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Species-Specific Growth Modelling Challenges The 25-Years Cutting Cycle in Sarawak

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Abstract

Selective logging in Sarawak continues to rely on a fixed cutting cycle; however, the biological adequacy of this interval for major commercial timber taxa remains uncertain. This study provides a species-specific empirical test of whether a policy-relevant cutting cycle is biologically compatible with harvestable diameter at breast height (DBH) attainment across multiple timber taxa and localities. Age and DBH data from 4,466 trees representing eight timber taxa across three localities in Sarawak were compiled from archived records and supported by field verification of tree identity and measurements, where possible. Species-specific negative exponential models were fitted to estimate the age at which trees attained a harvestable DBH, and analysis of covariance was used to test the effects of locality for taxa represented at more than one site. The predicted ages to harvestable diameter exceeded 25 years for all taxa examined. The shortest estimate was 52.3 years for *Shorea parvifolia* in Mujong Melinau, whereas *Dipterocarpus kunstleri* required 154.3 years; most other taxa required more than 70 years to attain a harvestable size. Locality significantly influenced the growth of *Shorea parvifolia* and *Shorea angustifolia*, indicating that growth trajectories were also sensitive to site conditions. These findings show that a uniform 25 years re-entry interval is biologically misaligned with the observed growth trajectories of the studied taxa. More broadly, the results challenge fixed-cycle selective-logging assumptions in tropical production forests and support species-specific, locality-sensitive cutting cycle planning rather than reliance on a single uniform schedule.

Keywords: species-specific growth models, harvestable age, cutting cycle policy, Sarawak tropical forests, sustainable forest management

1. Introduction

Selective logging remains one of the dominant forms of tropical forest use, and its long-term sustainability depends not only on reducing immediate harvesting damage but also on whether commercially valuable trees can biologically recover within the interval between successive harvesting entries. Although selectively logged tropical forests can retain important biodiversity and carbon values, timber stocks, and forest structure, they often do not recover to pre-disturbance conditions within short operational harvest intervals, especially where extraction intensity is high and residual stand damage is substantial [1]. Consequently, claims of sustained yield in tropical production forests depend heavily on whether cutting cycles are biologically aligned with the growth trajectories of target timber taxa, rather than being based only on administrative scheduling or minimum diameter rules [1–4].

Sarawak, the largest state in Malaysia, located on Borneo Island, represents part of a broader Malaysian forest research context in which forest ecosystems are recognized for their ecological, management, and societal importance [5]. In this state, selective logging in mixed dipterocarp forests is generally regulated through a fixed re-entry system together with minimum cutting diameter thresholds that determine harvest eligibility [6]. In this context,

the cutting cycle refers to the interval between successive harvesting entries into the same managed forest area, whereas the minimum cutting diameter is the tree-level threshold used to determine whether an individual stem can be legally felled. This distinction is important because a cutting cycle may be operationally convenient, yet still ecologically inadequate if trees do not regain a harves *Shorea parvifolia* diameter within that interval. Evidence from the Sarawak and Bornean forests shows that logged forest structures and recovery can remain incomplete decades after harvesting, indicating that short fixed cycles may not reflect the biological pace of recovery in these systems [1].

Despite the policy importance of cutting cycle length, the key biological question remains insufficiently addressed at the species level in Sarawak: Do major commercial timber taxa actually attain a harvestable diameter within the currently applied 25 years re-entry interval? Existing studies have largely focused on logged forest recovery, stand structure, carbon consequences, or general management sustainability [1–4], but these do not directly test whether individual target taxa can regain a harvestable diameter at breast height (DBH) within the policy-relevant time frame. This is an important gap because tree growth is not uniform across taxa, and site conditions can further alter the growth trajectories. Therefore, a uniform cutting cycle may mask substantial biological variation among species and localities, leading to harvest schedules that are administratively simple but ecologically unrealistic. The novelty of the present study lies in directly linking species-specific age to DBH relationships with a policy-relevant cutting cycle, rather than discussing recovery only in broad stand-level terms.

Accordingly, this study evaluated whether the observed growth trajectories of eight timber taxa in Sarawak were compatible with a 25-years cutting cycle by modelling the age required to attain a harvestable DBH. We also tested whether locality significantly influenced DBH development in taxa represented across more than one site to determine whether a single growth expectation could reasonably be applied across localities. By combining species-specific growth modelling with locality testing, this study provides an empirical assessment of whether a uniform re-entry interval is biologically defensible for the taxa examined or whether species-specific and locality-sensitive cutting cycle planning is more appropriate.

2. Materials and Methods

2.1. Study Sites

This study was based on data from three forest localities in Sarawak: The Gerenai Forest Management Unit (FMU), the Mujong Melinau FMU, and Lambir within the Lambir Hills National Park (**Figure 1**). Gerenai and Mujong Melinau were treated as managed production forest systems, whereas Lambir served as a protected forest reference site. The Gerenai FMU is situated in the Miri Division, within an approximate extent of 114°40′ to 115°10′E and 2°50′ to 3°20′N, and ranges in elevation from 152 to 1,716 m above sea level. The area is dominated by the Kapit soil series, with Meluan and Merit series also present. Its vegetation is composed mainly of hill mixed dipterocarp forest, together with submontane and kerangas forests. The site is a managed logged-over forest, and most mixed dipterocarp stands have reportedly undergone at least one harvesting cycle.

The Mujong Melinau FMU lies between Sungai Mujong and Sungai Melinau in the Kapit Division, within an approximate extent of 113°25′ to 113°40′E and 1°55′ to 2°10′N. It is a logged-over re-entry forest managed under a framework that follows the original 1998 felling plan [6,7]. The forest contains low, medium, and high-density mixed dipterocarp canopy classes, with medium-density stands occupying the largest area. Lambir, located within Lambir Hills National Park near Miri, was included as a contrasting near-natural forest site. It is centered at approximately 4°12′N and 114°02′E and represents a largely intact old-growth lowland dipterocarp forest. The area extends from approximately 20 to 470 m above sea level and is associated with clay and sandy loam soils.

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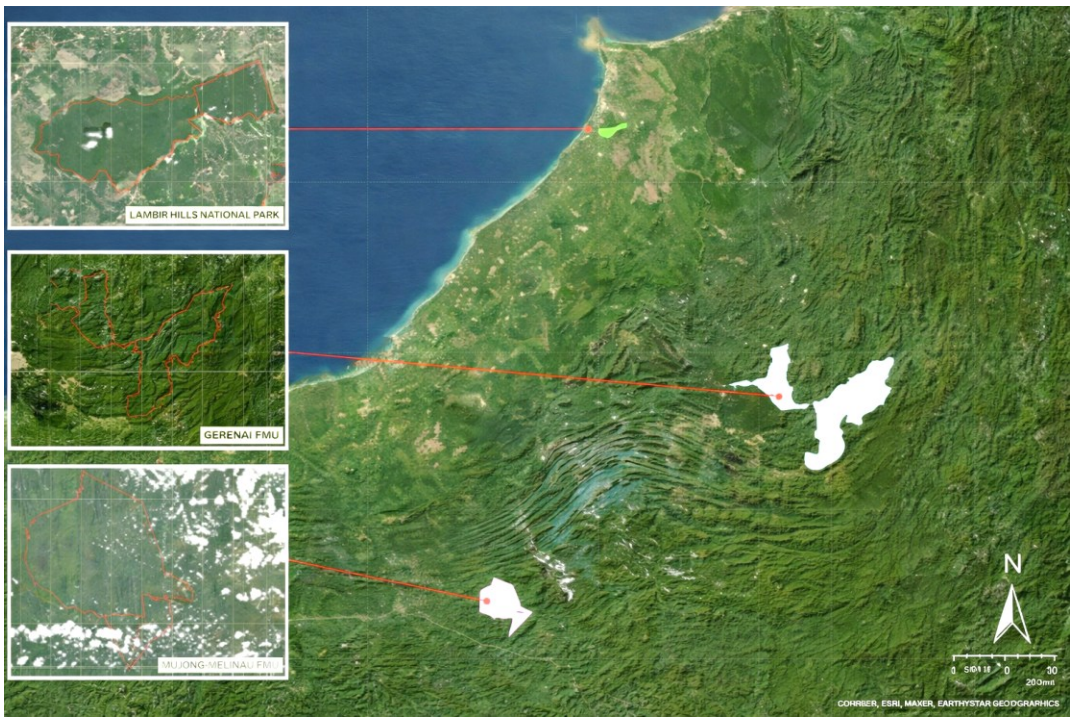

Figure 1. Map of study locations across Sarawak (Gerenai, Mujong-Melinau, and Lambir FMUs).

2.2. Taxon Selection

A total of eight timber taxa were analyzed, comprising four dipterocarp species, namely *S. parvifolia*, *S. angustifolia*, *D. kunstleri*, and *Dryobalanops oblongifolia*, and four non-dipterocarp groups, namely *Syzygium chloranthum*, *Xanthophyllum discolor*, Lauraceae, and Myristicaceae. The analytical dataset was restricted to taxa for which paired age and DBH records were available from at least one locality. Lauraceae and Myristicaceae were retained at the family level because species level identification was not consistently available across the archived records and field verification records. Therefore, these two groups were analyzed at the family level to preserve taxonomic consistency within the dataset.

2.3. Data Collection and Preparation

The data were compiled from two sources. First, archived tree inventory records containing age and DBH information were obtained from the Forest Department Sarawak (FDS) database. In these records, age was originally assigned based on the known planting year for tagged planted individuals or based on the year in which a naturally established seedling was first discovered, tagged, and recorded in the inventory system, with the first recorded year treated as year 1. In the present study, these archived age values were used as recorded by the FDS and were not re-estimated during field verification. Second, field verification was conducted using tagged tree inventory records to confirm tree identity and obtain current DBH measurements where verification was possible. The DBH was measured 1.3 m above the ground, and GPS coordinates were recorded for verified trees.

A total of 4,466 trees were retained in the final dataset across eight taxa. Only trees with usable paired age and DBH information were included in the analysis. Trees without usable age data were excluded from the study. Records that could not be matched confidently during field verification or that were affected by measurement conditions that prevented reliable DBH assessment were also excluded. The field measurement workflow is shown in Figure 2.

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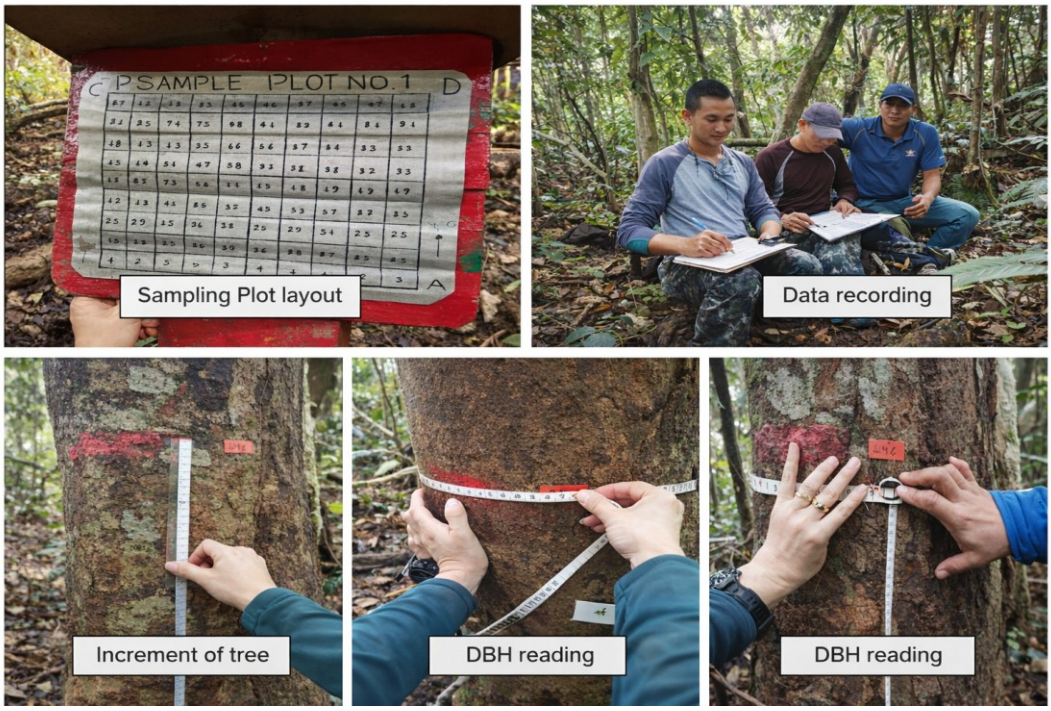

Figure 2. Field sampling and DBH measurements performed.

2.4 Growth Modelling

Species-specific DBH growth was modelled using a negative exponential growth function as shown in Equation 1.

$$DBH = a \times (1 - e^{-b \times Age}) \quad (1)$$

Where DBH is the diameter at breast height (cm), Age is the tree age (years), and *a* and *b* are fitted parameters representing the asymptotic diameter and growth rate constant, respectively. The negative exponential form was selected because it provides a biologically interpretable non-linear growth curve in which the diameter increases rapidly at earlier ages and then decelerates progressively toward an asymptote. This form was considered appropriate for the present analysis because the objective was not to simulate full stand development but to estimate the age at which individual trees would attain the harvestable DBH threshold under an observed age-diameter relationship [8,9].

Models were fitted using non-linear regression in SPSS version 25. Separate models were fitted for each taxon separately. For taxa represented in more than one locality, the localities were first evaluated statistically, as described below. Taxa showing a significant locality effect were modelled separately by locality, whereas taxa showing no significant locality effect were modelled using pooled data from the relevant localities. Taxa represented at only one locality were modelled using data from that locality only [10–14].

Harvestable DBH thresholds were defined as 50 cm for dipterocarps and 45 cm for non-dipterocarps, consistent with the minimum cutting diameter thresholds used in this study. The predicted harvestable age was obtained by solving Equation 1 for the age at the relevant harvestable DBH threshold for each fitted model.

2.5 Statistical Analysis

The effect of locality on DBH growth was evaluated using analysis of covariance (ANCOVA) for taxa represented in more than one locality. In each ANCOVA, DBH was treated as the dependent variable, age as the covariate, and locality as a fixed factor. Homogeneity of regression slopes was assessed before interpretation by testing the age and locality interaction [8,9]. Where the slope assumption was satisfied, the main effect of locality was

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interpreted to determine whether DBH differed significantly among localities after adjusting for age.

A mixed-effects model was not adopted as the primary framework because the present analysis was conducted separately by taxon and involved only a small number of locality levels per taxon, with highly unbalanced representation among localities and several taxa represented at a single site [8,9]. In addition, locality was of direct inferential interest as a named study condition rather than a random sample of sites from a broader population sample. Under these conditions, modelling locality as a fixed effect provided a more transparent and interpretable basis for testing site-related differences before fitting locality-specific or pooled non-linear growth models.

Model validation was conducted using a hold-out approach. Within each modelling unit, defined as each taxon locality dataset for taxa fitted separately by locality or each pooled taxon dataset where locality was not modelled separately, records were randomly partitioned into calibration (70%) and validation (30%) subsets in SPSS version 25. Randomization was performed without replacement by generating a random number for each record, sorting the cases by that value, and assigning the first 70% of cases to the calibration subset and the remaining 30% to the validation subset [13,14].

The calibration and validation assignment was generated once in SPSS version 25 and saved before model fitting, so that all subsequent analyses were based on the same, fixed data partition. Models were fitted using the calibration subset, and predictive performance was then evaluated using the validation subset based on the mean absolute error (MAE), calculated as the mean absolute difference between observed and model-predicted DBH values. Residual plots from the calibration models were also inspected to assess the residual distribution and homoscedasticity. Model fit was summarized using R^2 for the fitted model and MAE for the hold-out predictive error. This two-stage procedure allowed locality to be evaluated first as a potential source of growth variation and then incorporated directly into taxon-specific modelling only where statistically justified by the data.

3. Results and Discussion

3.1. Results

3.1.1. Sample Distribution and Species Composition

Based on the species totals reported in **Table 1**, the analytical dataset comprised 4,466 trees representing eight timber taxa across three study locations. *Shorea parvifolia* was the most abundant taxon overall (n = 2,018) and was strongly concentrated in Lambir (n = 1,972), with only 46 records from Mujong Melinau. *Shorea angustifolia* (n = 585) was the only dipterocarp species represented across all three localities. *Dipterocarpus kunstleri* (n = 375) and *S. chloranthum* (n = 162) were recorded only in Lambir, whereas *D. oblongifolia* (n = 128) was recorded only in Mujong-Melinau. Lauraceae (n = 902), Myristicaceae (n = 216), and *X. discolor* (n = 80) were represented only in Gerenai and Mujong-Melinau.

Overall, the dataset showed a marked imbalance in both taxon abundance and locality representation. This was especially evident for *S. parvifolia*, which was overwhelmingly dominated by Lambir records, and for several taxa restricted to a single locality. These distribution patterns limit the strength of cross-site comparisons for some taxa and should be considered when interpreting locality-specific estimates and generalizing the results beyond the sampled localities. **Figure 3** and **Figure 4** present exploratory scatterplots of the observed age-DBH patterns across taxa, whereas the fitted nonlinear growth models used for harvestable age estimation are summarized in **Table 4**.

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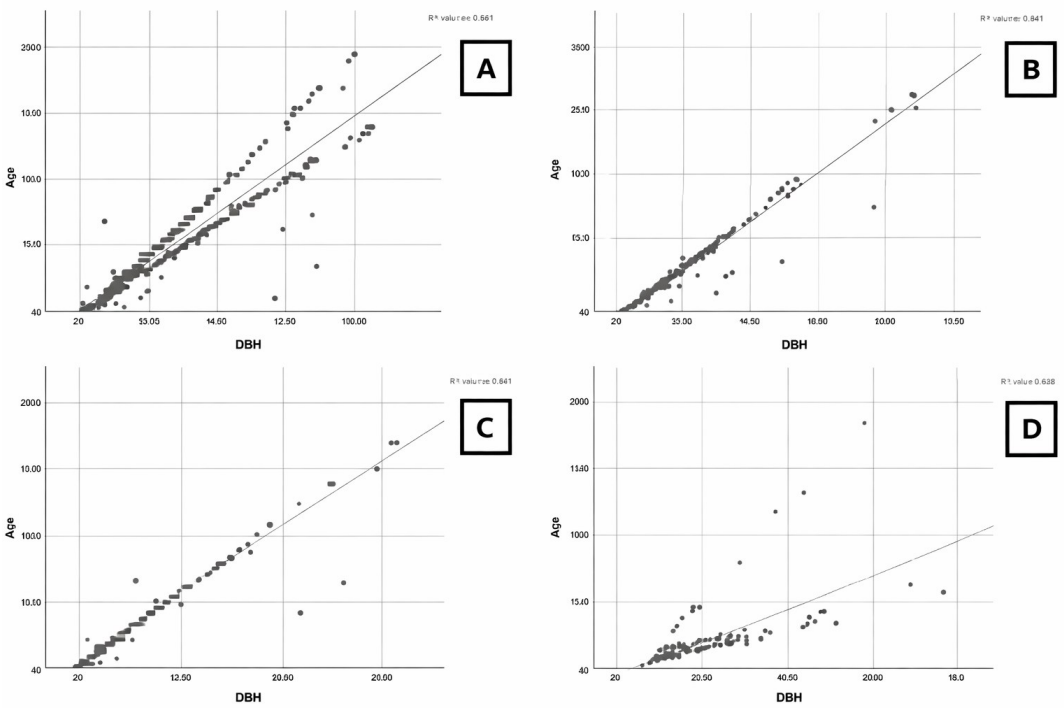

Figure 3. Observed age-DBH scatterplots for dipterocarp taxa analyzed in this study. The panels show (A) *Shorea parvifolia*, (B) *Shorea angustifolia*, (C) *Dipterocarpus kunstleri*, and (D) *Dryobalanops oblongifolia*.

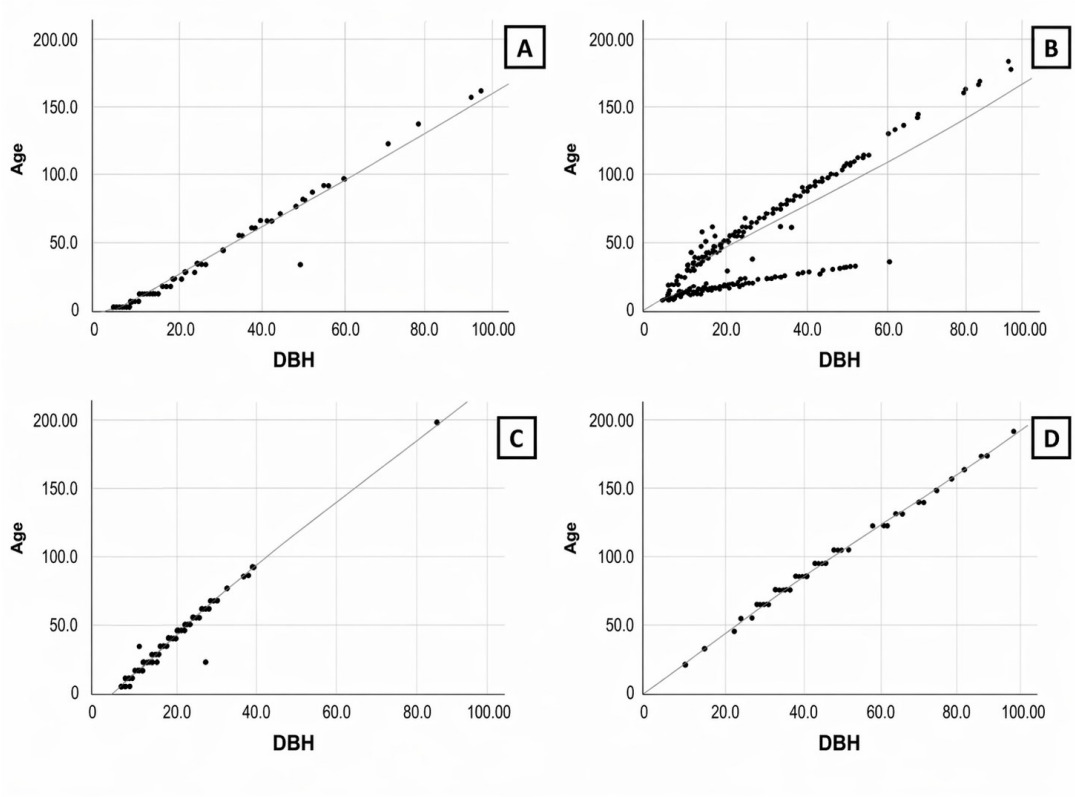

Figure 4. Observed age–DBH scatterplots for the non-dipterocarp taxa analyzed in this study. The panels show (A) *Syzygium chloranthum*, (B) Lauraceae, (C) Myristicaceae, and (D) *Xanthophyllum discolor*.

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Table 1. Distribution of eight timber taxa across three Forest Management Units (FMUs) in Sarawak (Mujong-Melinau, Gerenai, and Lambir), showing variations in sample size and site representation.

No.	Species	Mujong	Gerenai	Lambir	Total
1	*Shorea angustifolia*	366	88	131	585
2	*Shorea parvifolia*	46	0	1972	2018
3	*Dipterocarpus kunstleri*	0	0	375	375
4	*Syzygium chloranthum*	0	0	162	162
5	Lauraceae	344	558	0	902
6	Myristicaceae	130	86	0	216
7	*Xanthophyllum discolor*	42	38	0	80
8	*Dryobalanops oblongifolia*	128	0	0	128

3.1.2. Descriptive Growth Patterns by Species

The mean age and mean DBH varied substantially among the taxa (**Table 2**). The largest mean DBH values were recorded for *X. discolor* (21.70 ±1.13 cm), *S. angustifolia* (21.41 ±0.64 cm), and *D. oblongifolia* (21.21 ±1.09 cm). In contrast, the lowest mean DBH values were recorded for *S. chloranthum* (7.60 ±0.68 cm) and *D. kunstleri* (7.67 ±0.53 cm). The mean age ranged from 17.77 ±2.21 years in *S. chloranthum* to 40.09 ±1.24 years in *S. angustifolia*. Lauraceae and *X. discolor* also showed relatively high mean ages, at 38.15 ±1.22 and 38.50 ±2.25 years, respectively. These descriptive patterns indicate that the analyzed taxa differed not only in current size but also in age structure, suggesting that growth trajectories were unlikely to be uniform across taxa.

Table 2. The mean age and diameter at breast height (DBH) of eight timber taxa highlighted the interspecific variability in growth across sites.

No.	Species	N	Age (Mean ± SE)	DBH (Mean ± SE)
1	*Shorea parvifolia*	2018	19.72 ±0.59	16.59 ±0.44
2	*Shorea angustifolia*	585	40.09 ±1.24	21.41 ±0.64
3	*Dipterocarpus kunstleri*	375	18.81 ±1.7	7.67 ±0.53
4	*Dryobalanops oblongifolia*	128	17.80 ±1.49	21.21 ±1.09
5	*Syzygium chloranthum*	162	17.77 ±2.21	7.60 ±0.68
6	Lauraceae	902	38.15 ±1.22	18.69 ±0.43
7	Myristicaceae	216	28.33 ±1.37	16.79 ±0.68
8	*Xanthophyllum discolor*	80	38.50 ±2.25	21.70 ±1.13

Note: N = number of samples, SE = Standard Error.

3.1.3. Effects of Locality on Growth

Table 3 shows the ANCOVA findings, where after adjusting for age, locality was found to have a statistically significant effect on DBH in *S. parvifolia* ($F = 28.10$, $p < .001$, partial $\eta^2 = 0.014$) and *S. angustifolia* ($F = 8.24$, $p < .001$, partial $\eta^2 = 0.028$). In contrast, locality effects were not significant for Lauraceae ($F = 1.86$, $p = .173$, par tial $\eta^2 = 0.002$), Myristicaceae ($F = 3.66$, $p = .057$, partial $\eta^2 = 0.017$), or *X. discolor* ($F = 3.16$, $p = .079$, partial $\eta^2 = 0.039$). *Dipterocarpus kunstleri* and *D. oblongifolia* were not evaluated for locality effects because each was represented by a single locality. Across the tested taxa, the ANCOVA model R^2 values ranged from 0.769 to 0.996. Although the locality effects were statistically significant for the two *Shorea* taxa, the associated effect sizes were modest. This indicates that age remained the dominant predictor of DBH, but locality sufficiently modified growth to justify separate locality-specific modelling for these taxa. For Lauraceae, Myristicaceae, and *X. discolor*, the absence of significant locality effects supported pooled modelling across the available sites in the present study.

3.1.4. Species-Specific Growth Models and Estimated Cutting Age

The fitted nonlinear models showed variable but generally strong performance across taxa and model units, with R^2 values ranging from 0.612 to 0.996 (**Table 4**). Among dipterocarps, the predicted age required to reach a 50 cm DBH ranged from 52.3 years in *S. parvifolia* at

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Mujong-Melinau to 154.3 years in *D. kunstleri* at Lambir. For *S. angustifolia*, the predicted harvestable age varied among localities, from 75.4 years in Lambir to 85.0 years in Gerenai, whereas *D. oblongifolia* was predicted to reach 50 cm DBH at 77.7 years. Among non-dipterocarps, the predicted age required to reach 45 cm DBH ranged from 85.9 years in *X. discolor* to 173.3 years in *S. chloranthum*, with intermediate values of 89.1 years for Myristicaceae and 119.3 years for Lauraceae species. No modelled taxon approached the currently referenced 25-years cutting cycle.

Table 3. Results of ANCOVA testing the effect of locality on DBH for taxa represented in more than one locality.

Species	N	R^2	F (Age)	F (Locality)	p-value* (Locality)	Partial η^2 (Locality)
Shorea parvifolia	2018	0.858	12,022.78	28.10	< .001	0.014
Shorea angustifolia	585	0.933	7,608.65	8.24	< .001	0.028
Lauraceae	902	0.769	2,974.98	1.86	0.173	0.002
Myristicaceae	216	0.979	9,710.93	3.66	0.057	0.017
Xanthophyllum discolor	80	0.996	19,056.42	3.16	0.079	0.039

Note: *Dryobalanops oblongifolia* and *Dipterocarpus kunstleri* were sampled from a single locality; therefore, the locality effect is not applicable, N = sample size, R^2 = coefficient of determination, *p-value < .05 indicates significant difference.

The validation error, expressed as the MAE in DBH prediction, also varied among the taxa. Among dipterocarps, MAE ranged from 0.53 ±0.11 cm in *S. angustifolia* at Gerenai to 4.84 ±0.52 cm in *D. oblongifolia* at Mujong Melinau. Among non-dipterocarps, MAE ranged from 0.72 ±0.06 cm in X. discolor to 3.95 ±0.21 cm in Lauraceae species. These results indicate that model accuracy differed among taxa and localities, but the MAE values remain interpretable only as DBH prediction errors and not as uncertainty in the predicted age.

Taken together, the model outputs showed two clear patterns. First, harvestable DBH attainment was strongly species-dependent, with some taxa requiring more than a century to reach the harvest threshold. Second, locality affected growth trajectories in at least some commercially important taxa, especially the two Shorea species. The overall implication is that a fixed 25 years re-entry interval is not supported by the observed taxon-level growth patterns reported in this dataset.

3.2. Discussion

Taken together, the findings reveal three linked patterns that are central to interpreting the management relevance of this study. First, substantial variability was observed among taxa in the time required to attain a harvestable DBH, indicating that commercially important timber taxa cannot be treated as biologically interchangeable under a single recovery schedule. Second, locality significantly influenced DBH development in some taxa, particularly *S. parvifolia* and *S. angustifolia*, showing that site conditions can modify growth trajectories, even when age remains the dominant predictor. Third, these species and site-level differences collectively expose a policy mismatch in which a uniform 25-years cutting cycle does not reflect the biological realities of tree growth for the examined taxa. In practical terms, the results suggest that a fixed re-entry interval risks oversimplifying recovery dynamics and may overestimate the capacity of logged forests to replenish harvestable stems within a single operational time frame.

3.2.1. Fixed Cutting Cycles and Biological Realities

This study estimated the time required for individual trees to re-attain the minimum harvestable diameter rather than full stand-level recovery. Even at this narrower level, the modelled growth trajectories were not aligned with 25-years cutting cycle. The fastest predicted age in the dataset was 52.3 years for *S. parvifolia* in Mujong-Melinau, whereas several taxa required substantially longer periods, including 154.3 years for *D. kunstleri* and 173.3 years for *S. chloranthum*. The implication is straightforward: If trees do not regain legal

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harvest size within the re-entry interval, repeated harvesting becomes structurally biased toward removing the remaining large stems, rather than drawing on biologically replenished cohorts.

Table 4. Summary of species-specific growth model performance, predicted age to harvestable DBH, and validation error across taxa and localities.

Growth group	Taxon	Model unit	N	Harvestable DBH threshold (cm)	R^2	Predicted age to harvestable DBH (years)	Validation MAE (cm)
Dipterocarp	*Shorea parvifolia*	Lambir	1972	50	0.858	70.3	4.44 ±0.13
Dipterocarp	*Shorea parvifolia*	Mujong-Melinau	46	50	0.992	52.3	0.76 ±0.10
Dipterocarp	*Shorea angustifolia*	Gerenai	88	50	0.996	85	0.53 ±0.11
Dipterocarp	*Shorea angustifolia*	Lambir	131	50	0.924	75.4	2.48 ±0.48
Dipterocarp	*Shorea angustifolia*	Mujong-Melinau	366	50	0.894	78.5	1.45 ±0.17
Dipterocarp	*Dipterocarpus kunstleri*	Lambir	375	50	0.93	154.3	1.50 ±0.12
Dipterocarp	*Dryobalanops oblongifolia*	Mujong-Melinau	128	50	0.612	77.7	4.84 ±0.52
Non-dipterocarp	*Syzygium chloranthum*	Lambir	162	45	0.957	173.3	1.39 ±0.09
Non-dipterocarp	Lauraceae	Combined (Gerenai + Mujong-Melinau)	902	45	0.667	119.3	3.95 ±0.21
Non-dipterocarp	Myristicaceae	Combined (Gerenai + Mujong-Melinau)	216	45	0.961	89.1	1.27 ±0.10
Non-dipterocarp	*Xanthophyllum discolor*	Combined (Gerenai + Mujong-Melinau)	80	45	0.992	85.9	0.72 ±0.06

Note: N = sample size, R^2 = coefficient of determination; DBH = diameter at breast height; MAE = mean absolute error.

This is important because large trees contribute disproportionately to stand structure and biomass storage. When re-entry occurs before replacement cohorts attain comparable size, the likely outcome is progressive structural simplification and slower recovery of timber-dominant forest structure rather than simple short-term yield fluctuation [15,16]. Evidence from Sarawak further shows that the growth performance and predicted harvesting age of *S. angustifolia* vary with soil fertility across sites, indicating that biologically realistic harvest planning cannot be reduced to a single uniform interval [15].

This interpretation is consistent with the broader evidence from Borneo. In Sarawak, selectively logged forest structures have been reported to remain incompletely recovered even 37 years after logging, indicating that a 25-years harvesting cycle is insufficient for full structural recovery. A Bornean case study further showed that the effects of logging on forest carbon stocks remained perceptible 16 years after logging, and that higher logging intensity was associated with lower total carbon stocks than low-intensity logged or unmanaged forests [17]. Therefore, the present results do not demonstrate stand collapse, but they do show that the currently referenced 25-years interval is biologically too short for the taxa examined to re-attain a harvestable DBH in a consistent manner [18].

3.2.2. Comparison with Other Tropical Forest Studies

The mismatch between a uniform short cutting cycle and the observed growth trajectories was consistent with the literature on tropical forests. Selective logging outcomes are known to remain highly sensitive to harvest intensity, collateral damage, re-entry timing, and local ecological conditions. Therefore, the present results fit a broader regional pattern in which operational harvesting schedules may be shorter than the biological recovery horizon implied by tree growth, especially when commercial taxa with contrasting growth rates are managed under a single schedule.

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The exceptionally long estimate for *D. kunstleri* deserves a separate interpretation. The present dataset does not allow for the direct identification of the mechanism, but the results are biologically plausible. Experimental studies have shown that dipterocarp species differ markedly in their growth responses across light environments, that diameter growth generally increases under higher light, and that species performance can shift substantially across light gradients [17,18]. Seedling survival in Bornean dipterocarps is also influenced by canopy openness and varies among species [18]. More broadly, dipterocarp taxa include both faster and more light-responsive species and slower and more shade-tolerant groups [19–22].

Within this framework, the slow growth of *D. kunstleri* in the present dataset is consistent with a conservative life-history strategy in which canopy accession and diameter increment may be limited under shaded or competitive conditions. A species with such a strategy would not be expected to track the recovery pace of faster commercial taxa under a short, uniform re-entry schedule. However, because this study did not directly measure crown position, light availability, competition, or physiological traits, shade tolerance, canopy stratification, and life-history strategy should be interpreted as plausible explanations rather than demonstrated causal mechanisms [23,24].

3.2.3. Site-Specific Growth Variability

Locality significantly affected DBH in *S. parvifolia* and *S. angustifolia*, although the associated effect sizes were modest relative to the dominant effect of stand age. This does not make the locality biologically trivial. When harvestable age is projected from non-linear growth models, even moderate locality differences can shift the estimated time required to reach threshold DBH by decades [25–28], as shown by the separately modelled ages for both *Shorea* taxa in the present study. In practical terms, locality modified growth expectations for some taxa, even when it did not replace age as the primary determinant of diameter development.

Simultaneously, the non-significant locality effects for Lauraceae, Myristicaceae, and *X. discolor* should not be interpreted as proof of universal site independence. These analyses relied on pooled or limited cross-site representation, and two groups were analyzed only at the family level. A more defensible interpretation is that locality effects were taxon-specific and detectable where the data structure allowed them to be tested adequately [28]. This supports locality-sensitive planning, where taxon-specific evidence is available, while avoiding overgeneralization, where it is not.

3.2.4. Implications for Species Prioritisation and Cutting Cycle Planning

The modelled ages provide a practical biological range for interpreting cutting cycle planning, but do not support a single replacement interval for all taxa. For the faster-growing subset, the lowest estimates fell between 52.3 and 77.7 years, whereas several other taxa required substantially longer horizons, including more than 100 years for Lauraceae, *D. kunstleri*, and *S. chloranthum* species. Therefore, the management implication is not simply to replace 25 years with another uniform number. Rather, the data support a differentiated framework in which faster-growing taxa define the shortest plausible re-entry window, whereas slower-growing taxa are treated more conservatively in terms of yield expectations and harvest scheduling [16].

In practical terms, species that require much longer to regain a harvestable DBH should not be assumed to be equally available at every entry under a short-fixed cycle. More defensible planning would combine species- and locality-sensitive scheduling with conservative harvest intensity, retention of future crop trees, and systematic post-harvest monitoring of residual structures and growth [25–32]. Management should also avoid treating logged forests solely as future timber stocks because Sarawak forests support a wider range of culturally and medicinally important plant resources used by indigenous and local communities. Recent ethnobotanical studies in Sarawak show that forest plants remain important to community health practices and conservation value, reinforcing the need for harvesting regimes that maintain broader floristic integrity rather than focusing only on commercial timber recovery [5,30–32].

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The present data do not justify a blanket exclusion rule for slower-growing taxa, but they do show that treating all commercial taxa as biologically interchangeable under a short-cycle system would overstate the recoverable timber and understate the vulnerability of the slower-growing group.

3.2.5. Study Limitations

However, these interpretations remain constrained by the structure of the dataset. Because the archived age data were inventory-based rather than independently re-aged in this study, age should be interpreted as record-based age rather than the exact biological age. Records with missing or unusable age data were excluded. However, the study could not independently verify the original age assignment for all trees.

Lauraceae and Myristicaceae were analysed at the family level, which reduced species-level resolution and may have obscured within-group variation. Geographic representation also differed among taxa, with several taxa represented at a single locality only, limiting broader inferences on locality effects.

Accordingly, the present estimates are the strongest comparative evidence that harvestable DBH attainment differs markedly among taxa and that a uniform 25-years cutting cycle is not aligned with these differences. They should not be read as stand-level proof of complete recovery failure or as fixed scheduling prescriptions without complementary data on regeneration, residual stocking, and post-harvest stand dynamics.

4. Conclusion

This study shows that a uniform 25-years cutting cycle is biologically unsupported for the eight timber taxa examined in Sarawak. All modelled taxa required substantially longer periods to attain a harvestable DBH, and locality effects in key *Shorea* taxa further show that a single re-entry interval cannot adequately represent site-specific growth realities. The implication is clear, is to fixed short-cycle scheduling risks overstating sustainable timber recovery and underestimating depletion risk for slower-growing taxa. Although the analysis is constrained by archive-derived age records, uneven locality representation, and family level grouping for some taxa, the evidence supports a shift toward species-specific and locality-sensitive cutting cycle planning.

Author Contributions

AH: Conceptualization, Methodology, Software, Investigation, Writing - Review & Editing; **KSR**, **MRMK**, **AA**: Writing - Review & Editing, Supervision; **BLK** and **DSK**: Writing - Review.

Conflicts of Interest

There are no conflicts to declare.

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Generative AI Writing Statement

During the preparation of this manuscript, the authors used ChatGPT 5.4 for language editing and grammar checking. After using this tool, the authors carefully reviewed, verified, and edited all generated or modified content and accept full responsibility for the integrity and accuracy of the manuscript.

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References

1. Ashton, P.S.; Paoli, G.D.; Appanah, S. Tropical Forest Regeneration and Sustainable Management in Southeast Asia: Lessons from Long-Term Research. *For. Ecol. Manage.* **2022**, *503*, 119763.
2. Matias, G.; Cagnacci, F.; Rosalino, L.M. FSC Forest Certification Effects on Biodiversity: A Global Review and Meta-Analysis. *Sci. Total Environ.* **2024**, *908*, 168296, doi:10.1016/j.scitotenv.2023.168296.
3. Azhar, M.A.A.; others Comparative Analysis of Soil Quality in Natural, Logged, and Plantation Forests in Kuala Kubu Bharu, Malaysia. *Malaysian J. Soil Sci.* **2025**, *29*, 157–164.
4. Di Girolami, E.; Kampen, J.; Arts, B. Two Systematic Literature Reviews of Scientific Research on the Environmental Impacts of Forest Certifications and Community Forest Management at a Global Scale. *For. Policy Econ.* **2023**, *146*, doi:10.1016/j.forpol.2022.102864.
5. Rajoo, K.S.; Karam, D.S.; Abdu, A.; Rosli, Z.; Gerusu, G.J. Urban Forest Research in Malaysia: A Systematic Review. *Forests* **2021**, *12*, 903, doi:10.3390/f12070903.
6. Forest Department Sarawak Forest Harvesting Cutting Cycle 2026.
7. Forest Department Sarawak Forest Harvesting Sequence of Operations 2026.
8. Salas-Eljatib, C.; Mehtätalo, L.; Gregoire, T.G.; Soto, D.P.; Vargas-Gaete, R. Growth Equations in Forest Research: Mathematical Basis and Model Similarities. *Curr. For. Reports* **2021**, *7*, 230–244, doi:10.1007/s40725-021-00145-8.
9. Ciceu, A.; Chakraborty, D.; Ledermann, T. Examining the Transferability of Height-Diameter Model Calibration Strategies across Studies. *For. An Int. J. For. Res.* **2023**, cpad063, doi:10.1093/forestry/cpad063.
10. Gomes, D.G.E. Should I Use Fixed Effects or Random Effects When I Have Fewer than Five Levels of a Grouping Factor in a Mixed-Effects Model? *PeerJ* **2022**, *10*, e12794, doi:10.7717/peerj.12794.
11. Oberpriller, J.; de Souza Leite, M.; Pichler, M. Fixed or Random? On the Reliability of Mixed-Effects Models for a Small Number of Levels in Grouping Variables. *Ecol. Evol.* **2022**, *12*, e9062, doi:10.1002/ece3.9062.
12. O'Brien, M.J.; Hector, A.; Ong, R.; others Tree Growth and Survival Are More Sensitive to High Rainfall than Drought in an Aseasonal Forest in Malaysia. *Commun. Earth \& Environ.* **2024**, *5*, 179, doi:10.1038/s43247-024-01335-5.
13. Harrison, X.A.; others A Brief Introduction to Mixed Effects Modelling and Multi-Model Inference in Ecology. *PeerJ* **2018**, *6*, e4794, doi:10.7717/peerj.4794.
14. Silk, M.J.; Harrison, X.A.; Hodgson, D.J. Perils and Pitfalls of Mixed Effects Regression Models in Biology. *PeerJ* **2020**, *8*, e9522, doi:10.7717/peerj.9522.
15. Hamjah, A.; others Influence of Soil Fertility on Growth Performance and Optimal Harvesting Age of Shorea Angustifolia in Logged Forests of Sarawak. *Malaysian J. Soil Sci.* **2025**, *29*, 137–143.
16. Diway, B.; Yiing, L.C.; Wasli, M.E.; Takeuchi, Y. Forest Structure and Recovery in Selectively Logged Forests in Sarawak, Malaysia. *Tropics* **2023**, *32*, 1–14, doi:10.3759/tropics.MS22-07.
17. Rozak, A.H.; Rutishauser, E.; Raulund-Rasmussen, K.; Sist, P. The Imprint of Logging on Tropical Forest Carbon Stocks: A Bornean Case-Study. *For. Ecol. Manage.* **2018**, *417*, 154–166, doi:10.1016/j.foreco.2018.03.007.
18. van der Werf, E.; Indrajaya, Y.; Mohren, F.; van Ierland, E.C. Logging Damage and Injured Tree Mortality in Tropical Forest Management. *Nat. Resour. Model.* **2019**, *32*, e12210, doi:10.1111/nrm.12210.
19. Gustafsson, M.; others Life History Traits Predict the Response to Increased Light among 33 Tropical Rainforest Tree Species. *For. Ecol. Manage.* **2016**, *362*, 20–28, doi:10.1016/j.foreco.2015.11.017.
20. Zhang, C.; Gu, R.; Lin, L.; Russo, S.E. Functional Traits and Ecological Niches as Correlates of the Interspecific Growth-Mortality Trade-off among Seedlings of 14 Tropical Tree Species. *Funct. Ecol.* **2024**, *38*, 1888–1901, doi:10.1111/1365-2435.14624.
21. Bartholomew, D.C.; Hayward, R.; Burslem, D.F.R.P.; others Bornean Tropical Forests Recovering from Logging at Risk of Regeneration Failure. *Glob. Chang. Biol.* **2024**, *30*, e17209, doi:10.1111/gcb.17209.
22. Oshima, C.; Tokumoto, Y.; Nakagawa, M. Biotic and Abiotic Drivers of Dipterocarp Seedling Survival Following Mast Fruiting in Malaysian Borneo. *J. Trop. Ecol.* **2015**, *31*, 129–137, doi:10.1017/S026646741400073X.
23. Avalos, G. Shade Tolerance within the Context of the Successional Process in Tropical Rain Forests. *Rev. Biol. Trop.* **2019**, *67*, 53–77, doi:10.15517/RBT.V67I2SUPL.37206.

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24. Karam, D.S.; Rajoo, K.S.; Azhar, M.; Jeyanny, V.; Ahmad, K. A Narrative Review of the Impact of Forest Rehabilitation Programs on Soil Quality in Peninsular Malaysia. *Malaysian J. Soil Sci.* **2022**, *26*, 1–16.

25. Iida, Y.; Niiyama, K.; Aiba, S.; others The Trait-Mediated Trade-off between Growth and Survival Depends on Tree Sizes and Environmental Conditions. *J. Ecol.* **2023**, *111*, 1777–1793, doi:10.1111/1365-2745.14146.

26. Scholten, T.; others On the Combined Effect of Soil Fertility and Topography on Tree Growth in Subtropical Forest Ecosystems, a Study from SE China. *J. Plant Ecol.* **2017**, *10*, 111–127, doi:10.1093/jpe/rtw065.

27. Gourlet-Fleury, S.; others Competition and Site Weakly Explain Tree Growth Variability in Central African Forests. *J. Ecol.* **2023**, *111*, 1836–1851, doi:10.1111/1365-2745.14152.

28. Cerullo, G.R.; Edwards, D.P.; Milodowski, D.T.; Edwards, F.A.; Chazdon, R.L. Actively Restoring Resilience in Selectively Logged Tropical Forests. *J. Appl. Ecol.* **2019**, *56*, 107–118, doi:10.1111/1365-2664.13262.

29. Philipson, C.D.; others Active Restoration Accelerates the Carbon Recovery of Human-Modified Tropical Forests. *Science (80-.).* **2020**, *369*, 838–841, doi:10.1126/science.aay4490.

30. Rajoo, K.S.; Umayrah, N.A.; Lepun, P. Ethnomedicinal Study of Medicinal Plants Used by the Melanau Igan Community of Sarawak. *Ethnobot. Res. Appl.* **2024**, *27*, 1–31, doi:10.32859/era.27.9.1-31.

31. Rajoo, K.S.; Lepun, P.; Kayok, B.L.A.; Hakiman, M.; Irie, M. Ethnobotanical Survey of Medicinal Plants Used by the Punan People of Sarawak, Borneo: A Conservation Perspective. *Trop. Conserv. Sci.* **2025**, *18*, 1–13, doi:10.1177/19400829251328561.

32. Rajoo, K.S.; Lepun, P.; Kayok, B.L.A.; Umayrah, N.A.; Abdullah, N. Ethnomedicinal Survey of Antidiabetic Plants Used by Six Indigenous Communities in Sarawak, Borneo. *J. Herb. Med.* **2025**, *51*, 101011, doi:10.1016/j.hermed.2025.101011.

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