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Philippines dipterocarp research (2000-2025): Trends, gaps and future priorities

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ABSTRACT

This review synthesizes the trajectory of Dipterocarp Research and Development (R&D) in the Philippines from 2000 to 2025, drawing from 44 Scopus-indexed publications and other key sources. It covers six core research areas, with biodiversity and conservation planning (34%) emerging as the most studied, followed by reforestation and propagation (23%), ecological dynamics and functional traits (20%), and studies on technological monitoring tools, genetic diversity, and ethnobotany. Dipterocarps are ecologically and economically vital, supporting carbon sequestration, forest resilience, and biodiversity in tropical ecosystems. Despite progress in propagation techniques and the use of remote sensing and GIS, major research gaps persist, including the lack of long-term ecological monitoring, limited integration of socio-political factors, and insufficient understanding of genetic connectivity and faunal interactions. Emerging opportunities lie in functional trait-based species selection, prioritizing native species for restoration, and applying machine learning and spatial modeling to ecological planning. This review underscores the need for transdisciplinary collaboration among government agencies, academic institutions, NGOs, and local communities to ensure that research is both scientifically rigorous and socially relevant. A holistic approach that bridges scientific innovation with community and cultural knowledge is essential for sustaining Dipterocarp ecosystems amid mounting climate and land-use pressures. This synthesis offers strategic insights to inform policy development, forest management, biodiversity conservation, climate change mitigation, and ecosystem restoration in the Philippines, while offering lessons applicable across tropical forest regions globally.

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INTRODUCTION

Dipterocarps, belonging to the family Dipterocarpaceae, are ecologically dominant and economically valuable tropical hardwood trees. Characterized by towering heights and massive trunks, these trees shape the structure of Southeast Asian lowland forests and play a critical role in carbon sequestration, nutrient cycling, and biodiversity support (Sasaki, 2006; Kettle, 2010; Ashton and Kettle, 2012). Their high-value timber, aromatic resins, and medicinal properties have supported both commercial industries and rural livelihoods across the region (Deb *et al.*, 2017; Dyrmose *et al.*, 2017; Yu *et al.*, 2021).

Globally concentrated in tropical Asia, dipterocarps are most diverse in Malaysia, Indonesia, and the Philippines (Langenberger, 2006; Pang *et al.*, 2021). In the Philippines, dipterocarps are a defining component of native forests, particularly in biodiversity-rich areas such as Leyte, Cordillera, and Central Visayas (Langenberger, 2006; Sabado *et al.*, 2017). Many species are endemic, and their dominance in forest canopies contributes to ecosystem resilience and habitat provision. Yet these forests face alarming decline: a median reduction of 67% in species distributions has been reported, driven by logging, land-use change, and fragmentation (Pang *et al.*, 2021), while climate models predict further habitat losses by 2070 (Deb *et al.*, 2017).

To address these threats, programs such as the National Greening Program, assisted natural regeneration (ANR), and forest landscape restoration have been launched. However, these often face funding gaps, inconsistent policy support, and weak integration of biodiversity (Cagalanan, 2015; von Kleist *et al.*, 2021; Oluwajuwon *et al.*, 2025). On the scientific front, research on dipterocarps has expanded, aided by advances in remote sensing, genetics, and biotechnology (Tian *et al.*, 2022; Ramani *et al.*, 2025; Segelbacher *et al.*, 2022).

Despite these efforts, there has been no consolidated assessment of how dipterocarp research in the Philippines has evolved over the last two decades. Without such synthesis, it remains unclear whether research outputs are adequately addressing urgent biodiversity and climate challenges. This review therefore asks: What themes have dominated dipterocarp research in the Philippines between 2000 and 2025? Which areas remain underexplored? And how can future research be directed to better support policy, forest management, biodiversity conservation, climate change mitigation, and ecosystem restoration?

By answering these questions, this research synthesizes 44 Scopus-indexed publications on dipterocarps in the Philippines from 2000 to 2025. Specifically, it (1) examines the scope and thematic focus of dipterocarp research; (2) identifies underexplored areas and temporal or spatial patterns; and (3) offers strategic recommendations to guide evidence-based conservation and sustainable forest management.

MATERIALS AND METHODS

Data sources

To address the identified knowledge gaps, we conducted a systematic literature review focused on Scopus-indexed publications and other relevant sources covering the period from 2000 to June 2025. The Scopus database was selected for its comprehensive coverage of peer-reviewed journals. The search employed combinations of the keywords "Dipterocarp," "Dipterocarpaceae," and the names of all known genera under Dipterocarpaceae, paired with the term "Philippines." These keywords were applied to the title, abstract, and keyword fields to ensure relevance to the review's scope. The results were further refined by limiting the country/territory filter to "Philippines" and restricting the publication window to January 2000 through June 2025. We included only peer-reviewed publications (journal articles, book chapters, conference papers) that focused primarily on dipterocarps within the Philippine context. Studies that only mentioned dipterocarps tangentially, or that were global or regional in scope without country-specific relevance, were excluded (Fig. 1).

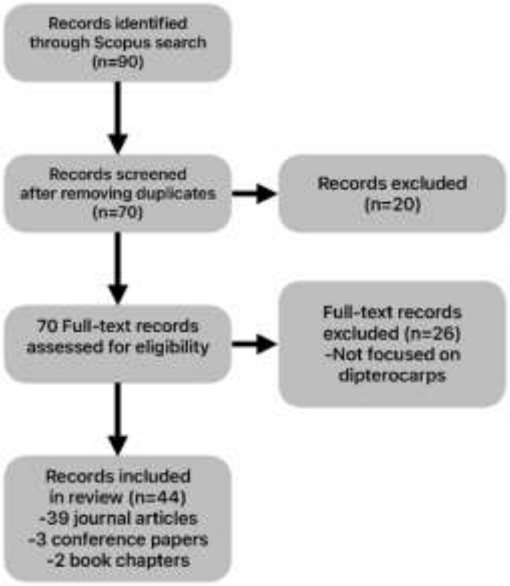

Fig. 1. Flowchart of records identification, screening, and inclusion in the review of dipterocarp research in the Philippines (2000–2025)

The initial search yielded 90 documents. After screening for relevance, duplication, and focus, 44 publications were retained for full review. Each document was coded for metadata (year, type, citation count, subject area, source title) and categorized into six thematic areas: (1) reforestation and propagation, (2) ecological dynamics and functional traits, (3) biodiversity assessment and spatial conservation planning, (4) technological tools for monitoring and management, (5) genetic diversity and faunal interactions, and (6) ethnobotany and cultural knowledge (Table 1). This classification was based on the primary research objective of each study.

In terms of document type, the review included 39 journal articles, three conference papers, and two book chapters (Fig. 2). These documents were published across 36 distinct journals and conference proceedings. The Biodiversitas Journal of Biological Diversity (ISSN: 1412-033X, E-ISSN: 2085-4722) contributed the highest number of publications (n = 3).

As of July 2025, 36 of the 44 documents had received at least one citation, accumulating a total of 533 citations. The resulting h-index for this body of literature is 12. These documents served as the core dataset for identifying key research themes, evaluating subject coverage, and assessing trends in dipterocarp research within the Philippine context. To further enrich the discussion, this review also incorporated additional recent and relevant literature, both local and international, on dipterocarps and related fields to provide a broader analytical framework for interpreting the findings.

Table 1. Scopus-indexed studies on dipterocarps in the Philippines (2000–2025)

Author(s)	Year	Major subject area
Jawani and Tulod	2024	Advances in dipterocarp reforestation and propagation strategies
Arnejo *et al.*	2023	
Aguilos *et al.*	2020	
Wills *et al.*	2017	
Nguyen *et al.*	2016	
Lumbres *et al.*	2016	
Schneider *et al.*	2014	
Sales-Come *et al.*	2010	
Utsugi *et al.*	2009	
Pollisco	2006	
Ebale *et al.*	2024	Ecological dynamics and functional traits of dipterocarp forests
Manila-Fajardo *et al.*	2023	
Balo *et al.*	2021	
Aureo *et al.*	2020	
Duya *et al.*	2020	
Tinio *et al.*	2019	
Yap *et al.*	2016	
Peque and Hölscher	2014	
Rana *et al.*	2009	
Galicia and Martin	2025	Biodiversity assessment and spatial conservation planning for dipterocarp forests
Buot Jr and Origenes	2024	
Origenes and Buot Jr	2024	
Zurbito *et al.*	2024	
Villanueva *et al.*	2022	
Coritico *et al.*	2022	
Fernandez *et al.*	2020	
Paclibar *et al.*	2020	
Zapanta *et al.*	2019	
Galias and Cuevas	2018	
Sabado *et al.*	2017	
Amoroso and Aspiras	2011	
Relox *et al.*	2011	
Amoroso *et al.*	2009	
Lasco *et al.*	2006	
Aureo *et al.*	2023	Technological tools for dipterocarp forest monitoring and management
Pasion *et al.*	2021	
Monzon *et al.*	2015	
Garcia *et al.*	2013	
Salvaña *et al.*	2019	Faunal dynamics, genetic diversity, and conservation of dipterocarps
Borja *et al.*	2015	
Gamboa-Lapitan and Hyun	2005	
Lyal *et al.*	2000	
Buot Jr *et al.*	2022	Integrating ethnobotany and cultural knowledge for dipterocarp conservation
Doyog *et al.*	2021	

Table 2. Summary of key findings, trends, and research gaps across major research areas on dipterocarps in the Philippines (2000–2025)

Research area	Key findings	Trends	Research gaps
Dipterocarp reforestation and propagation	Native species outperform exotics in growth. Hormone treatments and wildling recovery chambers improve survival. Nurse plants enhance seedling success.	Focus on native species. Use of nurse plants and ANR.	Need for long-term data. Species-site incompatibility. Scalable, cost-effective methods needed.
Ecological dynamics and functional traits	Functional traits (wood density, leaf morphology) aid drought resilience. Biodiversity is linked to forest integrity.	Focus on functional traits. Increasing study of disturbance effects on biodiversity.	Studies on lesser-known species. Regeneration in secondary forests. Phenological data are underexplored.
Biodiversity and conservation planning	Climate change impacts species distribution (MaxEnt). LCPI for prioritizing species.	Growth in GIS and spatial tools for prioritization. Integration of carbon and biodiversity data.	Need for long-term monitoring. Integrating socio-political factors in spatial planning.
Technological tools for monitoring and management	SAR and remote sensing tools aid biomass estimation. MaxEnt and GIS predict species distributions.	Reliance on GIS, remote sensing, and machine learning for management. Focus on predictive modeling.	Validation of data accuracy. Lack of temporal variation in monitoring data.
Genetic diversity and faunal interactions	Genetic diversity supports adaptability (Parashorea malaanonan). Seed-feeding beetles influence regeneration.	More focus on genetic diversity and faunal interactions. Emphasis on preserving genetic resilience.	Geographic limitations in genetic studies. Need for long-term studies on seed predation. Studies on genetic connectivity are needed.
Integrating ethnobotany and cultural knowledge	Ethnobotanical studies highlight dipterocarp's importance. P3DM aids community involvement.	Increased focus on community-based conservation. Integration of indigenous knowledge into conservation strategies.	Lack of long-term evaluations of participatory methods. Barriers to integrating local knowledge with formal policies.

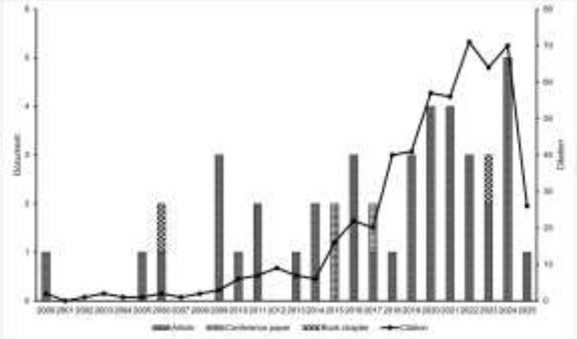

Fig. 2. Year of publication, document type, and citation count of Scopus-indexed studies on dipterocarps in the Philippines (2000–2025)

The dipterocarp RandD system encompasses interconnected research areas, with external factors such as climate change, socio-economic conditions, and government policies influencing research progress and outcomes. Key research areas, including reforestation, ecological dynamics, and biodiversity, collectively contribute to the overarching goals of sustainable forest management, biodiversity conservation, climate change mitigation, and ecosystem restoration. Table 2 and Fig. 3 highlight trends in these areas, identify critical research gaps, and emphasize the need for long-term, integrated conservation efforts.

Fig. 3. Conceptual framework of dipterocarp R&D system in the Philippines (2000–2025)

RESULTS AND DISCUSSION

Advances in dipterocarp reforestation and propagation strategies

Building a strong foundation for sustainable forest recovery, this section outlines the ecological and functional roles of dipterocarps. It highlights key advancements in reforestation, including the superior growth of native species over exotics (Schneider *et al.*, 2014; Aguilos *et al.*, 2020), improved propagation through hormone treatments and Wildling Recovery Chambers (Pollisco, 2006), and the use of nurse plants for better seedling establishment (Jawani and Tulod, 2024). It also emphasizes trait-based selection, assisted natural regeneration, and modeling tools for sustainable reforestation planning (Arnejo *et al.*, 2023; Nguyen *et al.*, 2016).

Empirical studies confirm the superior growth performance and ecological compatibility of native dipterocarps in reforestation programs. Schneider *et al.* (2014) evaluated 60 species in smallholder trials, revealing that native dipterocarps such as *Shorea contorta* and *Dipterocarpus grandiflorus* exhibited greater growth on limestone-influenced soils than exotics. Similarly, Aguilos *et al.* (2020) found higher early-stage growth and survival of native species in mixed plantations, emphasizing the need for localized, long-term trials integrating soil, microclimate, and socio-ecological variables. Propagation research has also advanced, improving seedling production and vigor. Pollisco (2006) demonstrated that hormone treatments and Wildling Recovery Chambers enhance seedling growth and survival. These innovations are promising for resource-limited nurseries, though large-scale validation is needed. Integrating drought-hardening and light acclimation improves adaptation of *S. contorta*, *D. grandiflorus*, and *Hopea plagata*.

Ecological facilitation approaches have emerged as effective restoration strategies. Jawani and Tulod (2024) demonstrated that *Piper aduncum* served as a nurse plant in degraded grasslands, improving microclimate and enhancing the establishment of dipterocarps. Despite these benefits, the use of exotic nurse plants may pose ecological risks, including invasiveness and competition with native flora. Physiological studies further support climate-resilient restoration; Sales-Come and Hölscher (2010) highlighted efficient water use and light capture among dipterocarps, while Utsugi *et al.* (2009) documented species-specific photosynthetic adaptations in *Shorea contorta* and *Dipterocarpus grandiflorus*, underscoring the importance of functional traits in restoration planning.

Modeling and trait-based analyses have become critical tools for guiding reforestation strategies. Arnejo *et al.* (2023) demonstrated through agent-based modeling that integrating ANR with selective logging enhances forest cover and timber yield. Nguyen *et al.* (2016) further found that traits such as shade tolerance and maximum tree size better predict survival than planting density, emphasizing functional trait-based planning. Lumbres *et al.* (2016) developed stem taper models for tropical species in Mt. Makiling, contributing to accurate biomass estimation and carbon accounting. At the landscape level, Wills *et al.* (2017) observed greater recruitment and functional diversity in mixed-species plantations in Leyte, featuring *Anisoptera thurifera*, *Dipterocarpus gracilis*, *D. grandiflorus*, *Hopea plagata*, *Shorea contorta*, *S. guiso*, and *S. polysperma*. Their findings affirm that mixed-species reforestation enhances biodiversity, nutrient cycling, and ecosystem resilience, strengthening the ecological foundation for sustainable dipterocarp forest recovery.

Compared with Philippine-based efforts, Southeast Asian studies show broader application of native species prioritization and advanced propagation techniques, with Thailand demonstrating superior early-stage growth on degraded sites (Sakai *et al.*, 2009) and Indonesia reporting strong performance of *Shorea platyclados* and *S. leprosula* in logged-over forests (Wahyudi *et al.*, 2018). More recently, an Indonesian study by Attarik *et al.* (2024) highlighted *Shorea leprosula*'s rapid growth and its positive effects on soil properties, emphasizing its suitability for large-scale forest rehabilitation projects.

In contrast, Philippine studies focus more on localized trials using hormone-assisted nursery techniques and wildling recovery chambers (Pollisco, 2006; Schneider *et al.*, 2014), underscoring the need for scaling and integration of advanced propagation and modeling approaches.

Collectively, these studies emphasize the importance of prioritizing native dipterocarp species, applying advanced propagation methods, and integrating functional trait data to improve reforestation outcomes. Persistent issues such as species site incompatibility, inconsistent propagation success, and insufficient genetic conservation hinder long-term restoration. Successful reforestation goes beyond seedling survival it requires ecological integration within diverse landscapes. A deep understanding of species-specific traits, environmental tolerances, and ecosystem functions enables adaptive, site-tailored interventions that enhance the resilience, productivity, and long-term sustainability of restored dipterocarp forests.

Ecological dynamics and functional traits of dipterocarp forests

Building on species-specific insights from reforestation strategies, this section explores how dipterocarps function within ecosystems, shaped by biodiversity, adaptive traits, and ecological interactions. It highlights how species traits, habitat heterogeneity, and disturbance regimes influence biodiversity and ecosystem functioning in dipterocarp forests. Forest type significantly affects species richness (Aureo and deCenA, 2023; Duya *et al.*, 2020), adaptive traits enhance resilience (Rana *et al.*, 2009; Ebale *et al.*, 2024), and phenological and genetic diversity drive regeneration and management (Tinio *et al.*, 2019; Manila-Fajardo *et al.*, 2023). Moreover, the ecological and economic importance of dipterocarps and site-specific conservation approaches are emphasized (Relox *et al.*, 2011; Peque and Hölscher, 2014; Yap *et al.*, 2016; Balo *et al.*, 2021).

Biodiversity patterns in dipterocarp forests are closely tied to forest integrity and structural complexity. Aureo and deCenA (2023) recorded higher amphibian richness in undisturbed lower montane forests within the Rajah Sikatuna Protected Landscape than in grasslands and farmlands. Similarly, Duya *et al.* (2020) attributed high fruit bat diversity in the Northern Sierra Madre Mountains to abundant fruiting dipterocarps. Interestingly, Balo *et al.* (2021) reported elevated bat diversity in secondary mixed-dipterocarp forests in the Awasian Water Forest Reserve, suggesting that secondary habitats may sustain biodiversity, though their long-term ecological stability remains uncertain amid anthropogenic pressures and climate change.

Habitat specificity further shapes dipterocarp community distribution. Relox *et al.* (2011) documented high herpetofaunal endemism in Mt. Hamiguitan's lowland dipterocarp forests, with endemic reptiles and amphibians comprising over 90% of recorded species. Peque and Hölscher (2014) found that *Shorea almon*, *Parashorea malaanonan*, *Dipterocarpus validus*, *Shorea palosapis*, and *Shorea contorta* were confined to limestone substrates with low population densities, where soil pH and stand structure governed habitat suitability. These findings challenge uniform reforestation models and advocate for site-specific approaches that consider local edaphic and microclimatic conditions often neglected in large-scale restoration programs.

Functional traits provide deeper insight into adaptability and ecological performance. Rana *et al.* (2009) revealed that endangered species such as *Hopea plagata* and *Dipterocarpus kerrii* possess higher wood densities that enhance drought tolerance and carbon storage. Similarly, Ebale *et al.* (2024) found that *P. malaanonan* displayed stable leaf morphology but variable vein density along Mt. Makiling's elevation gradient, reflecting physiological plasticity to microclimatic variation. Such trait-based evidence underscores the importance of selecting climate-resilient species for restoration in dynamic environments.

Regeneration dynamics also define long-term ecosystem recovery. Manila-Fajardo *et al.* (2023)

reported synchronized reproductive events among dominant taxa in Palanan, Isabela, during the dry season, emphasizing the need to align planting schedules with phenological cycles. Tinio *et al.* (2019) found high polymorphism in *P. malaanonan* populations, suggesting genetic adaptability to environmental changes. Meanwhile, Yap *et al.* (2016) observed that despite severe typhoon-induced mortality, aboveground biomass in Palanan's dipterocarp forests recovered within six years. Regional findings from Sabah (Veryard, 2023) and Borneo (Gaveau *et al.*, 2014) further reveal that dipterocarp resilience depends on species diversity, management strategies, and socio-political contexts, reinforcing the need for integrated conservation and restoration in the Philippines.

Collectively, these studies reveal the complex interplay between habitat conditions, species traits, and ecological processes in dipterocarp forest dynamics. Nonetheless, key research gaps remain, including the adaptive capacity of lesser-studied dipterocarps, the influence of genetic diversity in fragmented habitats, and regeneration dynamics in degraded or secondary forests. The effects of phenology on seedling success under climate variability are also insufficiently explored. Addressing these gaps requires ecologically nuanced, site-specific strategies. Integrating tools such as ecological modeling, spatial prioritization, and trait-informed species selection grounded in long-term monitoring can improve restoration effectiveness amid ongoing environmental change.

Biodiversity assessment and spatial conservation planning for dipterocarp forests

Following ecological insights into dipterocarp dynamics, this section transitions to how biodiversity data, habitat models, and conservation tools are applied to prioritize and manage dipterocarp-rich landscapes. It highlights how biodiversity surveys, species distribution models, and carbon assessments inform conservation across limestone forests, protected landscapes, and disturbed habitats. Studies emphasize the identification of endemic and threatened species (Fernandez *et al.*, 2020; Coritico *et al.*, 2022), the use of spatial tools and localized indices for prioritization (Buot Jr and Origenes, 2024; Galias and Cuevas, 2018), and the influence of vegetation structure and climate variables in defining conservation zones (Villanueva *et al.*, 2022; Sabado *et al.*, 2017; Garcia and Martin, 2025). Research also underscores the roles of carbon storage, forest recovery, and the conservation value of both intact and degraded sites (Lasco *et al.*, 2006; Zapanta *et al.*, 2019; Amoroso and Aspiras, 2011; Amoroso *et al.*, 2009; Paclibar and Tadiosa, 2020).

A major advancement in site-specific conservation is the Localized Conservation Priority Index (LCPI) developed by Buot Jr and Origenes (2024) for limestone forests in Guiuan Marine Resource Protected Landscape and Seascape, Eastern Samar. The LCPI integrates ecological, economic, and cultural criteria to rank species such as *Caryota rumphiana* and *Shorea negrosensis* and geotags them to guide local conservation planning. This geospatially anchored, community-based approach supports site-specific conservation, though its wider applicability still requires testing across various forest types and socio-ecological settings to ensure robustness.

Spatial analyses have further strengthened conservation diagnostics. Origenes and Buot Jr (2024) mapped 20 priority plant species in Samar Island Natural Park, contrasting abundant species such as *Shorea negrosensis* with rare taxa like *Cycas riuminiana*, offering spatially explicit guidance for zoning. Villanueva *et al.* (2022) also analyzed vegetation structure and found *Shorea* dominant, with patterns linked to microclimatic variables, particularly temperature. Their clustering approach provided deeper insight into forest composition, though further ground validation would enhance accuracy and ecological interpretation.

However, many studies are constrained by short-term sampling windows that may overlook seasonal variations. Galias and Cuevas (2018) assessed species richness in a regenerating ancestral domain forest in Bataan, identifying 76 tree species, including 17 threatened taxa such as *Anisoptera thurifera*, *Dipterocarpus gracilis*, and *Shorea contorta*. While plot-based surveys provide valuable baselines, they may underrepresent rare or patchily distributed species, emphasizing the need for long-term, multi-seasonal biodiversity monitoring.

Assessments in Luzon and Mindanao further expand the ecological scope. Garcia and Martin (2025) reported low tree diversity in Tumauini Watershed Natural Park despite legal protection, while Coritico *et al.* (2022) highlighted the role of small montane forests like Marilog Forest Reserve as refugia for rare dipterocarps. Paclibar and Tadiosa (2020) noted degradation threats in Quezon Protected Landscape. In Mindanao's Hamiguitan Range, Amoroso and Aspiras (2011) recorded 163 endemic species, including *Shorea astylosa*, *S. polysperma*, *S. contorta*, *S. guiso*, and *S. negrosensis*, while Amoroso *et al.* (2009) documented 878 plant species across four vegetation types, confirming Hamiguitan's exceptional conservation value.

Modeling approaches complement field surveys. Zurbito *et al.* (2024) used MaxEnt to model habitat suitability for *Shorea contorta*, identifying over seven million hectares of suitable habitat, while Sabado *et al.* (2017) modeled dipterocarp presence in Central Visayas and identified minimum temperature as the key predictor. Carbon assessments link biodiversity with climate goals: Lasco *et al.* (2006) found logged dipterocarp forests recover 70% of carbon stocks within 35 years, and Zapanta *et al.* (2019) recorded substantial diversity in disturbed Mt. Apo sites, including *Parashorea malaanonan*, *S. contorta*, and *S. negrosensis*.

In Southeast Asia, biodiversity assessments and spatial conservation planning are vital for managing dipterocarp dominated forests. In Thailand, surveys of dry deciduous dipterocarp forests documented species such as *Shorea obtusa*, *S. siamensis*, and *Dipterocarpus tuberculatus* as key species in dry deciduous forests (Wohlfart *et al.*, 2014), while in Borneo, long-term plots tracking *S. leprosula*, *S. parvifolia*, and *D. baudii* linked selective logging and enrichment planting to altered recovery and carbon storage (Gaveau *et al.*, 2014). These regional studies demonstrate that species-specific ecological traits, disturbance regimes, and governance practices critically shape forest resilience, providing valuable insights applicable to Philippine dipterocarp forests such as those in Mt. Hamiguitan, where high endemism and functional importance of key dipterocarps have been documented.

Together, these studies highlight the importance of integrating field-based biodiversity inventories, species distribution models, and carbon assessments to develop more effective and context-specific conservation strategies. Across limestone forests and regenerating landscapes, biodiversity hotspots in the Philippines require science-driven, site-tailored interventions. However, a key research gap remains in assessing how these integrated tools yield measurable conservation outcomes, especially in remote, socio-ecologically complex areas. As environmental pressures intensify, incorporating advanced technologies such as remote sensing, GIS, and ecological modeling is vital for guiding evidence-based restoration and sustainable dipterocarp forest management.

Technological tools for dipterocarp forest monitoring and management

As the urgency of climate change mitigation and biodiversity conservation intensifies, technological innovations provide vital tools for monitoring and managing dipterocarp forests. This section reviews studies employing remote sensing, GIS, and forest modeling to evaluate habitat conditions, predict species distributions, and support conservation planning for dipterocarps in the Philippines (Garcia *et al.*, 2013; Monzon *et al.*, 2015; Aureo *et al.*, 2020; Pasion *et al.*, 2021).

Garcia *et al.* (2013) utilized the MaxEnt algorithm to model habitat suitability for 14 threatened forest tree species, including dipterocarps, under projected 2050 and 2080 climate scenarios. Based on bioclimatic variables and occurrence data from herbarium and biodiversity records, results indicated that habitat suitability may expand or contract by species, *Shorea contorta* was projected to gain suitable areas, while *Dipterocarpus grandiflorus* was expected to lose them. These projections guide the identification of potential refugia and conservation priorities, although MaxEnt's reliance on presence-only data introduces uncertainty that warrants cautious interpretation.

Monzon *et al.* (2015) estimated above-ground biomass in dipterocarp forests within the Northern Sierra Madre Natural Park using quad-polarimetric Synthetic Aperture Radar (SAR) data from ALOS PALSAR-2. From 134 forest plots (20 × 20 m), SAR backscatter showed strong correlation with field-derived biomass estimates (100–300 Mg/ha; mean ≈ 200 Mg/ha). The study demonstrated SAR's utility for biomass monitoring in dense, cloud-prone tropical forests and for REDD+ carbon accounting, though uncertainties remain due to spatial resolution (12.5 m) and forest structural complexity.

Pasion *et al.* (2021) assessed tree diversity and carbon density in dipterocarp-dominated riparian zones in Mt. Hamiguitan, Mindanao. Using nested sampling plots, they recorded 66 species in 35 families, including 18 endemics and several threatened taxa. Mean carbon density reached 128.42 ± 39.04 MgC ha^{-1}, with canopy dipterocarps contributing about 80%. A strong correlation between species dominance and carbon density ($R^2 = 0.81$, $p < 0.001$) emphasized dipterocarps' ecological significance. However, short sampling duration and single-season data limited generalizability, underscoring the need to integrate ecological findings with governance and socio-economic dimensions.

Aureo *et al.* (2020) investigated plant diversity in the forest-over-limestone ecosystem of the Rajah Sikatuna Protected Landscape in Bohol using fifteen 20 × 100 m belt transects. They documented 368 species, including 93 endemics and 46 threatened taxa, with dipterocarps such as *Shorea negrosensis*, *Shorea astylosa*, and *Hopea foxworthyi* among the key species. Cluster analysis revealed heterogeneous species distribution, suggesting targeted conservation and reforestation approaches. Nonetheless, random transect placement without stratification may have introduced sampling bias, indicating a need for refined methodologies.

Compared to Malaysia and Indonesia, where remote sensing and forest monitoring are applied on larger regional scales (Gaveau *et al.*, 2014; Gangi *et al.*, 2015), Philippine research remains localized due to limited funding and institutional linkages. Strengthening collaboration among research institutions and ensuring sustained investment are essential to advance dipterocarp conservation science.

Collectively, these studies demonstrate the potential of spatial modeling and remote sensing technologies to inform dipterocarp conservation while exposing gaps in temporal coverage, spatial representation, and socio-political integration. Tools such as MaxEnt, SAR, and standardized biodiversity surveys have generated valuable insights into habitat suitability, biomass, and ecosystem function. Moving forward, enhanced institutional coordination and long-term funding are crucial to align Philippine research with regional progress and ensure that conservation strategies remain scientifically sound and socially relevant.

Faunal dynamics, genetic diversity, and conservation of dipterocarps

A comprehensive understanding of dipterocarp forest conservation requires examining not only technological monitoring tools but also the biological dynamics that influence species resilience and regeneration. This section reviews studies on faunal interactions, genetic diversity, and species traits that inform dipterocarp conservation and restoration in Philippine forests (Lyal and Curran, 2000; Gamboa-Lapitan and Hyun, 2005; Borja *et al.*, 2015; Salvaña *et al.*, 2019).

Lyal and Curran (2000) investigated seed-feeding beetles of the Mecysolobini tribe and their interactions with dipterocarp seeds across Southeast Asia. They described fifteen new *Alcidodes* species and revised four others from seeds of 70 dipterocarp species across five genera, *Shorea, Dipterocarpus, Hopea, Dryobalanops,* and *Vatica*. The study revealed that most beetles are genus-specific rather than host-specific, challenging assumptions of generalism among seed predators. These findings have implications for forest regeneration and resilience, though the study's taxonomic focus and limited spatial-temporal scope constrain broader ecological interpretation. Further research on seed predation effects and improved sampling coverage would enhance conservation relevance.

Gamboa-Lapitan and Hyun (2005) examined the genetic diversity of *Parashorea malaanonan*, reporting high outcrossing rates alongside biparental inbreeding. Their results highlight the need to maintain genetic variation through in situ and ex situ measures such as using genetically diverse seeds and preventing population isolation. However, limited sample size and geographic scope may affect representativeness, suggesting the need for expanded genetic sampling to strengthen conservation planning.

Salvaña *et al.* (2019) analyzed tree diversity and community structure in lowland and lower montane forests of Mt. Apo Natural Park, focusing on dipterocarps. Along two 1 km transects per forest type, they identified 67 species from 29 families, with greater richness in lowland forests. Dipterocarpaceae and Moraceae dominated, and the abundance of seedlings relative to mature trees indicated active regeneration. Despite these insights, limited sampling points and lack of seasonal data may have biased results, underscoring the need for broader ecological monitoring.

Borja *et al.* (2015) explored species associations involving *Coffea* spp. along Mount Makiling's eastern slopes and found that dense coffee plantings reduced native plant diversity, potentially hindering dipterocarp regeneration. While the study emphasized early management intervention, it would benefit from more detailed analysis of coffee's specific ecological impacts and the feasibility of targeted conservation measures.

In contrast, regional research in Thailand and Vietnam demonstrates broader integration of faunal and genetic perspectives. Kitamura *et al.* (2002) showed the key role of hornbills in dispersing dipterocarp seeds in Thailand, while Vu *et al.* (2019) reported genetic erosion in small, fragmented dipterocarp populations in Vietnam. Compared with these, Philippine studies remain localized and short-term, with limited linkage between faunal interactions, genetic processes, and large-scale conservation frameworks.

Collectively, these studies emphasize the need for integrated approaches that combine faunal ecology, genetics, and regeneration traits in guiding dipterocarp conservation. They reveal how insect-plant interactions, reproductive strategies, and regeneration patterns shape ecosystem resilience. However, significant gaps persist in understanding how these processes operate under real-world conditions. Long-term studies on seed predation, broader genetic assessments, and analyses of species interactions in human-modified landscapes are needed. Integrating these biological insights with adaptive, community-based management strategies will be essential to strengthen the resilience of dipterocarp ecosystems.

Integrating ethnobotany and cultural knowledge for dipterocarp conservation

As conservation efforts adopt more holistic frameworks, integrating cultural and ecological knowledge with scientific strategies becomes increasingly vital. This section underscores how combining local knowledge, species traits, and predictive models enhances dipterocarp conservation in the Philippines (Calderon *et al.*, 2015; Doyog *et al.*, 2021; Buot Jr *et al.*, 2022).

Buot Jr *et al.* (2022) conducted an ethnobotanical inventory in the limestone forests of Samar Island, documenting 196 woody plant species, including 60 threatened under Philippine law and 182 under IUCN criteria. Critically endangered dipterocarps such as *Shorea astylosa* and *Dipterocarpus gracilis* highlighted the conservation significance of these karst habitats. The authors proposed a framework integrating *in situ* and *ex situ* conservation with strong community participation through Participatory 3D Modelling (P3DM). While this holistic approach promotes the inclusion of local knowledge in management planning, its practical impact would benefit from evaluating measurable outcomes, such as forest cover improvement or regeneration success. Sustaining community engagement, validating local information, and integrating outputs into formal policies remain critical challenges.

Doyog *et al.* (2021) complemented this approach by developing species-specific allometric models for *Parashorea malaanonan* to improve biomass estimation and carbon stock assessment. These models support site-based forest monitoring and restoration planning but require further validation across varied ecological conditions and community-managed areas to ensure broader applicability.

Similarly, Calderon *et al.* (2015) demonstrated the integration of indigenous and scientific knowledge through participatory GIS and satellite-based mapping in Hungduan, Ifugao. Collaborating with local communities, they mapped four subwatersheds using natural landmarks and land tenure information, producing management plans grounded in both traditional and scientific data. However, challenges such as limited technical access, cultural differences, and difficulties in reconciling indigenous and formal systems may hinder implementation.

Comparable efforts in Thailand further highlight this integration, where community forestry programs incorporate traditional ecological knowledge into forest governance. Ethnobotanical studies, such as those by Panyadee *et al.* (2022), reveal how cultural practices guide species selection and resource management, influencing conservation priorities. These parallels demonstrate that aligning scientific tools with local knowledge is key to sustaining dipterocarp conservation in Southeast Asia.

Collectively, these studies illustrate the promise of integrating ethnobotanical insights, species-based modeling, and participatory planning in dipterocarp conservation. They emphasize that bridging scientific and cultural knowledge strengthens restoration efforts and promotes inclusive forest governance. Nevertheless, research gaps remain, particularly regarding the long-term impacts of participatory tools like P3DM and GIS on conservation outcomes. Future studies should assess how local cultural knowledge translates into measurable ecological and management improvements.

Research gaps matrix/Integrated research gap and opportunity framework

The Research Gaps Matrix provides an integrated overview of dipterocarp RandD in the Philippines, outlining key deficiencies such as the lack of long-term monitoring, limited validation of remote sensing tools, and weak integration of socio-political factors in conservation planning. It also identifies opportunities for advancing research through the use of native and trait-based species, functional trait analysis for enhancing climate resilience, and the application of machine learning and predictive modeling.

To address these gaps, future efforts should establish long-term silvicultural trials, incorporate genetic and ecological data into restoration programs, and strengthen collaboration among government agencies, research institutions, NGOs, and local communities. Integrating indigenous knowledge and community participation will ensure that conservation initiatives are both scientifically sound and socially relevant. Collectively, these strategies provide a framework for evidence-based forest management, biodiversity conservation, and ecosystem restoration in the Philippines.

Table 3. Research gaps matrix in dipterocarps R&D in the Philippines (2000–2025)

Theme	Gaps	Opportunities	Key actors
Reforestation and propagation	Need for long-term data on propagation success. Species-site incompatibility. Need for scalable, cost-effective methods.	Focus on native species. Use of nurse plants and ANR.	Government agencies (e.g., DENR) Environmental NGOs Academic researchers in forestry and ecology Local communities involved in reforestation
Ecological dynamics and functional traits	Gaps in studies on lesser-known species. Underexplored regeneration in secondary forests. Phenological data are underexplored.	Investigating functional traits to enhance climate resilience. Focusing on regeneration in degraded forests.	Ecologists Biologists Conservation Government agencies (e.g., DOST & DENR) Community-based Forest managers Research institutions
Biodiversity and conservation	Need for long-term monitoring. Integration of socio-political factors in conservation planning.	Integration of carbon and biodiversity data. Use of GIS and spatial tools for better conservation prioritization.	Conservation NGOs Local government units Forest managers Policymakers Academic researchers in biodiversity and conservation
Technological tools for monitoring and management	Need for validation of remote sensing and GIS data accuracy. Lack of temporal variation in monitoring data.	Greater reliance on machine learning and predictive modeling. Use of remote sensing for biomass and habitat monitoring.	Technology companies developing remote sensing and GIS technologies Academic researchers in geospatial science Government agencies (e.g., DOST & DENR) Environmental monitoring groups
Genetic diversity and faunal interactions	Geographic limitations in genetic studies. Lack of long-term studies on seed predation. Need for studies on genetic connectivity in fragmented habitats.	Greater focus on genetic diversity and faunal interactions. Emphasis on preserving genetic resilience.	Wildlife conservation organizations Research institutions in genetics and ecology Local communities involved in biodiversity monitoring
Integrating ethnobotany and cultural knowledge	Lack of long-term evaluations of participatory methods. Barriers to integrating local knowledge with formal policies.	Focus on community-based conservation and participatory GIS. Integration of indigenous knowledge into conservation strategies.	Local communities Cultural preservation groups Government agencies (e.g., DENR & NCIP) Research institutions focused on ethnobotany and participatory methods NGOs specializing in indigenous rights and conservation

CONCLUSION

This review demonstrates that dipterocarp research in the Philippines over the past 25 years has made major advances: (1) progress in reforestation and propagation techniques that prioritize native species, (2) growing application of remote sensing, GIS, and functional trait analysis for forest monitoring, and (3) contributions to biodiversity assessment and spatial conservation planning. These advances underscore the ecological and socio-economic importance of dipterocarps as keystone species supporting forest structure, carbon sequestration, and local livelihoods. Despite these gains, critical gaps persist. First, there is a lack of long-term ecological monitoring and species–site trials that can validate restoration approaches over time. Second, socio-political and cultural dimensions remain weakly integrated into conservation planning, limiting the relevance of research to local realities. Third, genetic connectivity and faunal interactions remain poorly understood, constraining adaptive management of fragmented dipterocarp populations. Addressing these gaps requires clear strategic priorities. Future research must integrate genetic and ecological data into restoration programs, institutionalize long-term monitoring networks, and embed indigenous and community knowledge into policy and management frameworks. Stronger collaboration among DENR, DOST, LGUs, academic and research institutions, NGOs, and local communities is essential to translate research into practice. In conclusion, the Philippine experience shows that dipterocarp research is most impactful when it directly informs policy development, forest management, biodiversity conservation, climate change mitigation, and ecosystem restoration. By maximizing these opportunities and addressing persistent gaps, future research can not only strengthen dipterocarp conservation in the Philippines but also provide a model for tropical forest regions worldwide facing similar challenges.

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