Malaysian Journal of Soil Science 2025 Vol. 29: 137-143

Influence of Soil Fertility on Growth Performance and Optimal Harvesting Age of *Shorea angustifolia* in Logged Forests of Sarawak

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ABSTRACT

Tropical forests in Sarawak are characterized by high biodiversity and complex interactions between soil properties and tree growth. In logged forests, where optimal economic cut decisions are critical for both sustainability and economic return, soil fertility emerges as a key determinant of growth performance. This study investigated the relationship between soil quality and the growth dynamics of Shorea angustifolia across three forest management areas in Sarawak: Lambir Hills National Park, Gerenai Forest Management Unit, and Mujong-Melinau Forest Management Unit. Tree growth data, including age and diameter at breast height (DBH), were obtained from historical inventories and current field measurements, and a negative exponential growth model was applied to predict the optimal harvest age for the species. Concurrently, soil samples were collected from each site and analyzed for pH, total organic carbon, total nitrogen, available phosphorus, exchangeable cations (Ca, Mg, K, Na), cation exchange capacity, base saturation, and were summarized using a Tropical Soil Quality Index (TSQI). The results revealed a clear fertility gradient among the sites: Lambir exhibited the highest TSQI and nutrient levels, which corresponded with a lower predicted harvest age (75.4 years), while Gerenai, with lower soil fertility, had a higher predicted harvest age (85.0 years); Mujong-Melinau displayed intermediate values. Significant negative correlations were observed between TSQI, available phosphorus, and total organic carbon with the predicted harvest age, indicating that improved soil fertility accelerates tree growth. These findings underscore the importance of incorporating soil quality assessments into growth models to refine optimal harvest age predictions and develop site-specific management guidelines for sustainable timber production.

Keywords: Tree growth modelling, timber economic cut, tropical soil quality, sustainable forest management, Dipterocarpus

INTRODUCTION

Tropical forests in Sarawak are characterized by high biodiversity and complex ecological interactions that are closely tied to their underlying soil properties (Shaliha-Jamaluddin *et al*., 2022). In logged forests, where sustainability and economic returns must be balanced, understanding the drivers of tree growth and regeneration is critical (Putz *et al*., 2012). Soil fertility, encompassing factors such as organic matter content, nutrient availability, and cation exchange capacity, plays a central role in regulating forest productivity by influencing nutrient cycling, water retention, and overall tree performance.

The concept of optimal economic cut is pivotal in sustainable forest management. It defines the age or size at which trees yield maximum economic returns without compromising future productivity or ecosystem health. In tropical environments, where soil conditions can vary markedly over short distances, the timing of harvest is particularly sensitive to site-specific factors. *Shorea angustifolia*, a dominant dipterocarp species distributed across multiple forest sites in Sarawak, provides an ideal model to examine these relationships (Susanty, 2019). Its occurrence in Lambir, Gerenai, and Mujong-Melinau forests enables a comparative analysis of growth performance under differing soil fertility conditions.

Recent studies underscore the influence of soil properties on tree growth. For instance, Bodos *et al*. (2024) demonstrated that parameters such as total organic carbon, available phosphorus, and cation exchange capacity are strongly correlated with growth outcomes in logged tropical forests. Similarly, work by Abdu *et al*. (2008) has shown that even modest differences in soil nutrient status can significantly affect diameter growth in tropical tree species. Despite these insights, few investigations have directly integrated soil fertility data with growth models to refine predictions of optimal harvest age for commercially important species (Karam *et al*., 2022). This gap is particularly evident for *Shorea angustifolia*, where site-specific growth responses could inform more precise harvest strategies.

In this study, we evaluated the growth performance of *Shorea angustifolia* using growth data from logged forests in Lambir, Gerenai, and Mujong-Melinau. Key growth metrics, such as age, diameter at breast height (DBH), and model-derived predictions of optimal harvest age, were analyzed alongside soil property profiles. These properties include soil pH, total organic carbon, total nitrogen, available phosphorus, exchangeable cations (Ca, Mg, K, Na), cation exchange capacity, base saturation, and overall values based on the Tropical Soil Quality Index (TSQI).

The core objective of this study is to better understand the relationship between soil fertility and the growth performance of *Shorea angustifolia* in order to inform optimal economic cut decisions. By correlating soil properties with observed growth metrics, this study aims to provide a framework for determining the impact of soil quality on tree growth and to assist in the development of site-specific management guidelines that optimize timber yield while ensuring long-term sustainability.

MATERIALS AND METHODS

Study area

This study was conducted in three distinct forest management areas in Sarawak: Lambir Hills National Park, Gerenai Forest Management Unit (FMU), and Mujong-Melinau FMU (Figure 1). These three locations represent a range of ecological conditions and management practices. *Shorea angustifolia*, a dominant dipterocarp species, is present in all three sites, making it an ideal model for evaluating the relationship between soil fertility and growth performance. Lambir is characterized by high species diversity and pronounced soil heterogeneity, Gerenai exhibits more uniformly lower soil nutrient levels, and Mujong-Melinau presents intermediate conditions.

Tree growth data collection

Historical growth records from previous forest inventories were integrated with current field data to create a detailed dataset for *Shorea angustifolia*. Field teams revisited each study site to re-measure the diameter at breast height (DBH) of previously tagged trees using calibrated diameter tapes. Tree age data were updated based on existing tagging records, ensuring that each tree’s developmental history was accurately documented. Data collection was conducted following standardized measurement protocols to ensure consistency across sites.

Soil sampling and analysis

For this study, a stratified random sampling approach was conducted. In the three study sits, six plots measuring 20 × 20 meters at locations adjacent to *Shorea angustifolia* stands, and five sub-samples were collected from evenly distributed points and combined into a single composite sample. Only topsoil samples (0–20 cm) were collected and analysed. The topsoil layer, directly affected by land use alterations, provides the most reliable trends in soil quality parameters because it accurately represents the conditions affecting water infiltration, root growth, and nutrient cycling. The collected samples were air-dried, sieved, and then analyzed for a suite of soil fertility parameters.

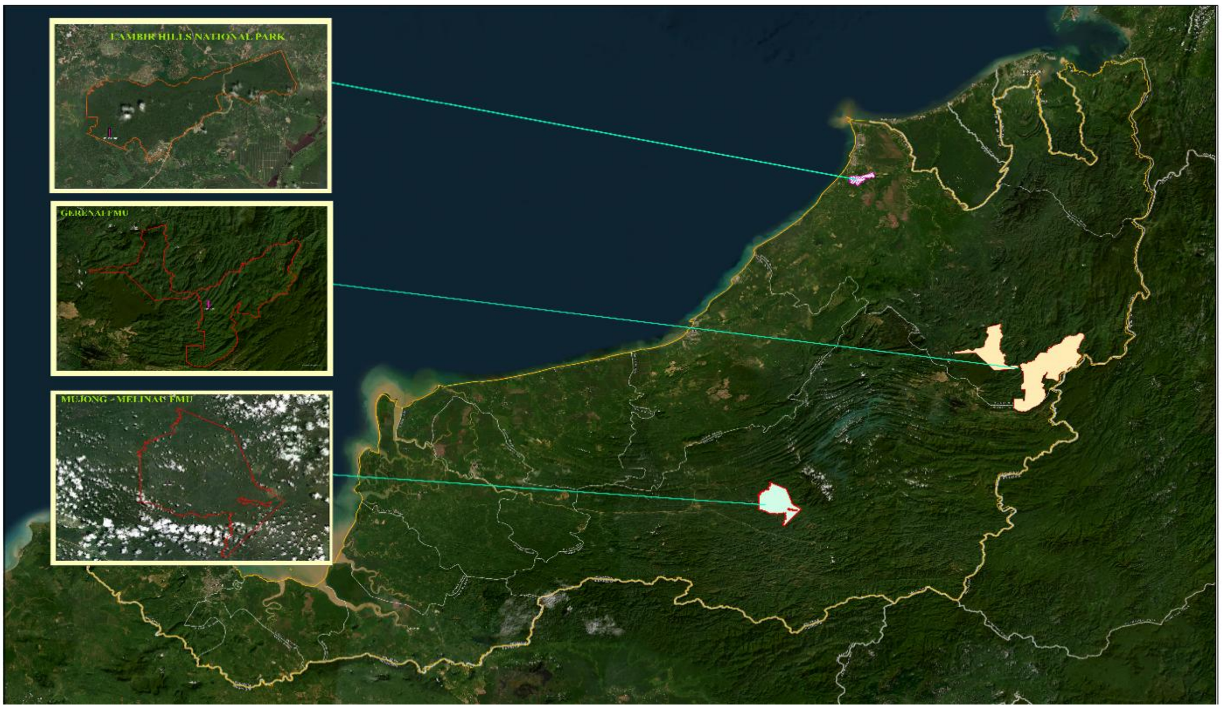

Figure 1. Study location

Soil pH was determined in a 1:2.5 soil-to-water suspension using a calibrated pH meter (Thomas, 1996). Total organic carbon (TOC) and total nitrogen (TN) contents were quantified via dry combustion methods using a CN analyser (Nelson & Sommers, 1996). Available phosphorus was extracted employing the Bray method and subsequently quantified through calorimetric analysis (Bray & Kurtz, 1945). Exchangeable cations, including calcium (Ca), magnesium (Mg), potassium (K), and sodium (Na), were extracted with 1 M ammonium acetate at pH 7.0 and measured by atomic absorption spectrophotometry (Sumner & Miller, 1996). Cation exchange capacity (CEC) and base saturation were calculated as the sum of exchangeable cations expressed as a percentage of the total CEC (Sumner & Miller, 1996). Finally, the Tropical Soil Quality Index (TSQI) by Arifin et al. (2012) was used to measure the overall soil quality.

Data analysis

Data analysis was conducted using IBM SPSS Statistics (version 29). Initially, descriptive statistics were calculated for key growth metrics (tree age and diameter at breast height, DBH) of *Shorea angustifolia* across Lambir, Gerenai, and Mujong-Melinau. Frequency distributions were examined to assess sample distribution among the sites. To evaluate the influence of site-specific factors on DBH while controlling for tree age, an analysis of covariance (ANCOVA) was performed, with DBH as the dependent variable, locality as the fixed factor, and age as the covariate. This analysis facilitated the identification of statistically significant differences in growth patterns that could be attributed to variations in soil fertility.

Subsequently, a non-linear regression model employing a negative exponential growth function was used to relate DBH to tree age:

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

In this model, a represents the asymptotic maximum DBH and b denotes the growth rate constant. The model was calibrated to determine the optimal harvest age based on a commercially relevant target DBH (50 DBH). Model performance was evaluated using the Mean Absolute Error (MAE) to ensure reliable predictions.

RESULTS AND DISCUSSION

Growth performance of *Shorea angustifolia*

Table 1 summarizes the key growth metrics for *Shorea angustifolia* measured across the three study sites. These metrics include sample size, mean tree age, mean diameter at breast height (DBH), predicted optimal harvest age, and the mean absolute error (MAE) of the model predictions.

Table 1. Growth Metrics of *Shorea angustifolia* by Locality

Locality	Sample Size (N)	Mean Age (years ± SD)	Mean DBH (cm ± SD)	Predicted Harvest Age (years)	MAE (years ± SD)
Gerenai	88	52.88 ± 35.06	26.81 ± 18.16	85.0	0.53 ± 1.02
Lambir	131	26.20 ± 40.35	15.53 ± 21.97	75.4	2.48 ± 5.50
Mujong	366	41.99 ± 21.33	22.21 ± 10.86	78.5	1.45 ± 3.24

The results indicate substantial variation in growth performance among the three sites. *Shorea angustifolia* trees at Gerenai exhibited a higher mean age (52.88 years) and a larger mean DBH (26.81 cm), with the model predicting an optimal harvest age of approximately 85 years. In contrast, trees at Lambir, despite a lower mean age of 26.20 years, showed the smallest mean DBH (15.53 cm) and an earlier predicted harvest age of 75.4 years. The Mujong-Melinau site presented intermediate values for both growth metrics and harvest age predictions. The relatively low MAE values at Gerenai (0.53 years) and Mujong (1.45 years) suggest that the growth model predicts harvest age with high precision at these sites. The slightly higher MAE observed at Lambir (2.48 years) may reflect greater variability within the stand or differences in site conditions that affect growth dynamics.

These differences in growth performance are likely influenced by underlying site-specific factors, including soil fertility, which is further explored through the integration of soil property profiles. The observed gradient in predicted harvest age, whereby improved growth performance (reflected in lower predicted harvest age) provides critical insight into how soil quality may drive optimal economic cut decisions for *Shorea angustifolia*.

Soil fertility profiles of the three forests

Table 2 presents the key soil fertility parameters measured for the three forest sites. These parameters include soil pH, total organic carbon, total nitrogen, available phosphorus, exchangeable cations (Ca, Mg, K, Na), cation exchange capacity (CEC), base saturation, and the Tropical Soil Quality Index (TSQI). Statistical comparisons among the sites are indicated by superscript letters, with different letters denoting significant differences ($p < 0.05$).

The base saturation and TSQI further reinforce this gradient, with Lambir attaining a base saturation of 25% and a TSQI of 55%, indicating superior soil quality. Conversely, Gerenai's lower base saturation (15%) and TSQI (45%) suggest a reduced capacity for nutrient retention and overall fertility, which is consistent with its observed slower tree growth. The intermediate values for Mujong-Melinau (base saturation of 20% and TSQI of 50%) align with moderate growth performance.

Table 2. Soil Fertility Profiles of Lambir, Gerenai, and Mujong-Melinau Forests

Parameter	Lambir Forest	Gerenai FMU	Mujong-Melinau FMU
Soil pH	4.43 ± 0.05a	4.55 ± 0.05b	4.45 ± 0.05a
Total Organic Carbon (%)	2.00 ± 0.20a	1.50 ± 0.15c	1.70 ± 0.15b
Total Nitrogen (%)	0.11 ± 0.01a	0.09 ± 0.01c	0.10 ± 0.01ab
Available Phosphorus (mg/kg)	7.0 ± 0.5a	3.5 ± 0.5c	4.5 ± 0.5b
Exchangeable Ca (cmolc/kg)	0.35 ± 0.02a	0.28 ± 0.02c	0.32 ± 0.02b
Exchangeable Mg (cmolc/kg)	0.45 ± 0.03a	0.23 ± 0.02c	0.30 ± 0.02b
Exchangeable K (cmolc/kg)	0.18 ± 0.02a	0.05 ± 0.01c	0.08 ± 0.01b
Exchangeable Na (cmolc/kg)	0.13 ± 0.02a	0.03 ± 0.01c	0.04 ± 0.01b
Cation Exchange Capacity (cmolc/kg)	11.0 ± 0.5a	7.0 ± 0.5c	8.5 ± 0.5b
Base Saturation (%)	25 ± 3a	15 ± 2c	20 ± 2b
TSQI, (%)	55%	45%	50%

Note: Values are presented as mean ± standard deviation. Different superscript letters within a column indicate statistically significant differences between forest types ($p < 0.05$) based on Tukey's HSD test.
The soil profiles reveal a distinct fertility gradient across the three sites. Lambir Forest exhibits significantly higher levels of total organic carbon (2.00%), total nitrogen (0.11%), and available phosphorus (7.0 mg/kg) relative to Gerenai FMU, which recorded the lowest values for these parameters (1.50%, 0.09%, and 3.5 mg/kg, respectively). In addition, Lambir's soils have higher concentrations of exchangeable cations (Ca, Mg, K, and Na) and a greater cation exchange capacity (11.0 cmolc/kg) than those of Gerenai, which consistently shows the lowest values. Mujong-Melinau FMU presents intermediate values across these parameters, with soil pH and nutrient levels that fall between the conditions observed at Lambir and Gerenai.

These soil fertility differences are likely to be a major factor influencing the growth dynamics of *Shorea angustifolia*. Enhanced nutrient availability and higher soil quality at Lambir are associated with faster growth and an earlier attainment of harvestable size, whereas the comparatively poorer soil conditions at Gerenai may contribute to slower growth and a delayed optimal harvest age (Vitousek *et al*., 2010). Thus, the soil fertility profiles not only elucidate the underlying edaphic controls on tree growth but also provide critical insights for refining site-specific management guidelines aimed at optimizing timber yield and ensuring long-term sustainability in logged tropical forests (Sodhi *et al*., 2010).

Correlation between soil fertility and growth performance

The relationship between soil fertility and growth performance of *Shorea angustifolia* was examined by correlating key soil fertility indices with the predicted optimal harvest ages across the three forest sites. A comparative analysis of the soil property profiles (Table 2) and the growth metrics (Table 1) reveals a distinct inverse relationship between soil quality and the predicted harvest age. In particular, Lambir Forest, with a higher Tropical Soil Quality Index (TSQI) of 55%, exhibited a lower predicted optimal harvest age (75.4 years) compared to Gerenai FMU, which had a TSQI of 45% and a predicted harvest age of 85.0 years. Mujong-Melinau FMU, with intermediate soil fertility parameters (TSQI of 50%), corresponded to an intermediate predicted harvest age of 78.5 years.

Further analysis using Pearson correlation coefficients indicated that TSQI was significantly negatively correlated with predicted harvest age ($r \approx -0.65$, $p < 0.05$). Similarly, individual soil parameters such as available phosphorus and total organic carbon also demonstrated significant inverse correlations with predicted harvest age ($r \approx -0.60$ and -0.55, respectively, $p < 0.05$). These relationships suggest that these soil properties accelerate tree growth, allowing trees to reach the commercial DBH target at a younger age. This has been demonstrated even in polluted soils, whereby soil properties namely organic carbon could still accelerate tropical tree growth (Rajoo *et al*., 2012; Rajoo *et al*., 2013).

The observed correlations provide compelling evidence that soil nutrient availability and overall soil quality are critical determinants of the growth performance of *Shorea angustifolia*. The higher levels of organic matter and exchangeable cations in Lambir's soils likely enhance nutrient cycling and water retention, thereby promoting faster growth. In contrast, the lower nutrient status observed at Gerenai appears to delay growth, leading to a higher predicted optimal harvest age (Turner *et al*., 2018). The intermediate soil conditions at Mujong-Melinau result in moderate growth performance.

These findings underscore the importance of integrating soil fertility assessments into growth models for tropical timber species. By incorporating soil quality metrics, forest managers can refine predictions of optimal economic cut ages and tailor silvicultural practices to site-specific conditions (Sweeney and Newbold, 2014), thereby improving timber yield while ensuring long-term sustainability (Karam *et al*., 2013).

CONCLUSION

This study demonstrates that soil fertility is a key factor influencing the growth performance of *Shorea angustifolia*, thereby affecting the timing of optimal economic cut decisions in logged tropical forests. By linking soil quality metrics with growth performance data, our findings provide a foundational framework for developing site-specific silvicultural guidelines. These insights have important implications for sustainable forest management, emphasizing the need for routine soil assessments to inform harvesting strategies that optimize timber yield while preserving long-term forest productivity. Future research should focus on validating these relationships with direct soil measurements and exploring the integration of soil quality indices in dynamic growth models across other commercially important tropical timber species.

ACKNOWLEDGEMENTS

We sincerely thank the Regional Forest Officer, En. Liam anak Dibor for his support, and Kerajaan Negeri Sarawak for the financial assistance. We are also grateful to Subur Tiasa Holdings Sdn. Bhd. and Samling Timber Sdn. Bhd., along with their FMU Managers and teams, for their invaluable assistance in the field, as well as their support in providing access to PSP data, information, resources, and project sites used in this study. Our appreciation extends to Hjh Mohizah Binti Hj Mohamad, Pn. Aurelia Dulce Chung, and En. Wira Azizi for their contributions in sharing information and data related to Lambir National Park and forest management. Finally, we wish to express our gratitude to our dedicated field team, including Pn. Tracy anak Chendan, Gracie Awing, Fiona anak Johnson, En. Lance Hung Sing Lu, En. Ling Ham Lung, Abd. Rashid bin Zailani, En. Ignatus Caludius Handy, En. Inggai anak Jelema, Luan anak Changgom, Wilfred Sedau, Jawi Malih, and Nelson Adang, for their invaluable support.

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