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Habitat characteristics, population structure, distribution, and regeneration status of *Taxus wallichiana* in South Vietnam

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Abstract. *Hop NV, Xiong CC, Quy NV, Luong NT. 2023. Habitat characteristics, population structure, distribution, and regeneration status of* Taxus wallichiana *in South Vietnam. Nusantara Bioscience 15: 179-188.* *Taxus wallichiana* Zucc. is an endangered plant species with high economic value, making it threatened with extinction. Biological information about this species is therefore essential for its conservation. This study is aimed to assess the habitat characteristics, population structure, distribution, and regeneration status of *T. wallichiana* in South Vietnam. Vegetation surveys were conducted from 2016 to 2021 in three regions in Lam Dong Province. The study revealed that it was distributed in regions with monsoon climate with a total extent of 379.57 ha, with habitats located on the hillside, narrow shelves, dissected terrain, high slope, on feralite soil with light brown to yellow, red, the soil layer thickness over 0.3 m and in clusters or streaks. The study recorded 634 trees with a diameter at breast height (DBH)≥25 cm and 137 trees with 6 cm ≤DBH<25 cm. The trees were found primarily at 1401-1500 m above sea level in a mixed broadleaved-coniferous forest. The growth indicators of DBH and overall height (Hvn) developed strongly, but the stand volume was low owing to low tree density. The exponential function was the most suitable for simulating the relationship between Hvn and DBH. Seven thousand six hundred and seventy-three regenerating young individuals were recorded with low density. The density of the regenerating trees decreased as the tree height increased. The finding of this study suggests that *T. wallichiana* faces the danger of extinction, so solutions are required to conserve and develop this threatened species.

Keywords: Conservation, ecological, *Taxus wallichiana*, threatened plant, Vietnam

INTRODUCTION

The conservation of any species requires a deep understanding of its biological characteristics and life history, as well as the biotic and abiotic conditions of suitable habitats where the species can survive and thrive (Yousaf et al. 2022). This is especially prominent for rare plant species with conservation significance and importance to national, regional, and global biodiversity. The knowledge of ecology, growth, development, distribution, and regenerating status is necessary for conserving species from extinction. Conifers, in general, are a plant group with various benefits and values, yet they have restricted geographical distribution and habitat requirements (Yousaf et al. 2022). Therefore, conifers conservation and sustainable management require scientific understanding backed up with reliable data and information.

Taxus wallichiana Zucc. (Himalayan Yew) is a conifer species native to the Central Himalayas, China (Northwest Yunnan), Southeast Vietnam, Sumatra, Sulawesi, and the Philippines (Plants of the World Online 2023). This species is listed as endangered (EN) by the International Union for Conservation of Nature (The IUCN Red List of Threatened Species 2023). It has high conservation importance and significant economic values, including for timber and medicine purposes (Gajurel et al. 2014b; Bhardwaj 2023). Previous studies have demonstrated that the leaves and bark of *T. wallichiana* produce taxol, which is the primary raw material of drugs to treat ovarian cancer, breast cancer, lung cancer, and melanoma (Paul et al. 2013; Iqbal et al. 2020; Bhardwaj 2023). The plant is essential in traditional medicine to treat common infections, colds, coughs, fever, and pain in several indigenous communities (Juyal et al. 2014; Sinha 2020; Bhardwaj 2023). This plant also provides livelihoods for local communities, such as timber and leaves for sale, to increase the income of local communities (Gajurel et al. 2014a). Such confirmed values have attracted and increased the pressures on this plant by increasing the risk of extinction.

Vietnam is a tropical country located in Southeast Asia. Vietnam's broad range of topography and climate has created many ecosystems, such as mangroves, dipterocarp forests, and semi-deciduous and evergreen forests (Luong et al. 2023). Furthermore, Vietnam is one of the centers of flora diversity worldwide, with about 12000 species (Ho, 1999). According to the Vietnam Red Data Book, 443 plant species were endangered, precious, and rare (Ban et al. 2007). Many threatened plant species face extinction due to natural and human factors, including *T. wallichiana*.

In Vietnam, two species of *Taxus* L. genus have been recorded, namely *Taxus chinensis* (Pilg.) Rehd. and *T. wallichiana*. The common name for *T. wallichiana* is

Thông Đỏ Lá Dài (*Thông Đỏ Nam*). This plant has a narrow distribution, with around 250 trees recorded in South Vietnam (Ban et al. 2007), and some trees have been discovered in North Vietnam (Trung 2014). This species is listed as vulnerable in the Vietnam Red Data Book (Ban et al. 2007) and belongs to group IIA of Decree 84/2021/ND-CP of the Government (Government of Vietnam 2021). The species is seriously threatened due to its limited distribution, while the number of individual trees is reduced due to illegal logging or harvesting of bark and leaves to be used for cancer drugs.

In South Vietnam, this plant species is still preserved with several mature individuals and some regenerating young trees. Moreover, some previous studies on *T. wallichiana* have been done by Hung and Nghia (2011) and Brum (2019), but they are incomplete and not systematic. Therefore, this study aimed to (i) determine habitat characteristics of *T. wallichiana* in the forest, (ii) determine density and distribution based on elevation, forest status, growth, and quality of mature trees, and (iii) assess the regeneration status of the existing population. This study provides a database of critical environmental factors, where *T. wallichiana* the distribution, growth, and reproduction. This can be utilized for developing conservation strategies for this species in South Vietnam.

MATERIALS AND METHODS

Study area and period

The study was conducted in Don Duong District (sub-district 324A, 324B, 324C, and 325A), Lac Duong District (sub-district 125, 128, 130), and Duc Trong District (sub-zone 168, 277A, 278A), Lam Dong Province, South Vietnam during multiple field surveys from 2016 to 2021. The study area is geographically located at 114^{0}7’48” - 120^{0}2’50” North latitude and 108^{0}25’30” - 108^{0}39’53” East longitude (Figure 1). The populations of *T. wallichiana* were distributed on the Lam Vien Plateau. The studied area had three different vegetation types: Coniferous - broadleaved mixed forest, *Pinus kesiya* Royle ex Gordon natural forests, and shrubs. The site has two seasons, i.e., the rainy season from April to October and the dry season from November to April.

Data collection procedure

Interviews were performed before the field survey by distributing 35 questionnaires to experienced forest people, forestry staff, households, and individuals involved in forest protection. Based on the initial interview information, a field survey was conducted using the transect method. Nineteen transect lines were established for vegetation sampling with a distance of 500 m between the transects. At each transect line, two sampling plots were created and systematically arranged, totaling 38 sample plots, with the size of each sample plot being 500 m^2. At each transect line and sample plot, we collected information about coordinates, elevation, area and distribution, name of tree species, diameter at breast height (DBH), and overall height (Hvn) of all trees with (DBH)≥6 cm and young trees. The young trees include DBH < 6 cm and Hvn < 6 m.

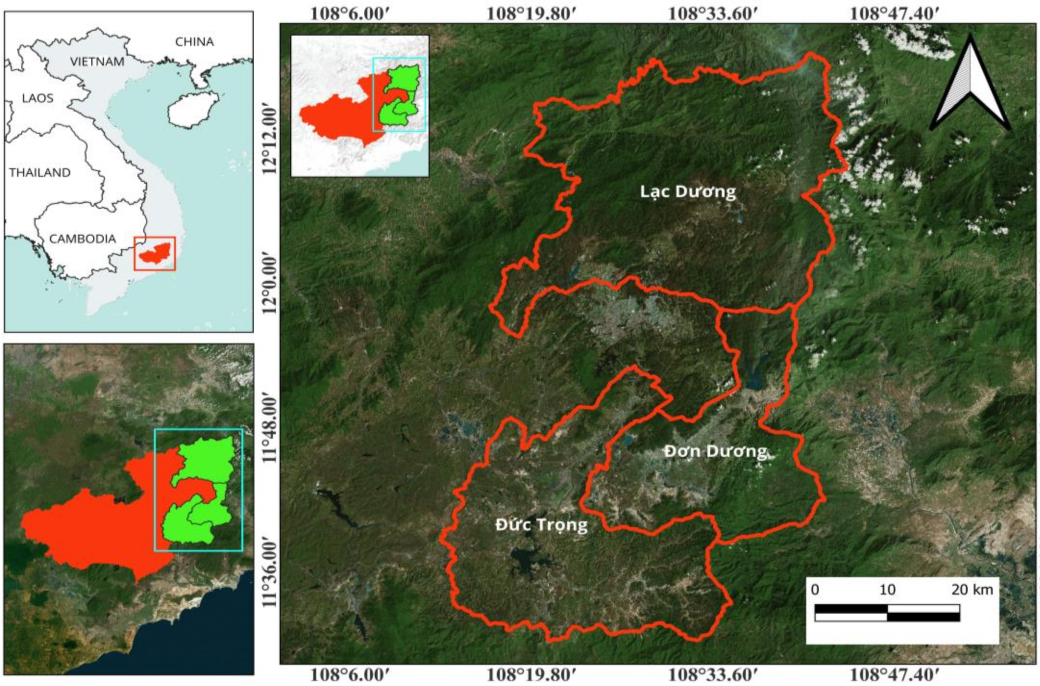

Figure 1. Map of the study area in Don Duong, Lac Duong and Duc Trong Districts, Lam Dong Province, South Vietnam

Data analysis

The species name was identified based on the morphological characteristics using An Illustrated Flora of Vietnam, volumes 1-3 (Ho 1999). The species' scientific name was corrected according to Plants of the World Online (2022). Climatic factors, i.e., temperature, humidity, and annual average rainfall, were collected from meteorological stations in the study areas. While slope was measured by Compass DC45-5C, rock mix ratio was determined by the estimator, and soil thickness was determined by soil profile. Trung (1999) stated that in the South of Vietnam, from above 1200 m, the temperature decreased from 0.5^0C to 1^0C when the altitude increased to 100 m. Field investigations showed that *T. wallichiana* was distributed in the 1200-1800m above sea level (asl) range. Therefore, to see the variation in altitude distribution, we divided the study area into six altitudinal ranges, namely: 1201-1300 m, 1301-1400 m, 1401-1500 m, 1501-1600 m, 1601-1700 m, 1701-1800 m.

Vegetation composition was measured using the Important Value Index (IVI) and calculated using the method by Daniel Marmillod as follows (Khanh 1996).

$$IVi\ (\%) = \frac{Ni\% + Gi\%}{2}$$

Where:

IVi is the Important Value of species i (%);

Ni is the percentage % of species (i) in the plant community;

Gi is the percentage % of the total basal area of species (i) in the plant community;

Daniel Marmillod states that tree species with IVi ≥ 5% is ecologically significant species. According to Trung (1978), a group of tree species with IVi>50% of the total number of individuals indicates that such a group is the dominant species group within a vegetation community. We, therefore, calculated the sum of the IVi of species with a value greater than 5%, ranked from high to low, and stopped when the total IVi reached 50%.

We also calculated the density of tree species as follows:

$$\text{Density}\ (\frac{\text{tree}}{\text{ha}}) = \frac{\text{Total number of trees of species in each sample plot (tree)} * 10000}{\text{Area of sample plot (m2)}}$$

The distribution of *T. wallichiana* was mapped by recording the coordinates of each tree encountered during the field survey using GPS64s and inputting them into spatial software (i.e., MapInfo ver. 15.0 and QGis ver. 3.28.3). Statistical analysis was conducted using one-way ANOVA (SPSS ver. 14.0) to compare the habitat characteristics, area, density, growth, and regeneration criteria.

RESULTS AND DISCUSSIONS

Abiotic characteristics of the habitat of *T. wallichiana*

Taxus wallichiana was observed in Don Duong, Duc Trong, and Lac Duong Districts, Lam Dong Province, Vietnam (Figure 2), primarily along hillsides and narrow terraces. The terrain was dissected by streams, northeast to southwest, with slopes ranging from 10^0-30^0. The species was mainly distributed on grey-brown to red-yellow feralite soil developed from granite, basalt, or acid. The soil's average depth is more than 0.3 m, with many exposed rocks, and the average proportion was more than 20% (Table 1).

In general, *T. wallichiana* was distributed in well-growing and well-developed forest vegetation communities. However, there were indications that humans moved some regenerated trees to make ornamental plants or encroached on forest land to grow coffee and fruit trees, which affects the distribution region and the number of regenerated trees in the areas.

Biotic characteristics of the habitat of *T. wallichiana*

Species composition

The species composition of the vegetation communities where *T. wallichiana* occurred was generally evergreen broad-leaved species and some conifer species. Especially in Lac Duong, *P. kesiya* predominated the vegetation. While in other areas, there were also conifers, although the number of individuals was limited and scattered, such as *Nageia wallichiana* (Presl) Kuntze, *Cephalotaxus mannii* Hook.f., *Podocarpus imbricatus* Blume, *Podocarpus neriifolius* D.Don, *Dacrydium elatum* (Roxb.) Wall. ex Loudon (Table 2).

In Don Duong, the dominant species was *Syzygium wightianum* Wall. ex Wight & Arn., followed by *Rhodoleia championii* Hook. and *Schima superba* Gardner & Champ. In Lac Duong, *P. kesiya* was the dominant species, followed by *S. superba* and *Castanopsis echinocarpa* Miq. In Duc Trong, *Quercus braianensis* A.Camus predominated, followed by *Craibidendron vietnamense* Judd, *Nyssa javanica* (Blume) Wangerin, and *Lithocarpus silvicolarum* (Hance) Chun (Table 2). The number of individuals of *T. wallichiana* in the sample plots in the study areas was not high. However, these individuals had a rather large DBH and height, so they appeared as an ecologically significant species in the vegetation community.

Table 1. Abiotic characteristics of the habitat of *Taxus wallichiana* in South Vietnam

Regions	Duc Trong	Don Duong	Lac Duong	Entire region
Soil type	Grey-brown feralite	Pale yellow feralite	Red yellow feralite	
The thickness of the soil layer (m)	> 0.8	> 0.8	0.3-0.4	> 0.3
Slope (°)	10-30	15-20	15-25	10-30
Mixed stone rate (%)	20	20	< 20	< 20
Supreme temperature (°C)	26	27	27	27
Lowest temperature (°C)	5	5	5	5
Average annual temperature (°C)	17.5	20	18	18.5
Average annual humidity (%)	85	80	83.5	83
Average annual rainfall (mm)	1600	1820	1800	1740

Table 2. Species with the highest Important Value Index (IV%) in the habitat of *Taxus wallichiana* in South Vietnam

Don Duong		Lac Duong		Duc Trong	
Species	**IV%**	**Species**	**IV%**	**Species**	**IV%**
Syzygium wightianum	14.57	*Pinus kesiya*	17.63	*Quercus braianensis*	13.16
Rhodoleia championii	9.86	*Schima superba*	11.38	*Craibidendron vietnamense*	12.52
Schima superba	9.76	*Castanopsis echinocarpa*	8.15	*Nyssa javanica*	8.67
Taxus wallichiana	7.16	*Lithocarpus truncatus*	7.24	*Lithocarpus silvicolarum*	7.25
52 other species	58.65	*Taxus wallichiana*	5.82	*Taxus wallichiana*	6.19
		71 other species	49.78	60 other species	52.21

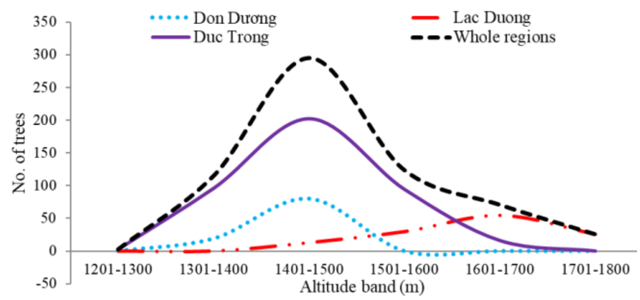

Figure 3. Distribution of *Taxus wallichiana* based on altitude

Table 3. Distribution of *Taxus wallichiana* based on area extent (ha)

Regions	Tree with DBH ≥ 25 cm	Tree with 6 cm ≤ DBH<25 cm
Don Duong	14.00±4.08	3.00±4.76
Lac Duong	32.67±18.15	2.67±4.62
Duc Trong	75.33±83.43	2.67±4.62
Remark	P-value<0.05	P-value>0.05

Distribution of T. wallichiana *based on area extent*

The total distribution area for *T. wallichiana* with DBH≥25 cm was about 379.57 ha. However, the distribution area in each region was statistically different (P-value<0.05). It spanned from 14.00±4.08 ha (Don Duong) to 75.33±83.43 ha (Duc Trong) (Table 3).

For trees with 6 cm≤DBH<25 cm, the total distribution area was 28.36 ha, and the distribution area was not significantly different across the study regions (P-value>0.05). The largest extent was in Don Duong (3.00±4.76 ha), while Lac Duong and Duc Trong were similar (2.67±4.62 ha) (Figure 2). The two populations of *T. wallichiana* in Don Duong and Duc Trong are distributed closer together than in Lac Duong. Moreover, in these two regions, the distribution of *T. wallichiana* is more concentrated than that in Lac Duong (Figure 2). The distribution area between trees with DBH≥25 cm and 6 cm≤DBH<25 cm had statistical differences (P-value<0.05). The results of the analysis showed that *T. wallichiana* was distributed in clusters.

Distribution of T. wallichiana *based on altitude*

The trees of *T. wallichiana* were found from 1276 m to 1750 m above sea level (Figure 3), but the number of trees spread across altitudinal ranges differed. The pattern of distribution of trees by altitude in the Don Duong and Duc Trong areas was not significantly different.

In general, the number of trees rose at low altitudes, peaked at 1401-1500 m, then reduced at 1501-1600 m, except for the Lac Duong region, which peaked at 1601-1700 m and decreased at 1701-1800 m (Figure 3). The whole area data analysis showed that the number of individuals increased at 1201-1300 m, peaked at 1401-1500 m, and decreased at 1501-1600 m. Based on this result, the management strategy of *T. wallichiana* should prioritize conservation in the elevation range of 1401-1500 m (Figure 3), besides additional planting measures and promoting natural regeneration.

Distribution of T. wallichiana *based on forest vegetation type*

Most *T. wallichiana* trees were found in the mixed broadleaved-coniferous forest (Figure 4). This species was distributed in the dominant ecological layer, joining the grouping with *Nageia* sp., *Pinus kremfii* Lecomte, *P. imbricatus*, *P. neriifolius*, *Dacrydium* sp., *Magnolia* sp., *Garcinia* sp., *Cinnamomum* sp., *Schima* sp., *Syzygium* sp., and *Rhododendron* sp.

The plant likes light and moisture but needs shade to germinate and develop in the early years. In general, the mixed broadleaf-coniferous forest is the most suitable place for the growth and development of *T. wallichiana*. These results might be useful for proposing silvicultural solutions; for example, forest restoration and restocking of *T. wallichiana* can be conducted under the forest canopy to conserve and enhance the population of this species.

Stand structure and characteristics

Stand structure of trees with DBH ≥ 25 cm

The density of *T. wallichiana* trees with DBH>25 cm was very low, and there was no significant difference across the three regions (P-value>0.05). It ranged from 2.00±1.00 (trees/ha) in Lac Duong to 3.00±2.16 (trees/ha) in Don Duong. On the other hand, the growth size in terms of DBH and overall height (Hvn) were both high, and there was a substantial difference among the regions (P-value<0.05). Specifically, the DBH ranged from 43.33±5.69 cm in Lac Duong to 76.67±11.02 cm in Duc Trong, while the Hvn ranged from 20.67±1.16 m (Lac Duong) to 22.67±2.52 m (Duc Trong). The tree volume per hectare was low, ranging from 3.67±4.04 (m^3/ha) (Lac Duong) to 11.33±2.08 (m^3/ha) (Duc Trong), and there was a statistically significant difference between these regions (P-value<0.05) (Table 4). Although the DBH and Hvn values were high, (V) was low due to low tree density. Thus, at Duc Trong, *T. wallichiana* grows and develops best. Therefore, this region should be prioritized for protecting and selecting seedlings for species restoration.

Stand struture of T. wallichiana *trees with 6 cm ≤ DBH<25 cm*

The density of *T. wallichiana trees* with 6 cm ≤ DBH<25 cm ranged from 1.33±0.58 (trees/ha) in Lac Duong to 4.25±4.27 (trees/ha) in Don Duong, and there was no difference between regions (P-value>0.05). ANOVA analysis for DBH, Hvn, and V showed a statistically considerable difference among the three regions (P-value<0.05). The DBH ranged from 10.07±0.35 cm (Lac Duong) to 15.00±1.26 cm (Duc Trong), while the highest Hvn was at Duc Trong (10.50±2.14 m), and the lowest was Don Duong (8.00±1.00 m); and the volume, ranged from 0.06±0.03 (m^3/ha) (Lac Duong) to 0.19±0.08 (m^3/ha) (Duc Trong) (Table 5).

Correlation between overall height (Hvn) and diameter at breast height DBH

We employed polynomial, power, linear, and exponential functions to select the appropriate function to predict the correlation between Hvn and DBH (Table 6). The analysis showed that the exponential function was the most suitable to predict the Hvn growth DBH parameter with R^2 = 0.42 and P-value<0.5.

Quality of mature trees

Overall, the quality across the three regions varied from good to medium to bad, with 40.85%, 38.49%, and 20.66%, respectively. This pattern was similar to that in Duc Trong (30.44%, 21.29%, and 13.09%, respectively) and slightly different in Don Duong and Lac Duong (Figure 5).

Regeneration status of *T. wallichiana*

The density of regenerating trees

A total of 7673 regenerating trees were recorded in the three regions, with the largest number of individuals found in Lac Duong (2038.00±1440.95 trees) and the lowest number in Duc Trong (89.67±15.57 trees). However, there was no statistically significant difference in the number of regenerating trees in these three regions (P-value>0.5). The regenerating trees were distributed over an area of about 379.57 ha, and there was a significant difference among the regions (P-value<0.05), which ranged from 14.00±4.08 ha (Don Duong) to 84.67±99.22 ha (Duc Trong). The comparison among the three areas showed that the regeneration density differed (P-value<0.05). Specifically, the density of regenerating trees was low in Don Duong, with 11.50±3.70 (trees/ha) and high in Duc Trong, with 18.33±2.89 (trees/ha) (Table 7). The tree likes light and moisture but needs shade to germinate and develop in the early years. As such, regenerating trees have a narrow distribution, small number, and low density, which increases the risk of extinction caused by the increasing human impacts on forest resources.

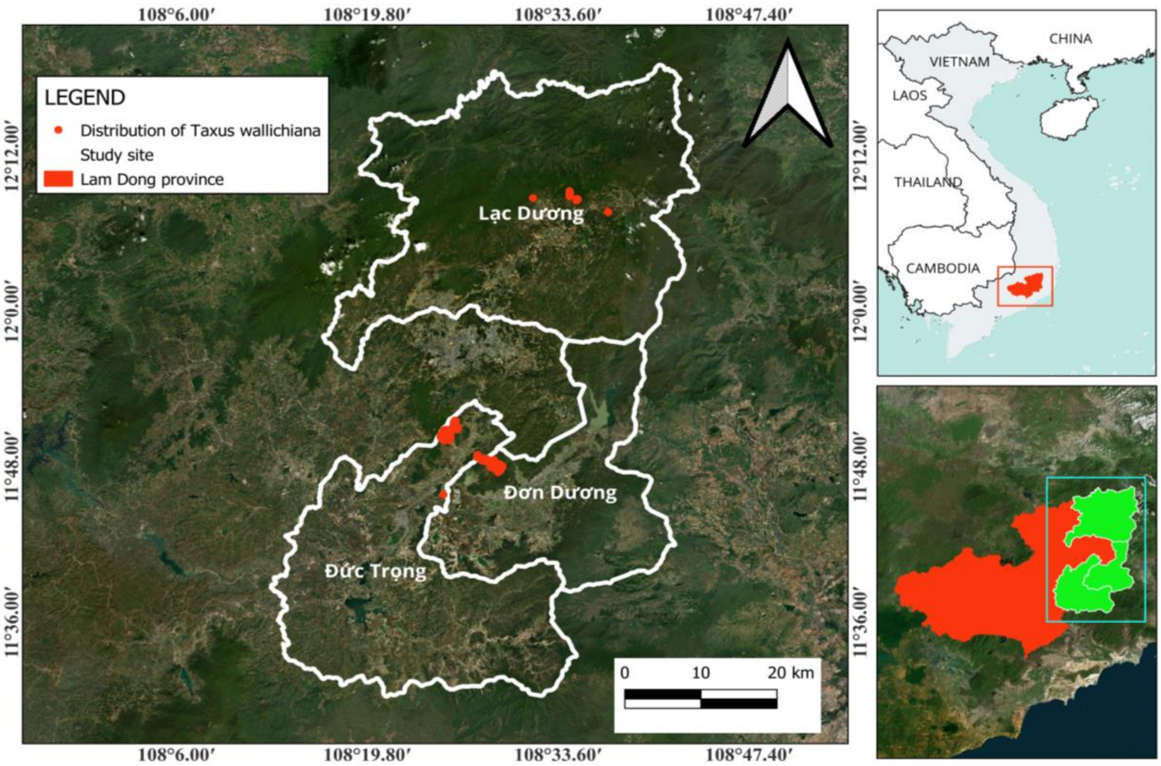

Figure 2. Distribution map of *Taxus wallichiana* in Don Duong, Lac Duong and Duc Trong Districts, Lam Dong Province, South Vietnam

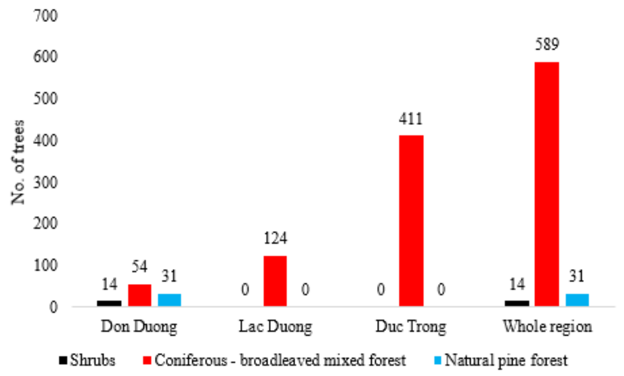

Figure 4. The abundance of *Taxus wallichiana* based on forest vegetation type

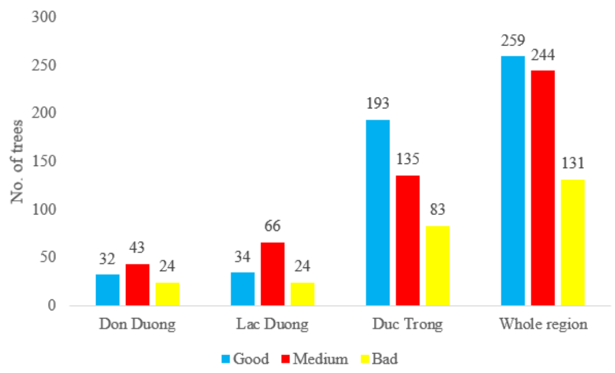

Figure 5. Quality of mature trees of *Taxus wallichiana*

Table 4. Stand struture of *Taxus wallichiana* with DBH ≥ 25 cm

Regions	D±SD (tree/ha)	DBH±SD (cm)	Hvn±SD (m)	V±SD (m^3/ha)
Don Duong	3.00±2.16	60.75±14.71	18.50±1.00	6.00±2.71
Lac Duong	2.00±1.00	43.33±5.69	20.67±1.16	3.67±4.04
Duc Trong	2.33±0.58	76.67±11.02	22.67±2.52	11.33±2.08
Remark	P-value>0.05	P-value<0.05	P-value<0.05	P-value<0.05

Note: D: Density (tree/ha); N: Number of the tree; V: Volume (m^3/ha); SD: Std. Deviation

Table 5. Stand struture of *Taxus wallichiana* with 6 cm ≤ DBH<25 cm

Regions	D±SD (tree/ha)	DBH±SD (cm)	Hvn±SD (m)	V±SD (m^3/ha)
Don Duong	4.25±4.27	12.58±0.48	8.00±1.00	0.10±0.05
Lac Duong	1.33±0.58	10.07±0.35	9.67±1.45	0.06±0.03
Duc Trong	3.00±3.46	15.00±1.26	10.50±2.14	0.19±0.08
Remark	P-value>0.05	P-value<0.05	P-value<0.05	P-value<0.05

Note: D: Density (tree/ha), V: Volume (m^3/ha); SD: Std. Deviation

Table 6. Correlation analysis between overall height (Hvn) and diameter at breast height (DBH) of *Taxus wallichiana*

Function	Don Duong	Lac Duong	Duc Trong	Entire regions
Polynomial	$H_{vn} = -0.04(DBH)^2 + 4.47(DBH) - 7.56$ ($R^2 = 0.32$)	$H_{vn} = 0.35(DBH)^2 - 10.37(DBH)+104.29$ ($R^2 = 0.53$)	$H_{vn} = 0.16(DBH)^2 - 2.88(DBH) + 51.00$ ($R^2 = 0.38$)	$H_{vn} =0.20(DBH)^2 - 4.36(DBH) + 60.23$ ($R^2 = 0.41$)
Power	$H_{vn} = 4.64(DBH)^{0.85}$ ($R^2 = 0.35$)	$H_{vn} = 0.50(DBH)^{1.46}$ ($R^2 = 0.50$)	$H_{vn} = 1.57(DBH)^{1.19}$ ($R^2 = 0.37$)	$H_{vn}=1.07(DBH)^{1.29}$ ($R^2 = 0.38$)
Linear	$H_{vn}=2.81(DBH) + 7.18$ ($R^2 = 0.31$)	$H_{vn}=3.65(DBH)-31.07$ ($R^2 = 0.45$)	$H_{vn}=4.22(DBH)-24.06$ ($R^2 = 0.36$)	$H_{vn}=4.34(DBH)-31.08$ ($R^2 = 0.37$)
Exponenial	$H_{vn} = 21.83e^{0.05(DBH)}$ ($R^2 = 0.35$)	$H_{vn} = 8.01e^{0.08(DBH)}$ ($R^2 = 0.54$)	$H_{vn} = 16.45e^{0.06(DBH)}$ ($R^2 = 0.40$)	$H_{vn}=13.40e^{0.07(DBH)}$ ($R^2 = 0.42$)
Remark	$H_{vn} = 21.83e^{0.05(DBH)}$ ($R^2 = 0.35$)	$H_{vn} = 8.01e^{0.08(DBH)}$ ($R^2 = 0.54$)	$H_{vn} = 16.45e^{0.06(DBH)}$ ($R^2 = 0.40$)	$H_{vn}=13.40e^{0.07(DBH)}$ ($R^2 = 0.42$)

Table 7. Regeneration status of *Taxus wallichiana*

Regions	A±SD (ha)	N±SD (tree)	D±SD (tree/ha)
Don Duong	14.00±4.08	322.50±125.80	11.50±3.70
Lac Duong	32.67±18.15	2038.00±1440.95	15.00±10.39
Duc Trong	84.67±99.22	89.67±15.57	18.33±2.89
Remark	P-value<0.05	P-value>0.05	P-value<0.05

Note: A: Area (ha); N: Number of trees (tree); D: Density (tree/ha); SD: Std. Deviation

Table 8. The density of *Taxus wallichiana* based on height level

Height level/regions	Don Duong D±SD (tree/ha)	Lac Duong D±SD (tree/ha)	Duc Trong D±SD (tree/ha)	Conclusion
<0.5 (m)	7.25±6.55	6.33±4.93	9.00±1.00	P-value>0.05
0.6-1.0 (m)	2.25±1.71	4.33±2.08	4.67±1.53	P-value>0.05
1.1-1.5 (m)	0.50±1.00	1.67±1.53	1.67 ±1.53	P-value>0.05
1.6-2.0 (m)	1.25 ±1.26	0.33±0.58	1.67 ±2.08	P-value>0.05
2.1-3.0 (m)	-	1.67±2.08	1.00±1.00	P-value>0.05
3.1-5.0 (m)	0.25±0.50	0.67±1.16	0.33±0.58	P-value>0.05
<6 (m)	4.00±0.25	-	-	
Whole height level	1.68±0.50	2.14±1.48	2.62±0.41	P-value>0.05

Note: D: Density (tree/ha); SD: Std. Deviation; P-value>0.05: no statistically significant difference

Height level of regenerating trees

The height levels of regenerating trees were not substantially different among the three regions (P-value>0.05). The tree density decreased as the height level increased, with the highest density found at a height of <0.5 m and the lowest at a height of <6 m. This indicated that the regeneration ability of the species was low, especially for the individuals with height levels >6 m (Table 8). Regenerating trees appeared in sites with little litter, ground herbs, and gaps with plenty of light. This can be a suggestion to propose solutions to improve regeneration capacity in the study regions.

Discussion

Taxus wallichiana (Himalaya Yew) is an endangered native species distributed in some subtropical regions in South Vietnam with high humidity and strongly dissected terrain. In Bidoup-Nui Ba National Park, Vietnam, under the canopy of *T. wallichiana* populations, there were many broad-leaved trees typical of humid subtropical Fagaceae, Lauraceae, and Magnoliaceae forests. In addition, plants indicating high humidity, such as *Illicium griffithii* Hook.fil. & Thomson, *Rhododendron* sp., ferns, mosses, and orchid species were found (Brum 2019). In North Vietnam, *T. wallichiana* is distributed in mixed evergreen broadleaved-coniferous forests on rocky terrain, belonging to the dominant ecological stratum (A2), where there are tree species from the genera *Pterocarpus* Jacq., *Syzygium* Gaertn., *Cinnamomum* Schaeff., *Acer* L., *Nageia* Gaertn., and the Fagaceae family (Trung 2014). Species co-occurring with *T. wallichiana* observed in Central Nepal were *Lyonia ovalifolia* (Wall.) Drude, *Daphniphyllum himalayense* (Benth.) Müll.Arg., *Rhododendron arboretum* Sm., *Symplocos ramosissima* Wall., *Quercus semecarpifolia* Sm., *Lindera pulcherrima* (Nees) Benth., *Eurya cerasifolia* (D.Don) Kobuski, *Mahonia nepalensis* DC. ex Dippel, *Viburnum erubescens* Wall., *Litsea cubeba* (Lour.) Pers. (Shreshta 2018). *T. wallichiana* was distributed at a depth of litter ranging from 3.2 to 32 cm, where the soil pH ranged from 4.84 to 6.48, indicating the soil's acidic property (Shreshta 2018).

The species grows in mixed broad-leaved and coniferous forests, on red-brown to red-yellow basalt soils, pH 4.08 to 4.56, in the midland terrain of the mountainside where it was difficult to follow the ravines, streams with exposed rocks, stand forests with 2-3 forest canopy layers (Hung and Nghia 2011). It occurs with an average monthly temperature of 21°C, rainfall of 135.3 mm, humidity of 80%, and number of sunny hours of 194 hours (Hung and Nghia 2011) and slope ranges of 10°-45º, consistent with the results of the present study. While in Northwestern Himalaya, the observed slope ranges from 10º-60º (Pant and Samant 2008).

In this study, *T. wallichiana* was found to have a narrow distribution in the alpine subtropical forest belt, where the altitude ranged from 1200 m to 1800 m above sea level. Previous studies have shown this species has a wide ecological range from tropical to temperate regions, with altitudes from 900 m to 3800 m asl (Gajurel et al. 2014a; Dissanayake et al. 2023). In Bidoup Nui Ba National Park, Vietnam, these populations were narrowly distributed based on altitude (100 m) between 1400-1500 m asl, with a soil layer thickness of 20-40 cm (Brum 2019). Hung and Nghia (2011) found that it was distributed at elevations from 1298-1770 m, where adult populations and regenerating individuals predominate. The study conducted by Trung (2014) in North Vietnam found it at a lower altitude than that in South Vietnam.

Moreover, the amplitude of variation in altitude is also narrower than that of South Vietnam (1178-1300 m against 1200-1800 m). This result was quite similar to the altitude range that *T. wallichiana* distributes in Central Nepal, where the range of elevation variation was 300 m (2200-2500 m) (Shreshta 2018). Some reports in Asia have also shown that this plant species was distributed at higher altitudes than in South Vietnam. In India, it is distributed in the temperate and subalpine zones of the Himalayan region between 1800-3300 m asl in the hills of Meghalaya and Manipur (Nazir et al. 2020). In comparison, Nimasow et al. (2016) found it in the humid temperate regions of the Eastern Himalayas at altitude distribution range from 1600 to 2700 m asl. Yousaf et al. (2022) found in different parts of Pakistan's Abbottabad, Mansehra, Tor Ghar, and Battagram Districts, between altitude ranges from 2100 to 3400 m. In Nepal, this species is found in the wild between 2200-3800 m asl, mainly at 2600 m (Gajurel et al. 2014a). When modeling the distribution of *T. wallichiana* based on climate variables, Gajurel et al. (2014b) also revealed that the most suitable altitudinal range was between 2600-3000 m als, where most populations are recorded (Table 9). These statistics show significant differences in the elevation pattern of *T. wallichiana* between the present study and other regions of Asia. Caused by geographical latitudes, there are differences in climatic conditions between regions: Vietnam belongs to the equatorial region characterized by a tropical monsoon climate, where this species is distributed with subtropical characteristics, while other ecoregions belong to temperate climates. Furthermore, this species grows and develops mainly in temperate biomes (Plants of the World Online 2022).

Table 9. Comparison of elevation distribution of *Taxus wallichiana* in some locations across the world

Location	Elevation (m asl)	References
South Vietnam	**1200-1800**	***This study***
Da Lat, Vietnam	1298-1770	Hung and Nghia (2011)
Bidoup-Nui Ba, Vietnam	1400-1500	Brum (2019)
North Vietnam	1178-1300	Trung (2014)
Himalaya	900-3800	Gajurel et al. (2014a), Dissanayake et al. (2023)
Himalayan, India	1800-3300	Nazir et al. (2020)
Eastern Himalaya	1600-2700	Nimasow et al. (2016)
Himalaya	2100-3400	Yousaf et al. (2022)
Nepal	2200-3800	Gajurel et al. (2014a)
Nepal Himalaya	2600-3000	Gajurel et al. (2014b)
Central Nepal	2200-2500	Shreshta (2018)

Taxus wallichiana is rare in the wild. On the surveyed transect line, only two mature trees were recorded in Phia Oac-Phia Den National Park, North Vietnam (Trung 2014). Shreshta (2018) found that the population of *T. wallichiana* in Central Nepal with the number was less, ranging from 12-110 trees. At the same time, there were only 181 adults found in different parts of Pakistan's Abbottabad, Mansehra, Tor Ghar, and Battagram districts (Yousaf et al. 2022). Altogether, 812 individuals were recorded in the six valleys of the Nepal Himalayas (Gajurel et al. 2014b). The size class distribution of this species recorded in the plots based on the circumference at breast height suggested limited regeneration. Over 42% of *T. wallichiana* were around 90 cm in circumference. While nearly 18% were 71~90 cm, almost 11% were 51~70 cm, and almost 30% were 30.1~50 cm (Pant and Samant 2008).

Brum (2019) reported that *T. wallichiana* composes the main canopy layer (A1), and some individuals are in the adjacent layer (A2) following the vertical structure of the stand. Hung and Nghia (2011) reported that the logarithmic function was the most suitable to simulate the correlation between DBH and Hvn with the coefficient of determination $R^2 = 0.7383$ (P-value <0.5). Hung and Nghia (2011) have established a correlation equation to determine Hvn through DBH, applied to the whole regions as follows: y = -1.63831 + 8.4648 Ln (DBH) + 2.72973x' + 0.31215x' Ln (BH), for Ho Tien: Hvn = 1.09142 + 8,77696 Ln (DBH), and Nui Voi: Hvn = -1.63831 + 8.46481Ln (DBH).

The plant community composition consists of significant species such as *Cinnamomum* sp., *Lithocarpus* sp., *Castanopsis* sp., *Quercus* sp., *Magnolia* sp., *Syzygium* sp., *C. mannii, D. elatum, Keteleeria evelyniana* Mast. and *T. wallichiana* forming the dominant stratum of the forest (Hung and Nghia, 2011). It often occurs with subtropical plants such as *Abies pindrow* (Royle ex D.Don) Royle, *Q. semecarpifolia, Quercus floribunda* Lindl. ex A.Camus, *Quercus leucotrichophora* A.Camus, *Betula utilis* D.Don, *Acer caesium* Wall. ex Brandis, *Pinus wallichiana* A.B.Jacks., *R. arboretum* and *Betula alnoides* Buch.-Ham. ex D.Don (Singh and Singh 1992). In the Arunachal Himalaya, it was found in plant communities of broadleaf and gymnosperm species such as *Castanopsis* sp., *Cinnamomum* sp., *I. griffithii, Michelia* sp., *Quercus* sp., *Rhododendron arizelum* Balf.fil. & Forrest, *Abies* spp., *P. wallichiana*, etc. (Paul et al. 2013).

This study found that the population density of *T. wallichiana* (2-3 trees/ha) was lower than in previous studies in South Vietnam. Hung and Nghia (2011) found that the density ranged from 2.5-16 (trees/ha). At the same time, other study reports recorded density fluctuations from 16-64 trees/ha (Brum 2019). Studies in different locations in Asia have shown that the density of *T. wallichiana* is higher in South Vietnam. A report in a temperate mixed conifer forest of western Himalaya showed even lower densities of *T. wallichiana*, with 72 trees/ha and present under the canopy of *Picea smithiana* (Wall.) Boiss. (Uniyal 2013). The *T. wallichiana* population found in the Arunachal Himalaya had a density of 52 individuals per ha-1 with a baseline area of 15.21 m^2/ha (Paul et al. 2013). Yousaf et al. (2022) discovered that *T. wallichiana* was rarely distributed, with only 181 adults in different parts of Abbottabad, Mansehra, Tor Ghar and Battagram districts, Pakistan.

The natural regeneration of *T. wallichiana* was not uniform among the study sites. Hung and Nghia (2011) could not find regenerating trees in 2 of 5 surveyed sites. The absence can be caused by several factors, including seeds that have a dormant physiological period, seeding regeneration under the canopy not happening due to the thick layer of litter, the regeneration period falling in the dry season, invasion of *P. kesiya* (Hung and Nghia 2011). Brum (2019) confirmed that the regenerating trees of *T. wallichiana* have a low percentage in the species composition. The density of regenerating trees recorded in Bidoup-Nui Ba National Park ranged from 500 to 3000 trees/ha (Brum 2019). The study by Trung (2014) in North Vietnam showed that there were 2 of 15 locations where mature, regenerating trees were found. Only 1 of 15 sites recorded two regenerated individuals with a height of 3-3.5 cm, 2-3 m from the parent tree (Trung 2014). So, it regenerates poorly from seed. After the seeds fall in September - October, they remain dormant for almost eighteen months. It has also been observed that this species is sparsely distributed. Only one seedling was recorded, while no saplings were observed at the Arunachal Himalaya (Paul et al. 2013). Lander et al. (2010) reported that it grows very slowly, with poor natural regeneration mainly due to low seed yield and production rate. The effects of overuse and habitat degradation are exacerbated by the species' relative intolerance to fire, drought, and poor regeneration. Its habitat has also been degraded by deforestation and human land use (Samant et al. 1999). Brum (2019) has determined that the East and Southeast regions have a higher regeneration rate than others. Furthermore, canopy cover negatively correlates with the density and rate of regenerated trees (Brum 2019). Our study shows that light is an essential factor in the regeneration ability of *T. wallichiana*.

Brum (2019) reported the distribution of the number of regenerating trees by height class and showed agreement with the present study. This study found that regenerating trees at a height lower than 1 m accounted for the most significant proportion (26.19%) and gradually decreased at the higher height level due to competition for nutrient space with other species and shrub vegetation (Brum 2019). The *T. wallichiana* seedlings and saplings were in relatively low abundance compared to the other associated species of the communities. Its seedlings were not found in *A. pindrow-Cedrus deodara* (Lamb.) G.Don mixed, *A. pindrow*, and *Q. semecarpifolia* communities. Neither seedlings nor saplings were recorded in the *Q. semecarpifolia* community. The low abundance of *T. wallichiana* compared to other associated species indicates either a competitive disadvantage compared to other species, selective exploitation, poor regeneration from seed, or all three effects. Given this trend, the species may soon be extirpated from the sanctuary.

Through field investigation, the present study shows that illegal logging because of the economic value of this species is the most important cause of population size reduction. Besides, the unlawful collection of young trees for ornamental purposes by local people is the cause of the decrease in the number of regenerated trees (Brum 2019). The loss of forest habitat, where *T. wallichiana* is distributed, is caused by the encroachment of households on forest land for agricultural cultivation, such as tea, coffee, and pepper cultivation. The sanctions to curb illegal exploitation are insufficient to protect against the decrease in the habitat size of this endangered, precious, and rare plant species. There is a growing demand for wood, firewood, and medicinal purposes; illegal cutting and smuggling of trees and conversion of forests for farming lead to habitat loss and environmental degradation (Haq et al. 2022). Yousaf et al. (2022) argued that the cause of the decline in the population size of *T. wallichiana* was habitat loss due to human activities, such as mining, which reduce the occurrence and hinder the regeneration of species. Other threats include the exploitation for medicinal purposes for taxol extraction, fuelwood collection, timber used for shingles and climate change (Yousaf et al. 2022). Local communities' over-exploitation of tree bark and leaves for medicinal purposes and trampling by herbivores are essential causes of poor regeneration, especially at lower altitudes. In addition to human factors, natural factors also significantly affect the growth and development of regenerated plants. Therefore, developing and implementing protection laws, policies, and appropriate management is necessary to conserve and develop this plant species (Yousaf et al. 2022).

In conclusion, 614 mature and 7673 regenerating young trees of *T. wallichiana* were recorded in three locations in South Vietnam. The species distribution area was characterized by a monsoon climate with an average annual temperature, humidity, and rainfall of 18.5^{0}C, 83%, and 1740 mm, respectively. The species was distributed within about 379.57 ha, with the largest in Duc Trong and the smallest in Don Duong. The tree density was low, and no apparent difference existed between the studied regions. *T. wallichiana* was found in the mixed broadleaved-coniferous forest from 1276-1750 m, mostly at 1401-1500 m. Tree with DBH trees ≥25 cm had good dimensional growth in diameter and height. Still, they had low volume per hectare due to the low density, which showed significant differences between the three regions. Meanwhile, trees with 6 cm≤DBH<25 cm were scattered with low volume per hectare. The exponential function was the most suitable for forecasting Hvn through DBH. Most of the trees were of good and medium quality. The regeneration density was low, and there were significant regional differences. While there was no obvious difference in regeneration by height class, mainly at the low height level (<0.5 m), there was primarily a shortage of regenerative trees at the class of 3.1-6 m. The low number of mature and regenerated trees, low-density hectare, poor regeneration ability, lack of promising regenerative tree class, clustered distribution, and narrow range show that it may soon become extinct from its scope. In the future, the habitat of *T. wallichiana* populations will face drastic changes due to disturbances caused by human activities and climate change. Therefore, this species is difficult to spread and regenerate naturally. Only with solid habitat protection and supported species conservation programs can these species be sustained under climate change.

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