

Silvicultural characteristic of *Hopea ferrea* Pierre in tropical semi-deciduous forests of Phou Khao Khouay National Park, Laos

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Đặc điểm lâm học của loài Săng đào (*Hopea ferrea* Pierre) ở rừng nhiệt đới nửa rụng lá Vườn Quốc gia Phou Khao Khouay, Lào

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ABSTRACT

Hopea ferrea Pierre is a valuable timber species facing a high risk of extinction. This study investigates the stand structure and natural regeneration characteristics of *H. ferrea* in tropical semi-deciduous forests at Phou Khao Khouay National Park (PKNP), Laos. Data were collected from six sample plots (2,000 m² each) across various elevation zones. Results show that *H. ferrea* consistently contributes to the main stand composition with an Importance Value Index (IVI) \geq 5%, and even becomes a dominant species in certain areas (IVI up to 17.58%). The average stand density was 1,099 trees/ha, with an *H. ferrea* density of 121 trees/ha. The diameter and height distribution exhibited a decreasing, unimodal pattern, which was well fitted by Burr, Dagum, and Logarithmic functions. Natural regeneration of *H. ferrea* was not promising, with only average density of 69 seedlings/ha, predominantly of seed origin (over 90%), and of good quality. The high similarity (57–87%) in species composition between the regeneration layer and the main canopy indicates successful successional replacement. These findings underscore the conservation value of PKNP for this endangered species. Conservation measures, including in-situ preservation, silvicultural treatments, and assisted natural regeneration are recommended for the sustainable management and conservation of *H. ferrea* at PKNP.

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Từ khóa:

Cấu trúc lâm phần, *Hopea ferrea*, loài nguy cấp, tái sinh tự nhiên, Vườn Quốc gia Phou Khao Khouay.

TÓM TẮT

Săng đào (*Hopea ferrea** Pierre) là loài cây gỗ quý hiếm, đang đối mặt với nguy cơ tuyệt chủng cao. Nghiên cứu này nhằm xác định cấu trúc tổ thành và khả năng tái sinh tự nhiên của loài Săng đào tại Vườn Quốc gia Phou Khao Khouay, Lào. Số liệu được thu thập từ 6 ô tiêu chuẩn (2.000 m²/ô) ở các đai độ cao khác nhau. Kết quả cho thấy Săng đào luôn tham gia vào công thức tổ thành với Chỉ số giá trị quan trọng (IVI) \geq 5%, thậm chí trở thành loài ưu thế ở một số khu vực (IVI lên tới 17,58%). Mật độ lâm phần trung bình là 1.099 cây/ha, trong đó mật độ Săng đào là 121 cây/ha. Phân bố đường kính và chiều cao tuân theo dạng giảm dần, một đỉnh, được mô phỏng tốt bởi các hàm Burr, Dagum và Logarithmic. Tái sinh tự nhiên của Săng đào rất triển vọng với mật độ trung bình 69 cây/ha, chủ yếu có nguồn gốc từ hạt (trên 90%) và chất lượng tốt. Độ tương đồng cao (57-87%) về thành phần loài giữa tầng cây tái sinh và tầng cây cao cho thấy sự kế thừa loài thành công. Những phát hiện này khẳng định giá trị bảo tồn của VQG Phou Khao Khouay đối với loài nguy cấp này. Các biện pháp bảo tồn như bảo vệ nguyên vị, xử lý lâm sinh và hỗ trợ tái sinh tự nhiên được khuyến nghị để quản lý và bảo tồn bền vững loài Săng đào tại đây.

1. INTRODUCTION

H. ferrea, commonly known as Săng đào (in Vietnamese) or Khen hin (in Laotian), is a large evergreen tree species belonging to the Dipterocarpaceae family. It can reach heights of 20–35 m and diameters of over 80 cm, primarily growing in tropical broadleaf

evergreen and semi-deciduous forests at elevations below 700 m [1, 2]. The species is highly valued for its durable, termite-resistant timber, used in construction, shipbuilding, and high-quality furniture [3, 4]. However, due to overexploitation and habitat loss, *H. ferrea* is now classified as Endangered (EN) on the IUCN

Red List [5]. In Laos, *H. ferrea* is recognized as a rare, precious, and endangered forest plant species. It is listed in the Lao Red Book and protected under national legislation, including the Forestry Law (No. 06/NA, dated 24 December 2019) and relevant decrees from the Ministry of Agriculture and Forestry, which strictly regulate its harvest and trade.

In Laos, *H. ferrea* is naturally distributed across several forest types. Previous studies in various protected areas, such as the Cervus Eldii Conservation Area and Phu Xieng Thong National Park, reported its presence but not as a dominant species [6, 7]. At Phou Khao Khouay National Park (PKNP), recent surveys indicate a declining population of mature *H. ferrea* individuals and limited regeneration, raising concerns about its long-term survival [8]. However, detailed quantitative data on its population structure, regeneration dynamics, and specific ecological role within the forest community at PKNP are still lacking.

Understanding the silvicultural characteristics—such as stand structure, species composition, and regeneration dynamics—of where *H. ferrea* grows is crucial for developing effective conservation and management strategies. While some morphological and ecological studies on *H. ferrea* exist in neighbouring countries like Thailand and Vietnam [9, 10], comprehensive silvicultural research in Laos, particularly at PKNP, remains limited.

This study aims to: (1) Determine the structural characteristics of forest stands where *H. ferrea* is distributed; (2) Analyse the natural regeneration features of *H. ferrea*; and (3) Propose conservation and development solutions for the species at PKNP. The findings will provide a scientific basis for the sustainable management and conservation of this valuable species in Laos.

2. RESEARCH METHODS

2.1. Study Area

The study was conducted in Phou Khao

Khouay National Park (PKNP), established in 1993, located between 18°14'–18°32'N and 102°38'–102°59'E, covering 191,942 ha across four provinces in central Laos. The topography is mountainous, with elevations ranging from 250 to 1,666 m. The climate is characterized by a tropical monsoon, with a distinct wet season (May–October) and a dry season (November–April). The average annual rainfall is 1,450 mm, and the average temperature ranges from 15.6°C to 33.2°C [11]. The predominant forest type in the study area is tropical semi-deciduous forest.

2.2. Data Collection

Field surveys were conducted from September to October 2024. A total of six temporary sample plots (SPs), each 2,000 m² (50 m × 40 m), were established along two survey transects in areas where *H. ferrea* naturally occurs (Table 1, Fig. 1). Plots were distributed across two elevation zones based on the typical distribution range of *H. ferrea* (below 700 m) and to assess its potential adaptation at higher elevations (above 700 m). Specifically, three plots were situated below 700 m (SP1, SP2, SP3) and three plots above 700 m (SP4, SP5, SP6).

Within each SP, all trees with Diameter at Breast Height (DBH) ≥ 6 cm were identified using field guides and botanical references for Lao flora, and voucher specimens were collected for uncertain species and verified at the herbarium of the Department of Forestry, Laos, and their DBH, total height (H_{total}), and crown height (H_{bole}) were measured. Tree quality was assessed and classified as Good (A: straight bole, healthy crown, no damage by wind or disease), Medium (B: minor defects or lean), or Poor (C: significant defects, damage by wind or disease). Regeneration surveys were conducted on five 25 m² sub-plots within each SP. All woody seedlings (DBH < 6 cm) were identified, and their height, quality, and origin (seed or sprout) were recorded. Canopy cover was determined using a spherical densiometer at 100 systematically distributed points per SP.

Table 1. Distribution of sample plots in the study area

Location (District)	Forest Type	Transect	No. of SPs	Elevation Zone
Thaphabat (Bolikhamsay)	Tropical semi-deciduous	1	3	< 700 m
Xaythany (Vientiane)	Tropical semi-deciduous	2	3	> 700 m
Total		2	6	

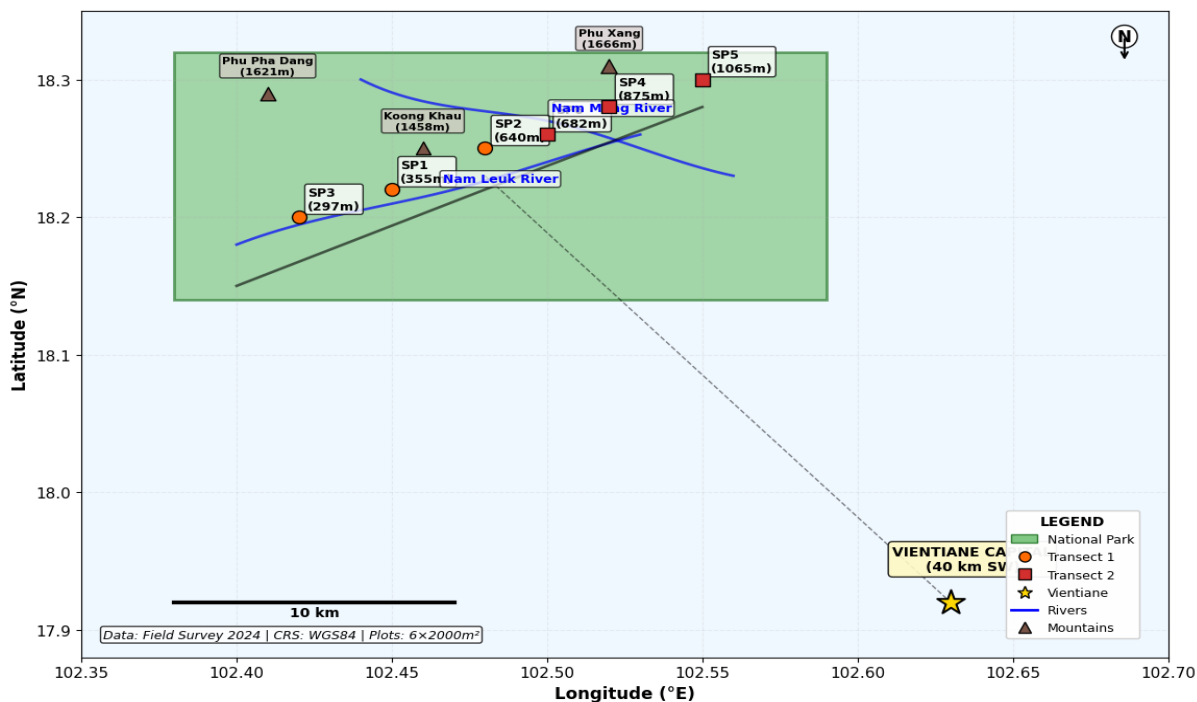


Figure 1. Study area – Phou Khao Khouay National Park with sample plot locations
(Map designed based on the current administrative and forest cover map of PKNP)

2.3. Data Analysis

Stand Structure: To quantify the ecological importance of each species within the forest community, the Importance Value Index (IVI) was calculated. This composite index synthesizes a species' relative abundance (density) and its relative dominance (basal area) in the stand [11]. The IVI for each species *i* was determined using the following formula (Marmillod, 1992):

(1) Relative Density (N_i%): This represents the proportion of individuals of a species relative to the total number of individuals in the sample plot.

$$N_i\% = (n_i / N) \times 100$$

Where,

n_i = number of individuals of species *i*;

N = total number of all individuals in the sample plot.

(2) Relative Basal Area (G_i%): This represents the proportion of the total cross-sectional area (a measure of dominance) accounted for by a species.

$$G_i\% = (g_i / G) \times 100$$

Where,

g_i = total basal area of species *i* (m²/ha);

G = total basal area of all species in the sample plot (m²/ha).

Basal area of a single tree was calculated as: $g = \pi \times (DBH)^2 / 4$ (with DBH in meters).

(3) Importance Value Index (IVI_i%): The IVI is the average of the Relative Density and Relative Basal Area. Its theoretical range is from 0 to 100%, and a higher value indicates a greater ecological importance of the species within the community.

$$IVI_i\% = (N_i\% + G_i\%) / 2$$

Species with an IVI ≥ 5% were considered significant contributors to the stand structure and were included in the species composition formula.

Species Diversity: Species richness (R), Shannon-Wiener index (H'), Simpson's dominance index (1-D), and Margalef index were calculated using PAST software [12].

Size-Class Distribution: The diameter (DBH) and height (H_{total}) distributions were analyzed by fitting 59 theoretical probability density functions using EasyFit Professional 5.6. The best-fit models were selected based on the Kolmogorov-Smirnov test (p > 0.05).

Regeneration: Regeneration density (seedlings/ha), species composition, quality, and origin were calculated. Species similarity between the regeneration layer and the main canopy was assessed using Sorensen's similarity index.

3. RESULTS AND DISCUSSION

3.1. Stand Structure and Composition

The general stand characteristics across the six SPs are summarized in Table 2. Stand density averaged 1099 trees/ha, ranging from 896 to 1292 trees/ha. The average basal area was 21.61 m²/ha and timber volume was 128.79 m³/ha. The average DBH and height were 17.46 cm and 11.98 m, respectively. Trees

of good and medium quality accounted for over 85% of the total. Forest stands at elevations above 700 m tended to have slightly higher average density (1,150 trees/ha) and basal area (23.01 m²/ha) compared to those below 700 m (1048 trees/ha and 20.20 m²/ha, respectively), but these differences were not statistically significant (t-test, $p > 0.05$).

Table 2. General stand characteristics across sample plots (mean \pm sd)

SP	Elevation Zone	Density (trees/ha)	H ^{total} (m)	DBH (cm)	G (m ² /ha)	Volume (m ³ /ha)	Quality Good-Med (%)
1	< 700 m	1,050	13.38 \pm 2.12	22.14 \pm 3.23	34.33 \pm 4.23	224.82 \pm 13.56	83.42 \pm 12.62
2	< 700 m	1,108	12.83 \pm 2.88	18.71 \pm 2.89	27.93 \pm 5.20	179.52 \pm 12.89	85.76 \pm 12.42
3	< 700 m	992	11.11 \pm 1.67	16.38 \pm 2.25	14.61 \pm 5.55	79.83 \pm 12.57	93.64 \pm 11.77
4	> 700 m	1,196	10.59 \pm 2.21	12.59 \pm 2.45	11.58 \pm 5.16	30.99 \pm 13.54	88.60 \pm 11.41
5	> 700 m	1,108	12.83 \pm 2.88	18.71 \pm 2.89	27.93 \pm 5.20	179.52 \pm 12.89	85.76 \pm 12.42
6	> 700 m	1,146	12.22 \pm 2.21	15.63 \pm 2.45	19.58 \pm 5.16	33.35 \pm 13.54	98.12 \pm 11.41
Mean		1,099	11.98 \pm 2.67	17.46 \pm 5.33	21.61 \pm 5.23	128.79 \pm 12.11	87.86 \pm 11.62

H^{total}: total height; DBH: diameter at breast height; G: basal area.

H. ferrea was present in the species composition formula of all SPs with IVI \geq 5% (Table 3). Its importance increased at higher

elevations (>700 m), where it became the dominant species in SP5 (IVI = 17.58%) and SP6 (IVI = 16.76%).

Table 3. Species composition (IVI \geq 5%) in sample plots

SP	Elevation (m)	Elevation Zone	Total Species	Species Composition Formula (IVI \geq 5%)
1	355	< 700 m	51	16.90Shob + 9.55Hofe + 8.10Diob + 7.38Xyxy + 58.07Others
2	640	< 700 m	56	13.19Dial + 11.63Hofe + 6.24Scwa + 5.42Crfo + 57.67Others
3	297	< 700 m	57	10.28Anco + 9.75Hofe + 7.32Anac + 5.56Fafr + 67.09Others
4	875	> 700 m	62	11.96Dial + 11.47Scwa + 8.51Hofe + 6.33Crfo + 56.99Others
5	1,065	> 700 m	54	17.58Hofe + 11.57Peda + 6.45Hood + 5.35Crfo + 58.87Others
6	682	> 700 m	48	16.76Hofe + 9.58Xyxy + 6.45Anac + 5.35Cyfr + 61.86Others

Species codes: Shob: *Shorea obtusa*; Hofe: *Hopea ferrea*; Diob: *Dipterocarpus obtusifolius*; Xyxy: *Xylia xylocarpa*; Dial: *Dipterocarpus alatus*; Scwa: *Schima wallichii*; Crfo: *Cratoxylum formosum*; Anco: *Anisoptera costata*; Anac: *Anogeissus acuminata*; Cyfr: *Cyrtophyllum fragrans* (syn. *Fagraea fragrans*); Peda: *Peltophorum dasyrhachis*; Hood: *Hopea odorata*.

3.2. Species Diversity

Table 4. Species diversity indices across sample plots

SP	Elevation Zone	Species Richness (R)	Simpson (1-D)	Shannon (H')	Margalef
1	< 700 m	5.20	0.96	3.86	14.22
2	< 700 m	5.18	0.96	3.85	13.96
3	< 700 m	5.12	0.96	3.91	13.91
4	> 700 m	5.01	0.96	3.86	13.79
5	> 700 m	4.60	0.95	3.70	12.43
6	> 700 m	4.70	0.95	3.74	12.54

The species diversity indices were relatively high and stable across SPs (Table 4), indicating rich and diverse plant communities. Species richness (R) ranged from 4.6 to 5.2, the Shannon index (H') from 3.70 to 3.91, and Simpson's index (1-D) from 0.95 to 0.96. Indices were slightly lower in the >700 m zone but the differences between elevation zones were not statistically significant (One-way ANOSIM, $p > 0.05$).

3.3. Diameter and Height Distribution

The diameter (DBH) distribution of the main stand showed a reverse J-shape, with a high concentration of trees in the smaller diameter classes (20–30 cm) and a gradual decrease towards larger classes (Fig. 2). This structure is typical of uneven-aged forests and indicates continuous regeneration [13]. The best-fit theoretical distributions for DBH were the Burr, Dagum, and Log-Logistic (3P) functions, as determined by the K-S test ($p > 0.05$). The

excellent fit of the Burr and Dagum distributions, which are known to model complex, skewed data, confirms the heterogeneous and uneven-aged nature of the stand, which is conducive to the continuous recruitment of *H. ferrea*. The selection of these functions was based on a systematic comparison of goodness-of-fit statistics (Kolmogorov-Smirnov and Anderson-Darling tests) for all 59 candidate functions in the EasyFit software. The Burr, Dagum, and Logarithmic functions consistently ranked highest across multiple plots.

The height distribution was unimodal or slightly bimodal, peaking in the medium height classes (17.5–20.5 m). The best-fit models were the Johnson SB, Pert, and Gumbel Min functions. The complex vertical structure suggests a multi-layered canopy, a common feature in tropical forests [14].

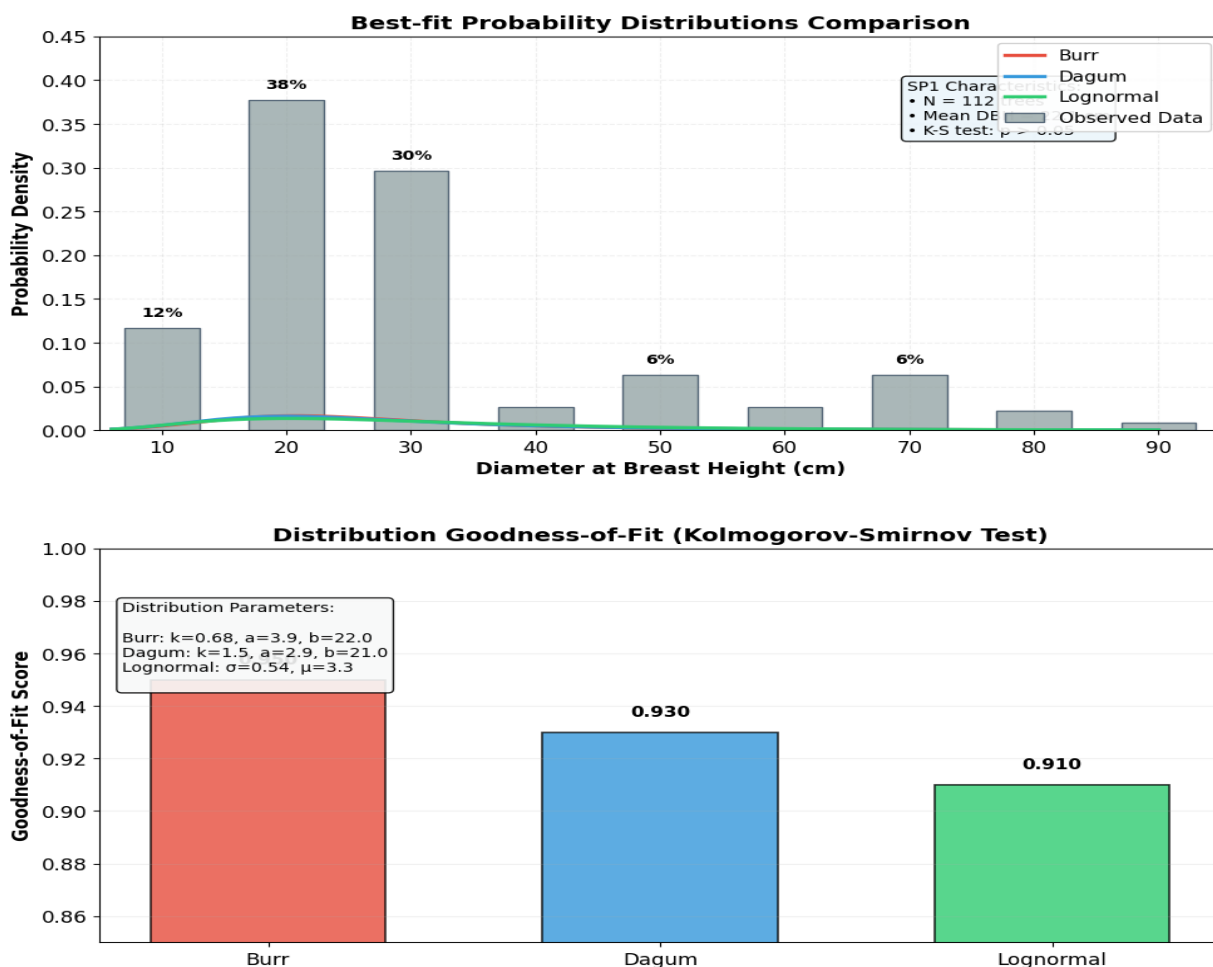


Figure 2. Diameter distribution modelling for sample plot

3.4. Natural Regeneration of *Hopea ferrea*

The regeneration of *H. ferrea* was promising (Table 5). Its average density was 69 seedlings/ha, and it appeared in the species composition formula of the regeneration layer in SP5 and SP6 (IVI \approx 0.6–0.7). The similarity index between the regeneration layer and the main canopy was high (57–87%), indicating successful species inheritance for the future stand. Most *H. ferrea* seedlings were of seed

origin (92.5% on average), which is favourable for long-term forest development as seed-origin trees generally have better form and longevity [15]. Seedling quality was predominantly good to medium (over 79%). Regeneration density and quality showed no clear trend between elevation zones (<700 m: 61 seedlings/ha, 77% Good-Medium; >700 m: 76 seedlings/ha, 81% Good-Medium).

Table 5. Regeneration characteristics of *H. ferrea* and general regeneration

SP	Elevation Zone	Density (seedlings/ha)		Quality (%)			Origin (%)	
		All Species	<i>H. ferrea</i>	Good	Medium	Poor	Sprout	Seed
1	< 700 m	3,600	58	37.9	42.4	19.7	3.6	96.4
2	< 700 m	2,965	78	32.4	49.1	18.5	9.7	90.3
3	< 700 m	4,019	47	36.8	46.6	16.6	4.9	95.1
4	> 700 m	3,781	61	32.7	42.9	24.5	7.1	92.9
5	> 700 m	4,628	86	23.1	53.9	23.0	9.4	90.6
6	> 700 m	3,917	81	37.1	42.0	20.9	6.8	93.2
Mean		3,818	69	33.0	46.3	20.7	7.5	92.5

3.5. Discussion

The results show that *H. ferrea* is a significant and sometimes dominant component of the tropical semi-deciduous forests at PKNP, particularly at elevations above 700 m. This contrasts with findings from southern Laos, where *H. ferrea* was not dominant [6, 7], suggesting that PKNP provides more favourable ecological conditions, possibly due to specific microclimates (e.g., higher humidity, reduced drought stress) or lower historical disturbance at higher elevations.

The stand structure, characterized by a reverse J-shaped diameter distribution and high species diversity indices, is indicative of a stable, uneven-aged, and regenerating forest community. The successful fit of complex distribution functions (Burr, Dagum) to the diameter data further confirms this structural complexity.

Natural regeneration of *H. ferrea* is viable, with satisfactory density, high seed origin, and good quality. The high species similarity between regeneration and canopy layers indicates a healthy successional trajectory.

However, the lower regeneration density compared to mature tree density suggests potential bottlenecks at later growth stages, warranting further investigation.

3.6. Conservation Implications and Recommendations

Based on the findings, the following conservation and management strategies are recommended for *H. ferrea* in PKNP:

In-situ Conservation: Strengthen the protection of the core zone of PKNP. Implement regular patrols and use geospatial tools (e.g., GIS) to monitor and manage individual *H. ferrea* trees, preventing illegal logging and habitat disturbance.

Silvicultural Treatments in the Buffer Zone: In areas where limited intervention is permitted, apply tending operations (e.g., liberation thinning) to reduce competition and favour the growth of high-quality *H. ferrea* saplings and poles. The study found that *H. ferrea* coexists well with species such as *Hopea odorata* and *Xylia xylocarpa*, which can be considered for enrichment planting programs.

Assisted Natural Regeneration (ANR): In the buffer and administrative service zones, implement ANR by controlling weeds and lianas that compete with *H. ferrea* seedlings. Our data on seedling quality and origin strongly support the implementation of ANR, particularly liana cutting and moderate canopy opening to 0.6–0.7 cover, to enhance light availability for the high-quality, seed-origin seedlings without causing excessive exposure.

4. CONCLUSION

This study provides the first comprehensive analysis of the silvicultural characteristics of *Hopea ferrea* in the tropical semi-deciduous forests of Phou Khao Khouay National Park, Laos. The key findings indicate that: *H. ferrea* is a significant component of the forest stands, with an Importance Value Index (IVI) consistently $\geq 5\%$, and acts as a dominant species in higher elevation areas. The stand structure is characteristic of uneven-aged, regenerating forests, with diameter and height distributions following a decreasing, single-peak pattern. Natural regeneration of *H. ferrea* is viable, with a satisfactory density of seedlings, predominantly of seed origin and of good to medium quality. The high species similarity between the regeneration layer and the main canopy indicates a positive outlook for the species' perpetuation.

Notably, this study establishes Phou Khao Khouay National Park as a vital stronghold for the endangered *H. ferrea*. The observed successful natural regeneration underscores the potential for its long-term recovery. To realize this potential, an integrated approach combining strict protection, targeted silvicultural interventions, and assisted natural regeneration is recommended.

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