.0806	-0.25	0.559	0.3125
<i>Polyosma cambodiana</i>	1.0142	0.1039	-0.125	-0.1818	0.6124	0.375

laui, *Walsura robusta*, *Engelhardia roxburghiana*, *Cryptocarya chinensis*, and *Polyosma cambodiana*, and revealing that they have a low correlation coefficient.

Association of *Hopea hainanensis* with shrub dominant species

The association results between *H. hainanensis* and the dominant species in the shrub layer (Table 4). *H. hainanensis* and shrub species pair statistics $X^2_t < 3.841$ ($P > 0.05$), indicate that *H. hainanensis* is not significantly associated with all shrub's dominant species. From the results of AC and PCC, *H. hainanensis* was positively associated with all shrub's dominant species. There is only one species with $|AC| > 0.5$, which is *Beilschmiedia percoriacea*, and its PCC, AC, OI, and PC value are all ranked first. There are six species with $0.3 < |AC| < 0.5$, accounting for 40% of the total number of shrubs. The PC value of the *Psychotria asiatica* and *Pygeum topengii* is higher, and the positive connection with the *H. hainanensis* is closer. There are four species with $0.1 < |AC| < 0.3$: *Ancistrocladus tectorius*, *Schefflera heptaphylla*, *Sarcosperma laurinum*, and *Polyalthia laui*. There are four species with $|AC| < 0.1$: *Brassaiopsis glomerulata*, *Vatica mangachapoi*, *Litsea variabilis*, *Tabernaemontana bovina*. The OI and PC value of *Hancea hookeriana* and *Glochidion philippicum* are both 0. The results show that *H. hainanensis* is utterly independent of the species of *Hancea hookeriana* and *Glochidion philippicum*.

Association of *Hopea hainanensis* with herb dominant species

The association results of the top 14 herb dominant species with importance value (IV) of *H. hainanensis* and herb layer. The statistic of *H. hainanensis* and herb species pair $X^2_t < 3.841$ ($P > 0.05$), indicates that the association between *H. hainanensis*

and dominant herb species is not significant (Table 5). From the results of AC and PCC, two species are positively linked to *H. hainanensis*, and 12 species are negatively correlated. There are two species with $0.3 < |AC| < 0.5$, *Diplazium donianum* and *Selaginella doederleinii*. However, the OI and PC value of these two species are both 0, indicating that there is no correlation with *H. hainanensis*, and the species are entirely independent. There are eight species with $0.1 < |AC| < 0.3$, accounting for 57.14% of the total number of herbs. Among them, the OI and PC value of *Licuala fordiana*, *Allantodia calogramma*, and *Daemonorops jankinsianus* are 0, and there is no correlation with *H. hainanensis*. The OI and PC value of *Pronephrium simplex* are ranked first and they have similar ecological habits and environmental requirements to *H. hainanensis*. There are four species with $|AC| < 0.1$: *Dinochloa utilis*, *Cayratia japonica*, *Smilax lanceifolia*, and *Alpinia galanga*. Among them, the OI and PC value of *Cayratia japonica* are relatively large, and their connection is more closely than the other three species. Based on AC, PCC, OI, and PC, two species are positively associated with *H. hainanensis* and dominant herbaceous species, seven are negatively associated, and five are completely independent.

Community stability analysis

The relative frequencies of all plants in the community were accumulated and plotted by using the M. Godron stability assay. The stability diagram of the community in which *H. hainanensis* is located was obtained (Figure 2). The results showed that the stable point of the community was 36.84/63.16, far from the stable point of 20/80, indicating that the community where *H. hainanensis* was unstable (Table 6). To judge the stability of each level of the community accurately, the maps were drawn according to the tree layer, the shrub layer, and the herb layer (Figure 2). With a coefficient of determination

TABLE 4 Indices of inter-specific association between *Hopea hainanensis* and shrub species.

Shrub species	Association indices					
	IV	X ²	PCC	AC	OI	PC
<i>Ancistrocladus tectorius</i>	4.452	0.2462	0.2894	0.1795	0.4714	0.2857
<i>Schefflera heptaphylla</i>	4.24	0.989	0.3812	0.2527	0.6547	0.4286
<i>Brassaiopsis glomerulata</i>	3.3586	0.3655	0.0216	0.0154	0.2582	0.1429
<i>Psychotria asiatica</i>	2.603	1.2308	0.4623	0.3846	0.5774	0.4
<i>Gomphandra tetrandra</i>	2.393	0.1143	0.3099	0.3929	0.5774	0.3333
<i>Sarcosperma laurinum</i>	2.1477	0.6042	0.3671	0.2615	0.5164	0.3333
<i>Hancea hookeriana</i>	2.0655	0.0103	0.2279	0.3462	0	0
<i>Vatica mangachapoi</i>	2.0644	0.1368	0.0925	0.0769	0.2887	0.1667
<i>Litsea variabilis</i>	2.0447	0.3655	0.0216	0.0154	0.2582	0.1429
<i>Diospyros hainanensis</i>	1.7803	0.0586	0.3026	0.3846	0.4082	0.25
<i>Polyalthia laui</i>	1.6368	0.0105	0.1795	0.1795	0.3333	0.2
<i>Beilschmiedia percoriacea</i>	1.3383	2.6213	0.5952	0.5952	0.8165	0.6667
<i>Pygeum topengii</i>	1.2629	1.2308	0.4623	0.3846	0.5774	0.4
<i>Glochidion philippicum</i>	1.1873	0.0103	0.2279	0.3462	0	0
<i>Tabernaemontana bovina</i>	1.1804	0.1368	0.0925	0.0769	0.2887	0.1667

TABLE 5 Indices of inter-specific association between *Hopea hainanensis* and herb species.

Herb species	Association indices					
	IV	X ²	PCC	AC	OI	PC
<i>Diplazium donianum</i>	3.5746	0.0711	0.2	0.2	0.5	0.3333
<i>Pronephrium simplex</i>	3.2418	0.381	-0.2777	-0.36	0	0
<i>Selaginella doederleinii</i>	2.9921	0.1524	0.0976	0.2	0.2887	0.1429
<i>Selaginella tamariscina</i>	2.7464	1.0009	-0.3678	-0.4167	0	0
<i>Dinochloa utilis</i>	2.3391	0.2462	-0.0413	-0.0667	0.2357	0.125
<i>Licuala fordiana</i>	2.0543	0.0871	-0.0738	-0.1333	0	0
<i>Cayratia japonica</i>	1.9989	0.0711	-0.0667	-0.0667	0.3333	0.2
<i>Licuala hainanensis</i>	1.8482	0	-0.1491	-0.2	0.2041	0.1111
<i>Daemonorops jankinsianus</i>	1.5794	0.0396	-0.1823	-0.275	0	0
<i>Allantodia calogramma</i>	1.3867	0.0871	-0.0738	-0.1333	0	0
<i>Smilax lanceifolia</i>	1.3683	0.2462	-0.0413	-0.0667	0.2357	0.125
<i>Daemonorops jenkinsiana</i>	1.337	0	-0.1491	-0.2	0.2041	0.1111
<i>Ancistrocladus tectorius</i>	1.2974	0	-0.1491	-0.2	0.2041	0.1111
<i>Alpinia galanga</i>	1.2499	0.2462	-0.0413	-0.0667	0.2357	0.125

($R^2 > 0.99$), the coordinates of the intersection points of each layer were 44.94/55.06 for the tree layer, 41.76/58.24 for the shrub layer, and 42.69/57.31 for the herb layer. It shows the stability of the community where *H. hainanensis* is located, and the community, the tree layer, the shrub layer, and the herb layer are all in an unstable state. The stability of each layer is shrub layer > herb layer > tree layer.

Discussion

Community stability of *Hopea hainanensis*

Interspecies connectivity can reflect community stability and succession status (Haak et al., 2019). The magnitude of interspecies connectivity reflects the interactions between populations and community dynamics. The progress of community succession, the interspecific and intraspecific competition of species, community structure, and community

species composition will continue to be stable. The interspecific relationship will also be positively correlated to achieve a steady equilibrium state between different populations (Hu and Ding, 2000; Wang et al., 2021). The positive and negative association between species implies the function of species in the community and affects the succession of the community. Analyzing the community's interspecific association can help to understand better the direction of the community's succession (Jin et al., 2013). The Chi-square test showed that the community where *H. hainanensis* was located showed a positive correlation ($VR > 1$) but did not reach a significant level [$W < X^2_{0.05(N)}$]. The interspecific connection of the community where *H. hainanensis* was relatively loose, followed by the ratio of species reciprocal percentage to cumulative relative frequency was 36.84/63.16, far from the stable point of 20/80. The community where the *H. hainanensis* was located was unstable, and the ecology was relatively fragile. The community where *H. hainanensis* is located is still in the early or middle stage of succession. The community structure and function are still unstable, the community species are in dynamic regulation, and a complex and stable

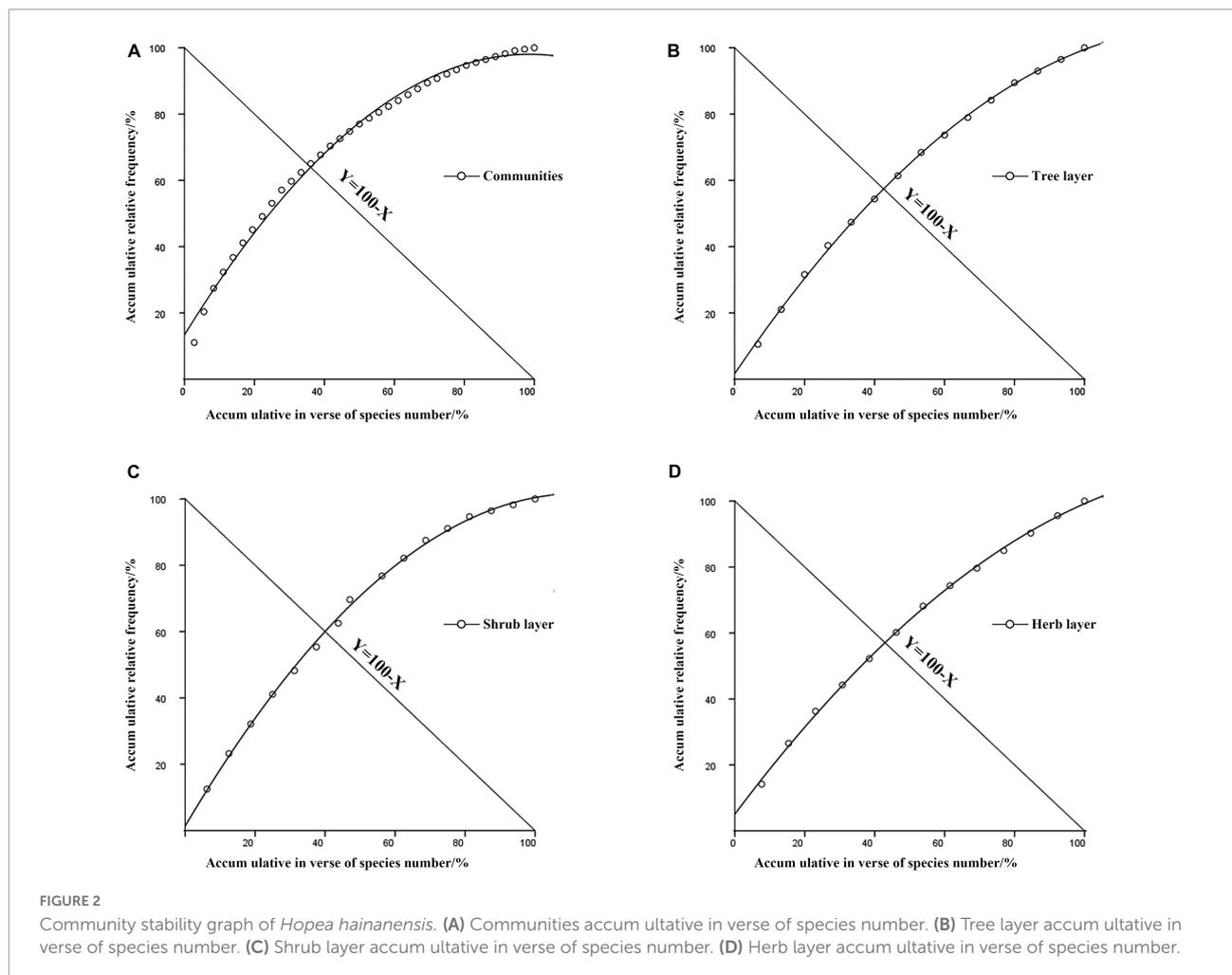


TABLE 6 Results of community stability (M. Godron's method).

Layers	Type of curves	Determination coefficient	P	Coordinate		Results
				X	Y	
Community as a whole	$y = -0.01x^2 + 1.72x + 13.37$	$R^2 = 0.9948$	$P < 0.01$	36.84	63.16	Unstable
Tree layer	$y = -0.005x^2 + 1.4136x + 5.062$	$R^2 = 0.9992$	$P < 0.01$	44.94	55.06	Unstable
Shrub layer	$y = -0.01x^2 + 1.78x + 1.34$	$R^2 = 0.9988$	$P < 0.01$	41.76	58.24	Unstable
Herb layer	$y = -0.006x^2 + 1.56x + 1.64$	$R^2 = 0.9994$	$P < 0.01$	42.69	57.31	Unstable

community with multi-species coexistence has not been formed. *H. hainanensis* and other species in the community exist to utilize resources competition.

Interspecies connectivity between *Hopea hainanensis* and companion species

The association between the *H. hainanensis* population and the dominant species of trees, shrubs, and herbs in the community did not reach a significant level. The correlation coefficient of interspecific association between *H. hainanensis* and most species was low, suggesting the vertical structure of *H. hainanensis* and the interspecific association of the dominant species in each community layer. The connection relationship was relatively loose and tended to be independent of each other, with great randomness. There was no direct connection between *H. hainanensis* and the dominant species in the community and this was similar to the research examining the associations between rare and endangered plants. It is similar to the results of the endangered species *Berchemiella wilsonii*, *Sinojackia rehderiana*, *Phyllitis scolopendrium*, and their associated species in their communities (Hu et al., 2005; Huang et al., 2015; Zhou et al., 2017). We argue that three possible reasons may help account for this. First, the biological characteristics of the *H. hainanensis* itself may lead to a loose interspecific connection loss. Besides, there is a low altitude that can be easily affected by human beings, so the community where it is located has suffered different degrees of damage for years. In addition, *H. hainanensis* is an indicator species of tropical rainforest, in which the species diversity is exceptionally high, and the community composition is relatively complex. This environment results in a low probability of encounters between species. Therefore, the phenomenon of weak connection, zero connection, or negative connection between *H. hainanensis* and other species appears, further confirming that tropical rain forests' constituent populations are characterized by relatively independent distribution.

The association between *H. hainanensis* populations and herbs was more complex than that between trees and shrubs, and it was more closely associated with the dominant tree species. The connection coefficient and point correlation

coefficient analysis showed six positively and negatively related species of *H. hainanensis* and arbor species. In the tree layer, the PCC, AC, OI index, and PC value of *Schefflera heptaphylla* were the highest. Although they did not reach a significant level, the connection between *Schefflera heptaphylla* and *H. hainanensis* was relatively close, and the ecological habits and demands on the environment of the two species had specific differences. The IV of *Schefflera heptaphylla* was 3.68%. It ranked first in the arbor layer and was in the upper layer of the community. It has a relatively strong ability to utilize resources. The population and distribution range of *Schefflera heptaphylla* is relatively large. The probability of encountering *H. hainanensis* is higher than in other species. Thirteen shrub species were positively related to *H. hainanensis*, accounting for 86.67% of the total number of shrub species. Still, the correlation coefficients were relatively low, and two species (*Hancea hookeriana* and *Glochidion philippicum*) were not related to *H. hainanensis*. The number of *H. hainanensis* saplings is scarce, and the interspecific relationship with other species tends to be positively correlated to promote coexistence. The low correlation coefficient of *H. hainanensis* also maintained a certain degree of independence in the community, reducing intraspecific competition, which was beneficial for the development of *H. hainanensis* saplings in the shrub layer. Two species were positively associated with herbs, seven were negatively associated, and five were completely independent. This behavior could be due to the high mortality rate of *H. hainanensis* seedlings. There is competition and interference between *H. hainanensis* seedlings and the dominant species in the herb layer, which is not conducive to their development. A larger importance value of a species typically indicates a larger niche breadth of the species and this will lead to more significant niche overlap and thereby a tighter interspecific association of the species with other species (Li et al., 2015; Chen et al., 2019).

H. hainanensis represented a major component both in the tree and the herb layer, and its importance value was in the order of herb layer (23.58) > arbor layer (3.30) > shrub layer (1.07). These results suggest that the resources in the community where *H. hainanensis* present are not fully utilized. It is still in an active development state, as indicated by the lack of a consistent relationship between *H. hainanensis*'s critical value and its tight association with other species. *H. hainanensis* is more dominant in the herb layer and

arbor layer. The number of adults of *H. hainanensis* in the community was relatively small, but its diameter at breast height is significant and its height was high. The number of seedlings in the herb layer is more, and the coverage is high. It initially shows a declining trend in the wild *H. hainanensis* population, which was consistent with the study examining the population structure of *H. hainanensis* in the Bawangling Nature Reserve (Zhang et al., 2022). It has been challenging to protect and reintroduce rare and endangered plants in minimal numbers (Godefroid et al., 2011). However, such practices of introducing *H. hainanensis* have been successful in three experimental sites of Puwen, Xishuangbanna, and Xunwang in Yunnan. Still, compared with plantations that typically have simple community structures, natural forests can better support biodiversity conservation and achieve ecosystem services such as surface carbon storage, soil conservation, and water conservation (Hua et al., 2022). Therefore, the restoration of wild *H. hainanensis* populations is essential. The interspecific relationship between the *H. hainanensis* population and herbs is more complex than trees and shrubs. The overall positive connection ratio between the *H. hainanensis* and other dominant species is lower, and the negative connection between the *H. hainanensis* seedlings in the herb layer is higher than Shrub layer and tree layer. The competition for resources among *H. hainanensis* and other species is fierce, and the mortality of *H. hainanensis* seedlings is high. Zhang et al. (2019) conducted a 6-month shading experiment on semi-annual *H. hainanensis* seedlings to study the effect of light intensity on *H. hainanensis* seedlings and found that light is an important environmental factor affecting *H. hainanensis* seedlings. *H. hainanensis* seedlings lower 7–8 months grew better under certain shading conditions, and the seedlings after 7–8 months are suitable for growing under insufficient light. However, many factors could cause the high mortality rate of seedlings. Further studies examining the causes of the high mortality rate of seedlings on *H. hainanensis* are warranted. The problem that seedlings cannot be transit to saplings should be solved and we should construct strategies for restoring wild *H. hainanensis* populations.

Conclusion

The community where *H. hainanensis* is found is unstable, and the ecology is also relatively fragile. The community where *H. hainanensis* is located is still in the early or middle stage of succession. The community structure and function are still unstable, the community species are in a dynamic adjustment, a complex and stable community with multi-species coexistence has not been formed, and there are still competitions for resources between *H. hainanensis* and other species in the community to exist. The correlation between *H. hainanensis* and the

dominant species in the community is not significant. The connection between the *H. hainanensis* population and herbs is more complex than that of trees and shrubs, and it is more closely connected with the dominant species of trees. To conserve the wild *H. hainanensis* population, future studies should conduct further research on the high mortality of seedlings.

Data availability statement

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

Author contributions

LZ, H-LZ, MN, and YC: conceptualization. YC and LZ: methodology. LZ: software, data curation, formal analysis, and investigation. LZ and H-LZ: validation. LZ, H-LZ, MN, QZ, and XS: writing—original draft preparation and writing—review and editing. YC: project administration. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

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

The reviewer SB declared a shared affiliation with the authors H-LZ, MN, and QZ to the handling editor at the time of review.

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