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POPULATION STRUCTURE AND REGENERATION DYNAMICS OF *DALBERGIA LATIFOLIA* ROXB. IN PENINSULAR INDIA: IMPLICATIONS FOR CONSERVATION

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Dalbergia latifolia Roxb. (Indian Rosewood), a high-value tropical hardwood native to the Indian subcontinent, is increasingly threatened by habitat loss, overharvesting, and human disturbances. This study assessed population structure, regeneration dynamics, and the effects of anthropogenic pressures across Karnataka, Kerala, and Tamil Nadu. A total of 262 forest transects revealed pronounced regional differences. Karnataka exhibited high seedling density and mature trees but lacked intermediate-sized individuals, indicating recruitment bottlenecks. Kerala showed high basal area and biomass but poor regeneration due to sparse saplings and poles. Tamil Nadu displayed critically low regeneration, primarily caused by recurrent fires, grazing, and human encroachment. Human Disturbance Index values negatively correlated with regeneration success. These results highlight the urgent need for site-specific conservation strategies, including protection of mature trees, fire and invasive species management, and assisted natural regeneration, to safeguard *D. latifolia*, sustain ecosystem functions, and ensure its long-term viability across southern India.

Keyword: *Dalbergia latifolia*, regeneration, population structure, human disturbance index, conservation, biomass, habitat degradation, anthropogenic pressure, forest management

INTRODUCTION

Approximately 31% of the Earth's land surface is covered by forests, with nearly 45% of these located in tropical regions, together accounting for about 14% of the planet's terrestrial surface (FAO & UNEP 2020). Despite their relatively small area, tropical forests harbour immense biodiversity and include species of significant ecological, medicinal, and economic value (Sullivan et al. 2020). Among these, tropical dry forests make up roughly 42% of all tropical forests but are especially vulnerable to land-use change, agricultural expansion, and climate-related stressors (Miles et al. 2006, Portillo-Quintero & Sánchez-Azofeifa 2010, Siyum 2020). Globally, about 11.4% of closed-canopy tropical dry forests were lost between 2001 and 2020 (Miles et al. 2006). In India, tropical dry deciduous forests comprise around 27% of the country's forests, mainly spread across the peninsular regions. These ecosystems are vital for biodiversity conservation and rural livelihoods but face increasing threats from fragmentation, overharvesting, and degradation (Reddy et al. 2016, Forest Survey of India 2023).

Dalbergia latifolia Roxb. (Indian rosewood; family: Fabaceae) is an important native tree species of Peninsular India, valued for both its ecological role and high-quality timber. It naturally occurs across the Western Ghats and neighbouring dry regions, thriving in tropical dry deciduous, moist deciduous, and semi-evergreen forests. Known for its durable and attractive wood, the species has been extensively exploited over many decades. Due to ongoing habitat degradation and unsustainable harvesting, *D. latifolia* is classified as Vulnerable on the IUCN Red List (first assessed in 1998; latest assessment on 1 August 2020, Criteria A1cd), a status that remains unchanged, and as Near Threatened within India (IUCN 2018). While populations remain relatively stable in parts of Karnataka, Kerala, and Tamil Nadu, *D. latifolia* continues to face increasing threats. In addition to historical overexploitation, modern challenges such as habitat loss, wildfires, grazing, invasive species, and climate change threaten its long-term survival. A comprehensive understanding of these interconnected threats is essential for guiding conservation efforts and ensuring sustainable management of the species.

The regeneration of *D. latifolia* varies considerably across India's climatic zones, with environmental factors playing a crucial role in seedling establishment, survival, and growth. Chave et al. (2014) developed widely used pan-tropical allometric models to estimate aboveground biomass and carbon sequestration potential in tropical trees, emphasising the ecological significance of *D. latifolia* in climate mitigation efforts. Historically, Kadambi (1954) highlighted the importance of species-specific silvicultural knowledge for developing effective regeneration strategies, especially in the context of overexploitation and habitat degradation.

Despite these pioneering contributions, significant gaps remain in understanding the population dynamics and regeneration ecology of *D. latifolia*, especially in Peninsular India. Studies in Southeast Asia have stressed the importance of examining regeneration patterns of native tree species to support restoration and conservation efforts. Notably, Nelson & Noweg (2021) identified key timber species exhibiting strong natural regeneration in disturbed primary forests of Sarawak, highlighting the ecological significance of site-specific regeneration data for informed reforestation planning. This study aims to address these knowledge gaps by analyzing the population structure and regeneration status of *D. latifolia* within the tropical dry forests of Karnataka, Kerala, and Tamil Nadu.

MATERIALS AND METHODS

Study Area

The study was conducted from 2019 to 2023 across 24 sites, including forest divisions, tiger reserves (TRs), and wildlife sanctuaries (WLSs) in the peninsular Indian states of Karnataka, Kerala, and Tamil Nadu. The study area spans a latitudinal range from 8°00'N to 15°30'N and a longitudinal range from 74°00'E to 78°30'E (Figure 1). These regions feature diverse tropical forest types, such as dry and moist deciduous and semi-evergreen ecosystems. Many are situated within globally recognised biodiversity hotspots like the Western Ghats and Eastern Ghats. The climate is subtropical monsoon with four distinct seasons: winter (January–February), summer (March–May), southwest monsoon (June–September), and post-monsoon (October–December). Annual rainfall varies from around 600 mm in inland dry zones to over 3,600 mm along the western escarpments. Elevation ranges from 378 to 1,168 metres above sea level, supporting various forest structures and microclimates that influence species distribution and regeneration. The sites include both Reserve Forests (RFs), which experience varying degrees of human disturbance, and Protected Areas such as Wildlife Sanctuaries and Tiger Reserves under stricter conservation management. This diversity allows a comparative assessment of *D. latifolia* across a gradient from disturbance to protection. Table 1 summarises the key ecological features (e.g., forest type, elevation, and mean annual rainfall) of the selected sites across the three states.

Site Selection

Forest divisions and protected areas were selected based on historical occurrence records and herbarium specimens of *D. latifolia*. These specimens were examined at the Botanical Survey of India (Coimbatore and Dehradun), the French Institute of Pondicherry, and the JCB Herbarium at the Indian Institute of Science (IISc), Bengaluru. Furthermore, digitised herbarium databases and relevant floristic literature were consulted, including The Flora of Karnataka (Saldanha 1984), The Flora of the Presidency of Madras (Gamble 1915–1936), Forest Flora of the Bombay Presidency and Sind (Talbot 1909–1911), district floras such as Hassan (Saldanha & Nicolson 1976), and official Working Plans and Management Plans of forest divisions and protected areas.

Survey Design

Within each selected forest division, one beat per section was randomly chosen for sampling. Fieldwork was carried out across multiple sites within each state, not limited to a single locality per state. A total of 192 transects in Karnataka, 42 in Kerala, and 28 in Tamil Nadu were surveyed. Each transect measured 1 km in length, following the method of Gentry (1988), which is well-suited for assessing tropical tree species with clumped distributions. Along each transect, ten 10 m × 10 m quadrats were established at 100-metre intervals, placed alternately on either side of the line to improve spatial coverage and reduce edge effects (Figure 2). In total, over 3,550 sampling points were established across Karnataka (2,779), Kerala (479), and Tamil Nadu (292) (Figure 1).

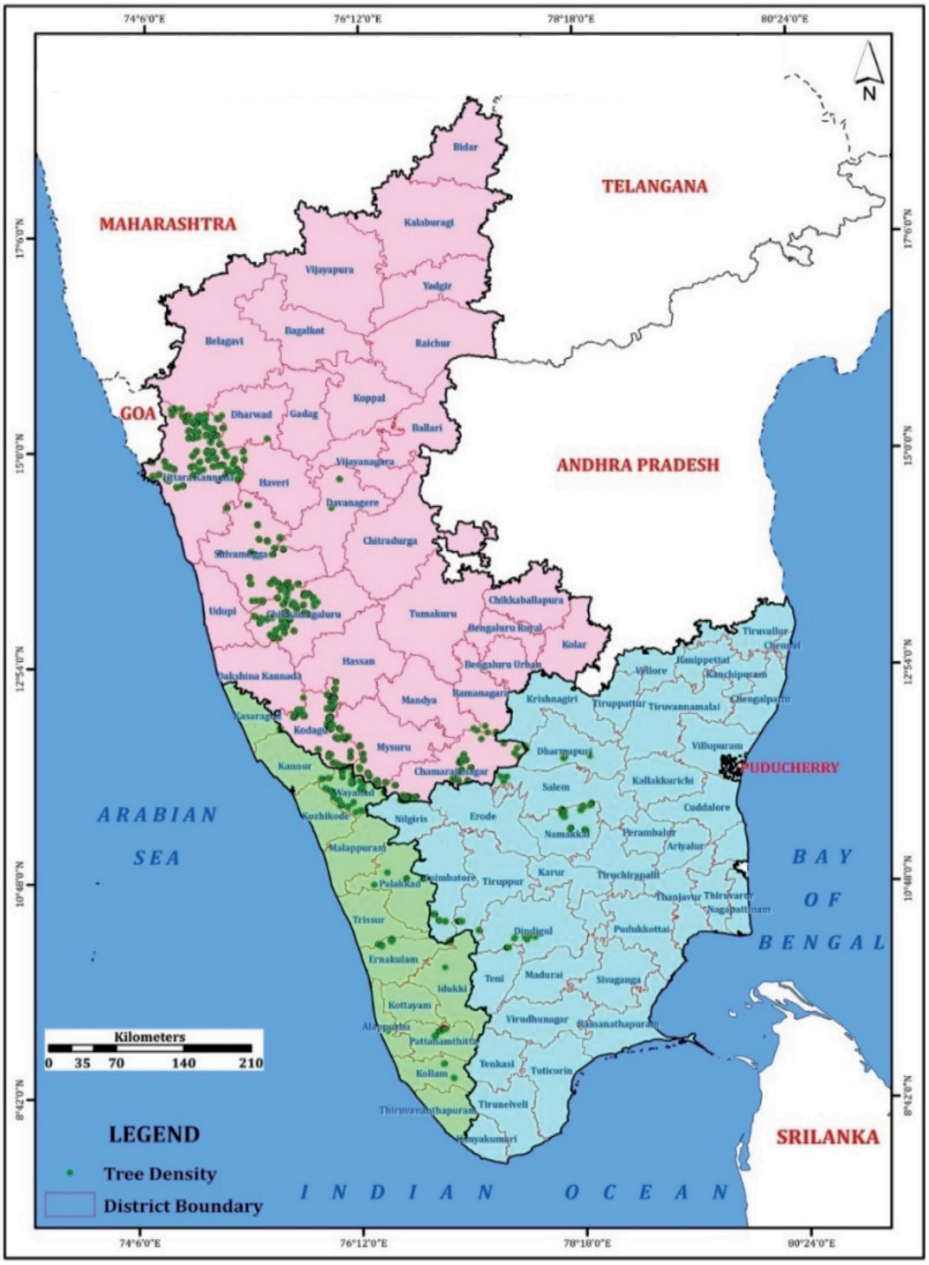

Figure 1 Survey locations within the Forest Circles of Karnataka, Kerala and Tamil Nadu

Table 1 Ecological characteristics of selected forest divisions and protected areas in Karnataka, Kerala, and Tamil Nadu

State	Sl. No.	Location	Elevation (m)	Rainfall (mm)	Forest Type
Karnataka	1	Haliyal Forest Division	578	1328	Tropical dry deciduous
	2	Yellapur Forest Division	599	1153	Tropical mixed deciduous
	3	Karwar Forest Division	378	2983	Dry deciduous
	4	Koppa Forest Division	668	1301	Semi-evergreen & moist deciduous
	5	Madikeri Forest Division	773	2693	Mainly deciduous & moist deciduous
	6	Virajpet Forest Division	906	2878	Tropical wet & semi-evergreen
	7	Shimoga Forest Division	654	2400	Dry & moist deciduous

State	Sl. No.	Location	Elevation (m)	Rainfall (mm)	Forest Type
	8	Sagara Forest Division	669	2450	Dry deciduous
	9	Bhadra Tiger Reserve	713	2600	Tropical mixed deciduous
	10	Cauvery Wildlife Sanctuary	564	2100	Wet & semi-evergreen
	11	Bandipur National Park	953	2050	Dry deciduous
	12	Nagarahole National Park	785	2300	Dry & moist deciduous
	13	Biligiriranganatha Swamy Temple Tiger Reserve	1168	1362	Moist deciduous & semi-evergreen
Kerala	14	South Wayanad Forest Division	2100	2400	Moist deciduous
	15	Punalur Forest Division	1100	1400	Tropical dry deciduous
	16	North Wayanad Forest Division	2100	2000	Moist deciduous
	17	Palakkad Forest Division	2000	1800	Evergreen, moist deciduous, dry deciduous
	18	Ranni Forest Division	2100	2800	Moist deciduous & wet evergreen
	19	Wayanad Wildlife Sanctuary	2000	2200	Moist deciduous
	20	Parambikulam Tiger Reserve	1438	1600	Semi-evergreen, moist deciduous, dry deciduous, and shola
Tamil Nadu	21	Pollachi Forest Division	2400	1200	Evergreen, moist deciduous, and dry deciduous
	22	Dharmapuri Forest Division	1100	1100	Tropical dry deciduous
	23	Salem Forest Division	1700	980	Mixed dry deciduous & scrub
	24	Annamalai Tiger Reserve	2695	1200	Semi-evergreen, moist deciduous, and shola forests

Field Data Collection

Within each quadrat, all individuals of *D. latifolia* were counted and classified into three size categories based on Girth at Breast Height (GBH):

Seedlings: GBH < 10 cm; Poles: GBH 10–30 cm; Trees: GBH > 30 cm

GBH measurements were converted to Diameter at Breast Height (DBH) using the formula:

$DBH = GBH / \pi$, where $\pi = 3.143$.

For each individual, tree height, GBH, and geographic location were recorded using a Garmin Montana® 680 GPS unit (software version 4.20), with a positional accuracy of approximately 3–5 metres. Data management was performed with Garmin Base Camp™ software. Additionally, all associated woody species were documented in each quadrat to analyse species composition and community structure.

In addition to quantitative measurements, qualitative field observations were documented during surveys, including girth measurement procedures, evidence of cattle browsing, and fire-affected forest patches, to characterise site-level disturbance conditions (Figure 3).

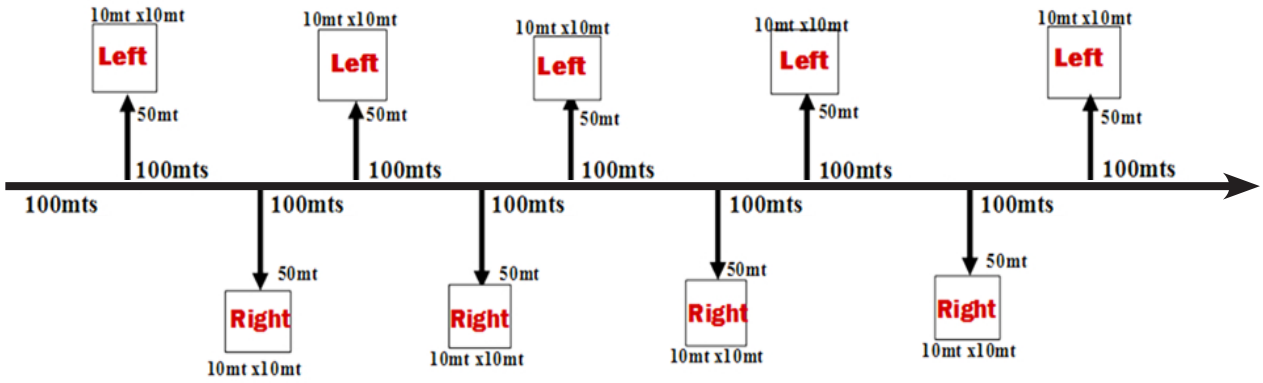

Figure 2 Schematic diagram of the line transects employed in the study

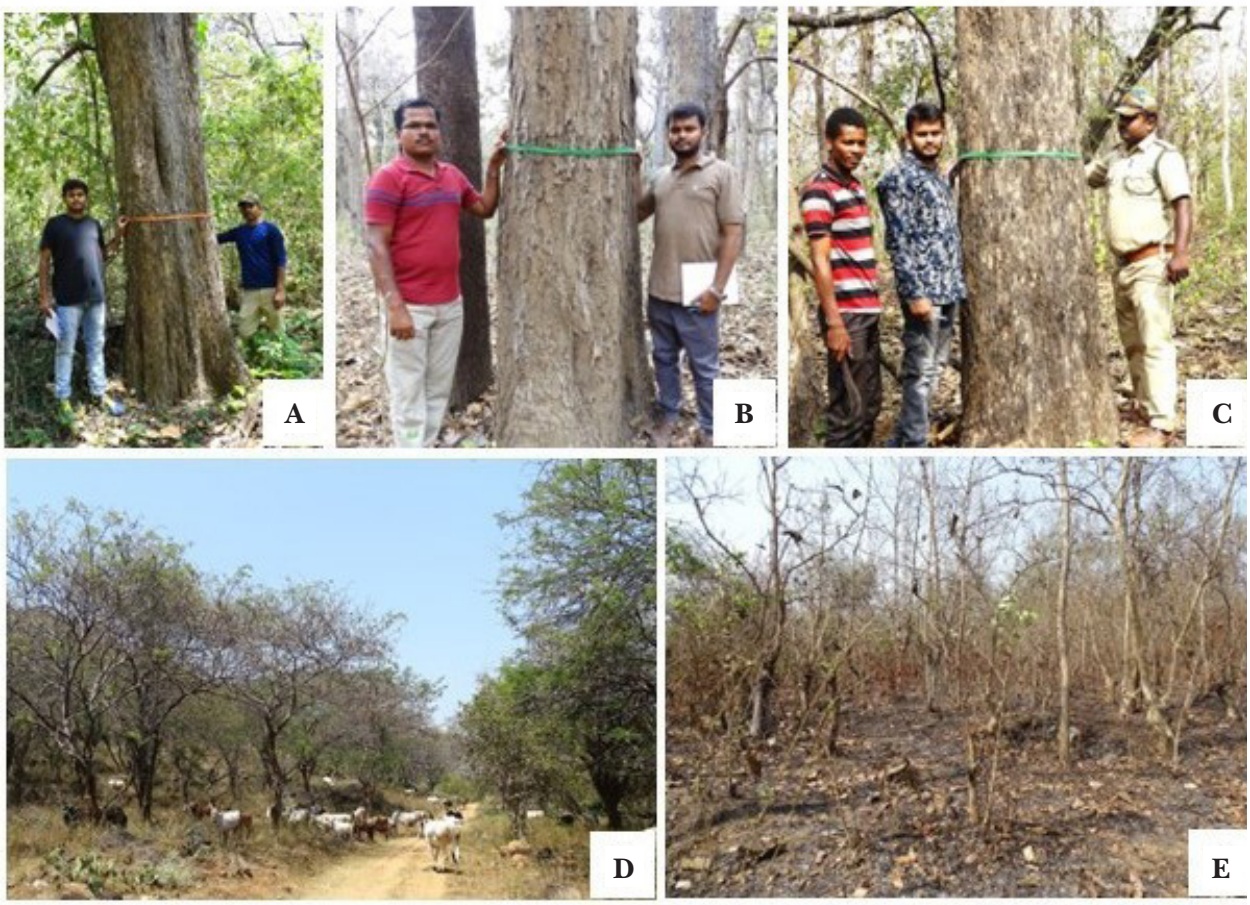

Figure 3 Field observations from the *Dalbergia latifolia* population survey: A–C. Girth measurement of *D. latifolia* trees: D. Cattle browsing within the forest: E. Forest area affected by fire (burnt site).

Identification of regeneration origin

Regeneration was classified as either seed-originated or vegetative (root suckers). Root suckers were distinguished by their thicker basal stems, their close clustering around mature trees, and visible root connections, and confirmed by consultation with forest staff and local ecological knowledge. When uncertain, individuals were conservatively considered seed-originated to prevent overestimating vegetative regeneration.

Human disturbance index (HDI) assessment

To evaluate human impact across forest divisions, a Human Disturbance Index (HDI) was developed using six key indicators: browsing by domestic or wild animals, human trails, cattle paths, stem cutting, fire events, and proximity to human settlements. Each indicator was scored from 0 (no disturbance) to 10 (severe disturbance). The total score (maximum of 60) was then divided by 60 to normalise it, producing an HDI value ranging from 0 to 1. This combined index facilitated comparisons of disturbance levels across different regions and forest types.

Statistical analysis

All quantitative data were analysed using PAST (v4.13), IBM SPSS Statistics (v22.0), and Microsoft Excel 2019. Population density (individuals/ha), basal area (m^2/ha), and biomass were calculated using standard forestry formulas. Proportions of regeneration categories were utilised to assess population structure.

To compare variables across forest categories (RFs vs. WLS/TRs), Welch's t-test was used due to unequal sample sizes and variances. One-way ANOVA was applied to identify differences in tree densities across states. The Kolmogorov–Smirnov (K–S) test was employed to compare the distribution of individuals across DBH size classes, both within and between forest types. Spearman's rank correlation was utilised to assess the relationship between basal area and biomass. Although the number of transects varied between forest divisions, all groups included more than 30 observations, ensuring statistical robustness.

Taxonomic validation

All scientific names of plant species, including *D. latifolia*, were cross-checked with the World Flora Online database (https://worldfloraonline.org/) to ensure consistency with accepted botanical nomenclature.

RESULTS

Size class distribution analysis

The size-class distribution of *D. latifolia* across Karnataka, Kerala, and Tamil Nadu was analysed to assess regeneration status and population structure in different ecological settings. Girth at breast height (GBH) was the key measurement used to evaluate population structure, and the results (Figure 4) show significant regional differences, reflecting varying regeneration dynamics across the study sites. These patterns suggest that some populations may face limited

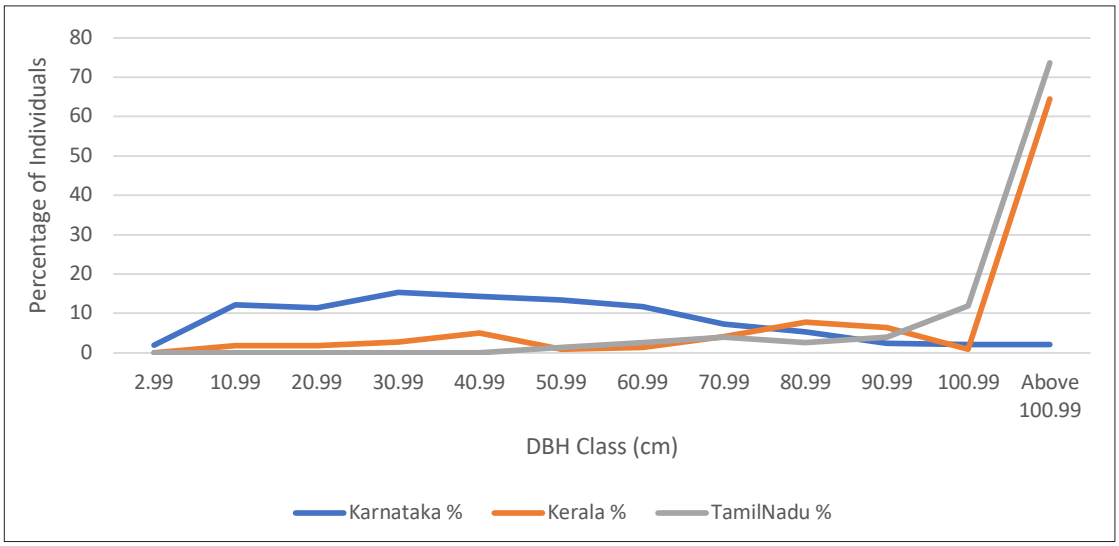

Figure 4 Comparison of diameter class distribution (%) of *Dalbergia latifolia* in Karnataka, Kerala, and Tamil Nadu

recruitment or skewed age-class distributions, emphasising the importance of site-specific management strategies to promote sustainable regeneration of *D. latifolia*. In Karnataka and Kerala, approximately 20% of individuals fell into the <10 cm GBH category, indicating ongoing recruitment and healthy regeneration. In contrast, only 5% of individuals in Tamil Nadu belonged to this category, indicating limited regeneration potential in that region. In Kerala, a high proportion of mature trees was observed, with 86% of individuals in the >100.99 cm GBH class. Tamil Nadu, however, had a concentration in intermediate GBH classes (70.99–100.99 cm), comprising nearly 64% of individuals. Karnataka exhibited a more balanced population structure, with significant representation in both intermediate and larger GBH classes (>30 cm), suggesting a well-established and actively regenerating population.

Stratification by forest management type (e.g., Reserve Forests versus Wildlife Sanctuaries/Tiger Reserves) further revealed differing regeneration outcomes. Reserve Forests (RFs) generally exhibited a higher proportion of younger girth classes, indicating active regeneration. In contrast, Wildlife Sanctuaries and Tiger Reserves (WLS/TRs) displayed a greater concentration of mature trees and limited presence in early GBH classes (<10 cm), suggesting potential regeneration constraints—possibly due to ecological pressures such as herbivory, competition, or microclimatic conditions.

Despite regional and site-specific differences in size-class proportions, statistical analysis using the Kolmogorov–Smirnov (KS) test showed no significant variation in the overall distribution patterns across the three states ($D = 0.1666$, $p = 0.98$). This indicates that although absolute frequencies and localised trends fluctuate, the broader population structure of *D. latifolia* remains consistent with a reverse J-shaped distribution—highlighting the species' inherent regenerative potential, although influenced by local environmental conditions and forest management practices.

Kolmogorov–Smirnov test for population distribution

To assess regional variations in the population distribution patterns of *D. latifolia* across Karnataka, Kerala, and Tamil Nadu, the two-sample Kolmogorov–Smirnov (KS) test was employed. This non-parametric test compares the cumulative distribution functions (CDFs) of two samples to determine if they come from the same distribution. The Kolmogorov–Smirnov (KS) test statistic is defined as:

$$D = \sup_x |F_1(x) - F_2(x)|$$

where $F_1(x)$ and $F_2(x)$ represent the empirical distribution functions (EDFs) of the two samples being compared, and D is the maximum absolute difference between them.

All KS tests were conducted using PAST software (version 4.13). The distribution of trees across size classes (based on GBH) in each state was used for comparison. In Karnataka and Kerala, both the Welch's t-test and KS test revealed no significant differences in tree distribution ($t = 0.0377$, $p = 0.97029$; $D = 0.5$, $p = 0.0656$). Conversely, a significant difference in population distribution was observed between Karnataka and Tamil Nadu ($D = 0.6667$, $p = 0.0046$), as well as between Kerala and Tamil Nadu ($D = 0.6667$, $p = 0.0046$), although the t-test between Kerala and Tamil Nadu did not indicate a difference in mean number of trees ($t = 2.2978 \times 10^{-11}$, $p = 1$).

These results emphasise regional differences in the structure and spatial distribution of *D. latifolia*, particularly between Tamil Nadu and the other two states, despite similarities in overall size class trends.

Distribution of life forms across forest divisions in Karnataka, Kerala, and Tamil Nadu Karnataka

Table 2 shows the distribution of *D. latifolia* across different life stages: seedlings, poles, and mature trees: in various forest divisions of Karnataka. The data highlight significant differences in the composition of these life forms across the regions. The Madikeri Forest Division recorded the highest number of seedlings (468), indicating strong regeneration potential. Conversely, the Yellapur Forest Division had the highest number of mature trees (200), reflecting a well-established mature population. These results emphasise the diverse regeneration patterns and demographic structures of *D. latifolia* in Karnataka, with Madikeri favouring early growth stages and Yellapur maintaining a stable mature tree population.

Table 2 Distribution of *Dalbergia latifolia* life forms across various Forest Divisions and Protected Areas in Karnataka

Life Forms	Madikeri Forest Division	Virajpete Forest Division	Haliyal Forest Division	Yellapur Forest Division	Shimoga Forest Division	Sagara Forest Division	Koppa Forest Division	Karwar Forest Division	Bhadra Tiger Reserve	Bandipura Tiger Reserve	Nagarahole Tiger Reserve	B R T Tiger Reserve	Cauvery Wildlife Sanctuary
Seedlings (<10 cm)	468	6	36	3	0	0	1	12	32	0	0	1	0
Poles (10-30 cm)	6	0	16	3	7	7	7	0	4	0	5	1	0
Trees (>30 cm)	267	11	174	200	18	40	80	17	104	39	72	67	1

Kerala

Table 3 shows the distribution of *D. latifolia* life forms across Kerala's forest divisions and protected areas. Seedlings are the most common in most surveyed regions, especially in the South Wayanad Forest Division, which recorded 187 seedlings. However, there is a notable lack of poles throughout the state, indicating a gap in the development from seedling to pole-sized trees. Higher densities of mature trees in North Wayanad and Palakkad Forest Divisions suggest stable older populations. The scarcity of poles highlights a critical bottleneck in regeneration, which could threaten the long-term sustainability of the population.

Tamil Nadu

Table 4 illustrates the distribution of *D. latifolia* across forest divisions in Tamil Nadu. Seedlings were found in all divisions, with Dharmapuri Forest Division showing the highest number (5 seedlings). Notably, poles were entirely absent in all surveyed areas, underscoring a significant barrier to progression beyond the seedling stage. Mature trees were present in every division, with Salem Forest Division exhibiting the highest density (26 mature trees). The absence of poles raises concerns about regeneration issues potentially driven by human activities such as grazing, fire, or invasive species.

Ecological and distributional comparison of *D. latifolia* in Karnataka, Kerala, and Tamil Nadu

Table 5 presents a comparative overview of the forest structure and biomass of *D. latifolia* in Karnataka, Kerala, and Tamil Nadu, based on parameters such as abundance, basal area, and biomass. Karnataka recorded the highest number of transects (192), followed by Kerala (42) and Tamil Nadu (28), highlighting variations in survey effort.

Table 3 Distribution of *Dalbergia latifolia* life forms across various forest fivisions and Protected Areas of Kerala

Life forms	South Wayanad Forest Division	Punalur Forest Division	Wayanad Forest Division	North Forest Division	Palakkad Forest Division	Ranni Forest Division	Parambikulam Tiger Reserve
Seedlings (<10 cm)	187	24	2	24	2	4	1
Poles (10-30 cm)	3	0	0	2	0	0	0
Trees (>30 cm)	108	7	8	32	26	20	15

Table 4 Distribution of *Dalbergia latifolia* life forms across various forest divisions and Protected Areas in Tamil Nadu

Life forms	Coimbatore Forest Division	Pollachi Forest Division	Dharmapuri Forest Division	Salem Forest Division
Seedlings <10 cm	0	3	5	3
Poles (10-30 cm)	0	0	0	0
Trees >30 cm	8	8	20	26

Table 5 Forest structure and biomass of *Dalbergia latifolia* across Karnataka, Kerala, and Tamil Nadu.

State	Number of Transects	Total Abundance (per hectare)	Basal Area (m^2/ha)	Biomass (tons/ha)
Karnataka	192	61.96	10.812 ± 8.314	101.28 ± 59.36
Kerala	42	53.80	40.706 ± 9.890	208.72 ± 127.44
Tamil Nadu	28	28.51	9.181 ± 8.076	45.63 ± 34.31

In terms of abundance, Karnataka led with 61.96 individuals per hectare, followed by Kerala (53.80) and Tamil Nadu (28.51). This indicates a higher density of *D. latifolia* in Karnataka. However, Kerala exhibited the highest basal area (40.706 ± 9.890 m^2/ha), suggesting a denser forest with larger trees, which also contributed to its superior biomass values. In contrast, Tamil Nadu recorded the lowest basal area (9.181 ± 8.076 m^2/ha), reflecting potential ecological challenges. In summary, while Karnataka has greater tree abundance, Kerala's forest structure and productivity seem more robust.

Natural regeneration

Table 6 outlines the regeneration mechanisms of *D. latifolia* across the three states, highlighting seed-based and sucker-based regeneration. In Karnataka, 94.27% of seedlings (527) came from seeds, with only 5.72% (32) from root suckers. Likewise, Kerala showed 93.03% seed-based regeneration (227 seedlings) and 6.96% via suckers (17 seedlings). In Tamil Nadu, regeneration was solely seed-based, with no sucker regeneration observed (29 seedlings).

This predominance of seed-based regeneration, along with the presence of mature individuals, indicates potential for natural recovery. However, the regeneration process remains vulnerable to threats such as competition from invasive species like *Lantana camara* and *Chromolaena odorata*. Overall, the current regeneration pattern fosters optimism for long-term population stability.

Table 6 Regeneration pattern of *Dalbergia latifolia* across various Forest Divisions in Karnataka, Kerala, and Tamil Nadu

Forest Divisions	Seedlings through Seeds	Seedlings through Suckers
Karnataka	527 (94.27%)	32 (5.72%)
Kerala	227 (93.03%)	17 (6.96%)
Tamil Nadu	29 (100%)	0

Associate species distribution

Table 7 shows the occurrence and distribution of species associated with *D.latifolia* in Karnataka. *T.elliptica* was the most common, found in 7 forest divisions and 37 transects (22.69%). Other frequently recorded species include *T. arjuna* (11.04%) and *T. paniculata* (9.82%). Less common associates such as *Adina cordifolia*, *Holoptelea integrifolia*, and *Albizia amara* also add to the overall biodiversity, though with lower presence.

Table 7 Occurrence and distribution of associate species of *Dalbergia latifolia* across forest divisions and ranges in Karnataka

Species	Number of Forest Divisions	Number of Transects	% Occurrence
Terminalia elliptica Willd.	7	37	22.69
Terminalia arjuna (Roxb. ex DC.) Wight & Arn.	4	18	11.04
Terminalia paniculata B. Heyne ex Roth	3	16	9.82
Adina cordifolia (Roxb.) Brandis	2	12	7.36
Holoptelea integrifolia (Roxb.) Planch.	2	10	6.06
Albizia amara (Roxb.) Boivin	1	8	4.91
Terminalia chebula Retz.	1	8	4.91
Hardwickia binata Roxb.	2	7	4.29
Lagerstroemia microcarpa Wight	2	7	4.29
Tectona grandis L.f.	2	7	4.29
Grewia tiliifolia Vahl	1	6	3.68
Tabernaemontana dichotoma Roxb. ex Wall.	1	5	3.06
Butea monosperma (Lam.) Kuntze	1	4	2.45

Species	Number of Forest Divisions	Number of Transects	% Occurrence
Terminalia anogeissiana Gere & Boatwr.	1	3	1.84
Artocarpus lacucha Roxb. ex Buch.-Ham.	1	3	1.84
Melia dubia Cav.	1	3	1.84
Limonia acidissima L.	1	3	1.84
Hydnocarpus pentandrus (Buch.-Ham) Oken	1	2	1.23
Pterocarpus marsupium Roxb.	1	2	1.23
Sapindus trifoliatus L.	1	2	1.23

Table 8 illustrates the distribution of associated species in Kerala. *T. elliptica* again dominates, recorded in 5 divisions and 12 transects (28.57%). Other key species include *T. paniculata* (14.29%) and *T. arjuna* (11.90%). Less common species, such as *D. sissoides* and *Cinnamomum verum*, emphasise the diversity and complexity of Kerala's Forest ecosystems.

Table 9 presents data on associated species in Tamil Nadu. *T. elliptica* and *T. paniculata* are the most prevalent, each occurring in 4 divisions and 9 transects (24.32%). *T. arjuna* has an occurrence rate of 18.91%. Several species, such as *A. lebbeck* and *Ailanthus excelsa*, are recorded in only one division, reflecting their localised distribution.

Table 10 provides a comparative overview of the occurrence of associate species across Karnataka, Kerala, and Tamil Nadu. Species such as *T. elliptica* and *T. paniculata* are found in all three states, although with varying levels of prevalence. Some species, like *Ailanthus excelsa* and *A. lebbeck*, are exclusive to Tamil Nadu, whereas others, such as *Hardwickia binata*, are unique to Karnataka. This cross-state comparison emphasises the diverse ecological dynamics and species compositions across the regions.

Table 8 Occurrence and distribution of associate species of *Dalbergia latifolia* across forest divisions and ranges in Kerala

Species	Number of Forest Divisions	Number of Transects	% Occurrence
Terminalia elliptica Willd.	5	12	28.57
Terminalia paniculata B. Heyne ex Roth	4	6	14.29
Terminalia arjuna (Roxb. ex DC.) Wight & Arn.	3	5	11.90
Terminalia chebula Retz.	3	4	9.52
Artocarpus lacucha Roxb. ex Buch.-Ham.	3	3	7.14
Albizia amara (Roxb.) Boivin	2	2	4.76
Dysoxylum malabaricum Bedd. ex Hiern	2	2	4.76
Lagerstroemia microcarpa Wight	2	2	4.76
Adina cordifolia (Roxb.) Brandis	1	1	2.38
Cinnamomum verum J.Presl	1	1	2.38
Dalbergia sissoides Wight & Arn.	1	1	2.38
Grewia tiliifolia Vahl	1	1	2.38
Pterocarpus marsupium Roxb.	1	1	2.38
Terminalia anogeissiana Gere & Boatwr.	1	1	2.38

Table 9 Occurrence and distribution of associate species of *Dalbergia latifolia* across Forest Divisions and Ranges in Tamil Nadu

Species	Number of Forest Divisions	Number of Transects	% Occurrence
Terminalia elliptica Willd.	4	9	24.32
Terminalia paniculata B. Heyne ex Roth	3	9	24.32
Terminalia arjuna (Roxb. ex DC.) Wight & Arn.	3	7	18.91
Terminalia chebula Retz.	2	4	10.81
Terminalia bellirica (Gaertn.) Roxb.	2	2	5.41
Pterocarpus marsupium Roxb.	2	2	5.41
Santalum album L.	2	2	5.41
Albizia lebbeck (L.) Benth.	1	1	2.70
Ailanthus excelsa Roxb.	1	1	2.70

Table 10 Distribution and percentage occurrence of associate species of *Dalbergia latifolia* across Karnataka, Kerala, and Tamil Nadu

Species	Karnataka (%)	Kerala (%)	Tamilnadu (%)
Adina cordifolia (Roxb.) Brandis	7.36	2.38	-
Ailanthus excelsa Roxb.	-	-	2.70
Albizia lebbeck (L.) Benth.	-	-	2.70
Albizia amara (Roxb.) Boiv.	4.91	4.76	-
Artocarpus lacucha Buch.-Ham.	1.84	7.14	-
Butea monosperma (Lam.) Taub.	2.45	-	-
Cinnamomum verum J.Presl	-	2.38	-
Dalbergia sissoides Graham ex Wight & Arn.	-	2.38	-
Dysoxylum malabaricum Bedd. ex C.DC	-	4.76	-
Grewia tiliifolia Vahl	3.68	2.38	-
Hardwickia binata Roxb.	4.29		-
Holoptelea integrifolia (Roxb.) Planch.	6.06	-	-
Hydnocarpus wightianus Blume	1.23	-	-
Lagerstroemia microcarpa Wight	4.29	4.76	-
Limonia acidissima L.	1.84	-	-
Melia dubia Cav.	1.84	-	-
Pterocarpus marsupium Roxburgh	1.23	2.38	5.41
Santalum album L.	-	-	5.41
Sapindus emarginatus Vahl	1.23	-	-
Tabernaemontana dichotoma Roxb. ex Wall.	3.06	-	-
Tectona grandis L.f.	4.29	-	-
Terminalia anogeissiana Gere & Boatwr.	1.84	2.38	-
Terminalia arjuna (Roxb.) Wight & Arn.	11.04	11.90	18.91
Terminalia bellirica (Gaertn.) Roxb.	-	-	5.41
Terminalia chebula Retz.	4.91	9.52	10.81
Terminalia crenulata Roth	22.69	28.57	24.32
Terminalia paniculata Roth	9.82	14.29	24.32

Analysis of the human disturbance index (HDI)

Fire regimes raried strongly across states, with higher annual fire incidence associated with reduced regeneration sucess (Table 11). Table 12 shows the Human Disturbance Index (HDI) for forest divisions across Karnataka, Kerala, and Tamil Nadu. HDI was calculated by assessing six factors: browsing, human paths, cattle paths, stem cutting, fire incidence, and proximity to settlements. Each factor was scored from 0 to 10, then summed and normalised to a 0–1 scale.

In Karnataka, divisions such as Haliyal (0.62) and Cauvery WLS (0.63) experienced high disturbance levels, mainly caused by grazing and human activity. Protected areas like Bhadra TR (0.13) and Biligiri Ranganatha Swamy Temple TR (BRT) (0.15) showed lower disturbance levels, indicating effective conservation.

In Kerala, South Wayanad (0.22) and Punalur (0.13) recorded low HDI values. Parambikulam TR had the lowest HDI (0.12), indicating minimal human interference. Wayanad WLS showed moderate disturbance (0.28).

In Tamil Nadu, Dharmapuri and Salem experienced the highest disturbance levels (0.47 each), mainly due to grazing and proximity to settlements. Coimbatore (0.35) and Pollachi (0.38) showed moderate disturbance levels.

Overall, Karnataka exhibited higher HDI values, while Kerala showed the least disturbance. Tamil Nadu displayed a mixed pattern. HDI findings highlight the importance of targeted conservation strategies in high-impact regions and ongoing protection in well-preserved areas.

Table 11 State-wise summary of fire impact on regeneration

State	Annual Fire Incidents (Latest Season)	Regeneration Impact on *D. latifolia*
Karnataka	~5,500 fires; ~3,793 km² area burned	High seedling and sapling mortality; dominance of mature trees
Tamil Nadu	3,380 incidents	Widespread seedling loss; lack of pole-sized individuals
Kerala	Localized but severe events	Long recovery periods; poor regeneration in dry deciduous compartments

Note: Figures are based on Forest Survey of India and state forest department data; actual fire frequency may be underreported due to unrecorded low-intensity fires.

Table 12 Human Disturbance Index (HDI) across Forest Divisions in Karnataka, Kerala, and Tamil Nadu

Division Karnataka State	Browsing	Human Path	Cattle Path	Stem Cut	Fire Incidence	Nearness to Human Settlement	Human Disturbance Index
Haliyal	9	8	10	0	2	8	0.62
Yellapur	7	6	6	0	0	7	0.43
Bhadra Tiger Reserve	2	2	2	0	1	1	0.13
Biligiri Rangaswamy Temple Tiger Reserve	2	2	1	0	3	1	0.15
Karwar	1	4	2	0	0	2	0.15
Koppa	2	3	3	0	2	4	0.23
Madikeri	3	5	5	0	2	5	0.33
Virajpete	2	6	6	0	2	5	0.35
Cauvery WLS	9	8	9	0	5	7	0.63
Bandipura Tiger Reserve	2	2	2	0	5	3	0.23
Nagarahole Tiger Reserve	3	2	2	0	5	3	0.25
Shimogga	6	5	4	0	3	6	0.40

Division Karnataka State	Browsing	Human Path	Cattle Path	Stem Cut	Fire Incidence	Nearness to Human Settlement	Human Disturbance Index
Sagara	4	6	5	0	2	6	0.38
Kerala State							
South Wayanad	3	5	2	0	1	2	0.22
Punalur	1	3	1	0	1	2	0.13
Wayanad Wildlife	4	5	4	0	2	2	0.28
North Wayanad	1	4	3	0	0	2	0.17
Palakkad	1	4	3	0	0	2	0.17
Ranni	1	5	4	0	0	2	0.20
Parambikulam Tiger Reserve	1	3	1	0	0	2	0.12
Tamil Nadu State							
Coimbatore	4	6	5	0	2	4	0.35
Pollachi	4	6	5	0	3	5	0.38
Dharmapuri	5	7	6	0	4	6	0.47
Salem	5	7	7	0	3	6	0.47

DISCUSSION

This study provides a detailed analysis of the population structure, regeneration dynamics, and conservation challenges faced by *Dalbergia latifolia* across three major states in southern India—Karnataka, Kerala, and Tamil Nadu. The findings build on the limited ecological literature available for this high-value species, aligning with studies from Southeast Asia, particularly Indonesia (Atikah et al. 2021, Yulita et al. 2022) and Borneo (Nelson & Noweg 2021), which also document the persistence and regeneration potential of timber species under human-induced stress. Similar to regeneration patterns observed in Sarawak's mixed dipterocarp forests, this study emphasises the importance of site-specific ecological assessments in guiding effective restoration strategies.

Despite regional differences, a major finding across all states is the demographic imbalance of *D. latifolia* populations, which are skewed towards mature individuals, along with a significant lack of saplings and pole-sized trees. This structural gap indicates recruitment failure and long-term vulnerability. These findings align with earlier studies reporting very low frequencies of *D. latifolia* in dry deciduous forests—0.4% in Bannerghatta (Kakkar et al. 2021), 0.3% in Mudumalai (Sukumar et al. 1992), and just 0.14% in Mahendragiri (Khadanga et al. 2023). Although slightly more common in the Western Ghats, *D. latifolia* remains considerably less prevalent than associated native species (Botanical Survey of India 2018).

The regeneration of *D. latifolia* is largely seed-based, with vegetative propagation via root suckers observed primarily in Karnataka and Kerala. While clonal reproduction offers short-term demographic stability, it poses long-term genetic risks (Buckland et al. 2007). Seed-origin regeneration, though dominant, is often irregular and constrained by ecological pressures such as soil degradation, fire damage, and competitive exclusion by invasive species like *Lantana camara* and *Chromolaena odorata* (Sasidharan et al. 2020; Ramaswami & Sukumar 2013).

Impact of Fire and Anthropogenic Stress

Southern India's dry deciduous forests—key habitats for *D. latifolia*—are increasingly under threat from human activities such as selective logging, grazing, invasive species, and recurrent wildfires. Forest degradation in India accelerates rapidly, with annual loss estimates between 0.8% and 2% (Sagar et al. 2003, Reddy 2016). These pressures disproportionately impact early life

stages, causing seedling mortality and impeding sapling growth. Fire trends highlight this issue. In Tamil Nadu, fire incidents rose from 1,035 in 2021–2022 to 3,380 in 2023–2024, with nearly all caused by human actions. In Karnataka, although the frequency of fires decreased, the area affected expanded sixfold from 2021 to 2023. Even in Kerala, which is comparatively less prone to fires, small-scale fires in fragmented forests can result in long-term ecological setbacks, particularly where ground flora and seed banks are already depleted. Post-fire landscapes often become dominated by invasive species, preventing the re-establishment of *D. latifolia* seedlings. The demographic outcome is a population heavily skewed towards mature individuals, with very little recruitment—a pattern consistently observed across multiple divisions.

Size-Class Distribution and Regeneration Bottlenecks

Size-class analysis remains a dependable method for evaluating regeneration, with seedlings defined as ≤30 cm in height, saplings as >30 cm but less than 10.2 cm DBH, and mature trees as >10.2 cm DBH (Odum 1971, Swaine & Whitmore 1988). However, under disturbance regimes, size does not always correspond to age, as anthropogenic stress and interspecific competition can inhibit growth.

Invasive species such as *L. camara* further distort these dynamics by limiting light and soil resource availability, delaying or arresting transition from seedlings to saplings (Ramaswami & Sukumar 2013). These ecological pressures create demographic bottlenecks, especially where fire and grazing co-occur.

Regional Variations in Regeneration Success

Regeneration outcomes vary significantly across states and forest divisions. Karnataka has the highest population density (61.96 individuals/ha) and a relatively balanced structure, especially in divisions like Madikeri, which support strong seedling recruitment. Kerala shows high basal area and biomass, indicating healthy mature populations, but also faces a regeneration gap due to the near absence of pole-sized trees. Tamil Nadu demonstrates the weakest regeneration performance, with low seedling density and a complete lack of saplings or poles in most divisions—particularly in high-disturbance zones such as Dharmapuri and Theni. Even in Kerala, only six of the 14 surveyed forest divisions displayed evidence of successful recruitment beyond the seedling stage. Tamil Nadu's fire-prone divisions show minimal regeneration despite the presence of mature individuals. These findings highlight the importance of local ecological factors—such as fire history, grazing intensity, and invasive species load—in influencing regeneration success.

Human Disturbance Index and Forest Health

The Human Disturbance Index (HDI), derived from indicators such as browsing, fire incidence, and proximity to settlements, further confirms the impact of human-induced stress on regeneration. High HDI values in divisions like Cauvery WLS (Karnataka) and Salem (Tamil Nadu) align with poor regeneration outcomes, especially in early and intermediate size classes. This aligns with previous findings by Bhuyan et al. (2003) and Buckland et al. (2007), who showed that repeated disturbances diminish forest structural diversity and inhibit seedling establishment.

CONCLUSION

D. latifolia, a species of both ecological and commercial importance, faces widespread regeneration challenges in the dry deciduous forests of Peninsular India. This study highlights consistent demographic gaps across regions—especially the absence of intermediate-sized trees critical for population continuity. Although Karnataka exhibits relatively favourable conditions for regeneration, the scarcity of saplings and poles remains a concern. Kerala shows high biomass and basal area but suffers from a recruitment bottleneck. Tamil Nadu performs poorest overall, with regeneration almost entirely arrested in several fire-affected divisions.

Key ecological barriers—including fire, invasive species, and anthropogenic disturbances—are central to these patterns. The study reinforces the need for region-specific conservation strategies, including:

i. *In-situ* protection of remaining mature populations,
ii. Assisted Natural Regeneration (ANR) to improve seedling establishment and reduce recruitment failure,

iii. Fire management and control of invasive species,
iv. *Ex-situ* propagation and clonal trials to preserve genetic diversity,
v. Integration with national forestry programs (e.g., CAMPA, AICRP, MGNREGA) for restoration and monitoring.

As observed in Southeast Asia (Nelson & Noweg 2021), success in restoring degraded tropical forests depends on understanding species-specific ecological constraints. Applying these insights to *D. latifolia* in India is critical. Regeneration must be supported across all life stages—from seedling to mature tree—to ensure viable populations and the long-term sustainability of this valuable timber species in the Indian subcontinent.

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