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RESEARCH ARTICLE

Comparative analysis of carbon stock in *Hevea brasiliensis* using different allometric equations

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ABSTRACT

Rubber tree (*Hevea brasiliensis*) plantations represent both an economic resource and a potential carbon sink, yet reliable estimation of their carbon storage capacity remains challenging due to variability among allometric equations. This study evaluated aboveground biomass and carbon stock in a rubber plantation at Kampung Pasir Dusun, Jeli, Kelantan, Malaysia, using four established allometric equations which is (i) $AGB = -3.84 + 0.528(BA) + 0.001(BA)^2$, (ii) $AGB = 34.4703 - 8.0671(DBH) + 0.6589(DBH)^2$, (iii) $AGB = 3.42(DBH)^{1.15}$ and (iv) $AGB = \exp[-2.134 + 2.530 \ln(DBH)]$. Diameter at breast height (DBH) was measured for 1,588 trees within a 9.2 ha plot, and biomass was converted to carbon stock using a standard conversion factor (0.47). Estimated carbon stocks varied widely, ranging from 21.72 MgC/ha (allometric equation no. iii) to 41.05 MgC/ha (allometric equation no. i). One-way ANOVA indicated significant differences among models ($p < 0.05$), while Tukey's HSD post-hoc test identified allometric equation no. i and iv as consistently producing higher estimates compared to allometric equation no. ii and iii. These discrepancies reflect differences in model calibration, ecological context, and stand conditions. The findings highlight that model selection substantially influences carbon stock estimation, and emphasise the importance of employing site- and species-appropriate equations to minimise systematic error. Accurate carbon accounting in rubber plantations is therefore essential for understanding their contribution to climate change mitigation and for guiding sustainable forest management practices.

1. INTRODUCTION

Increasing concerns about climate change and its global environmental impacts have highlighted the importance of understanding the role of forests and plantations in carbon storage. Forest ecosystems, including plantations, act as carbon sinks by absorbing atmospheric carbon dioxide (CO_2) and storing it in biomass and soils, thereby contributing to the regulation of the global carbon cycle (IPCC, 2022; Pan et al., 2011). Rubber tree (*Hevea brasiliensis*) is particularly significant, not only for its economic importance in latex production but also for its considerable capacity to store carbon (de Blécourt et al., 2013; Gutiérrez-Vélez et al., 2022). Quantifying the carbon stored in rubber plantations is therefore essential to recognise their role in climate change mitigation, especially in regions where rubber cultivation predominates (Qin et al., 2019).

In Southeast Asia, where rubber plantations are widespread, increasing attention has been directed towards their potential contribution to carbon storage. While traditionally cultivated for latex, rubber trees are now increasingly regarded as a means to offset carbon emissions. Previous studies (Tang et al., 2009; Liu et al., 2016) demonstrated that rubber plantations store substantial amounts of carbon in both aboveground biomass and soil (belowground biomass). Older plantations generally sequester greater amounts of carbon as biomass accumulates with age. However, regional assessments remain necessary, as carbon storage capacity is influenced by factors such as plantation age, management practices, and ecological conditions (Kongsager et al., 2013; Xu et al., 2020). Carbon stock assessment can be performed indirectly through allometric equation, which estimate aboveground biomass using measurable tree attributes such as diameter at breast height (DBH), tree height, and wood density (Brown, 1997; Chave et al., 2014).

Although rubber plantations are increasingly recognised as important contributors to carbon sequestration, several critical research gaps remain unaddressed. Regional initiatives such as the UN-REDD Southeast Asia inventory have expanded the availability of generalised allometric equations, site-specific calibration for Malaysian plantations remains scarce, leading to potential systematic errors in biomass and carbon estimates (UN-REDD, 2018). Besides, many previous studies relied on a single allometric equation without conducting comparative evaluations, thereby limiting the robustness of carbon stock assessments (Picard et al., 2015). Although, recent advancements in remote-sensing approaches, such as Sentinel-2 red-edge metrics and LiDAR integration, have been shown to improve large-scale biomass estimation, their accuracy has not yet been systematically tested against field-based allometric equation in rubber plantation ecosystems (Bhumiphan et al., 2023).

Addressing these research gaps is crucial for both scientific and policy perspectives. From a methodological standpoint, the lack of comparative validation among different allometric equations increases uncertainty in biomass and carbon stock estimation, which undermines the reliability of rubber plantations in global carbon accounting frameworks. From a policy perspective, inaccurate estimates may misrepresent the ecological role of rubber plantations in climate change mitigation strategies, thereby affecting carbon credit mechanisms, sustainable forest management, and national reporting under the Paris Agreement (Griscom et al., 2017; IPCC, 2019). By conducting a comparative evaluation of four widely cited allometric equations under local ecological conditions in Malaysia, this study aims to enhance the precision of carbon stock assessment, minimise estimation bias, and provide a stronger scientific basis for incorporating rubber plantations into climate mitigation and land-use policy frameworks.

2. MATERIALS AND METHODS

2.1 Study area

The study was conducted in rubber plantations at Kampung Pasir Dusun, Jeli, Kelantan, Malaysia (05°37'59.9"N, 101°51'51.1"E), about 195.4 ha under RISDA management. Three sampling plots covering 9.2 ha (≈5% of the total area) was established as shown in Figure 1.

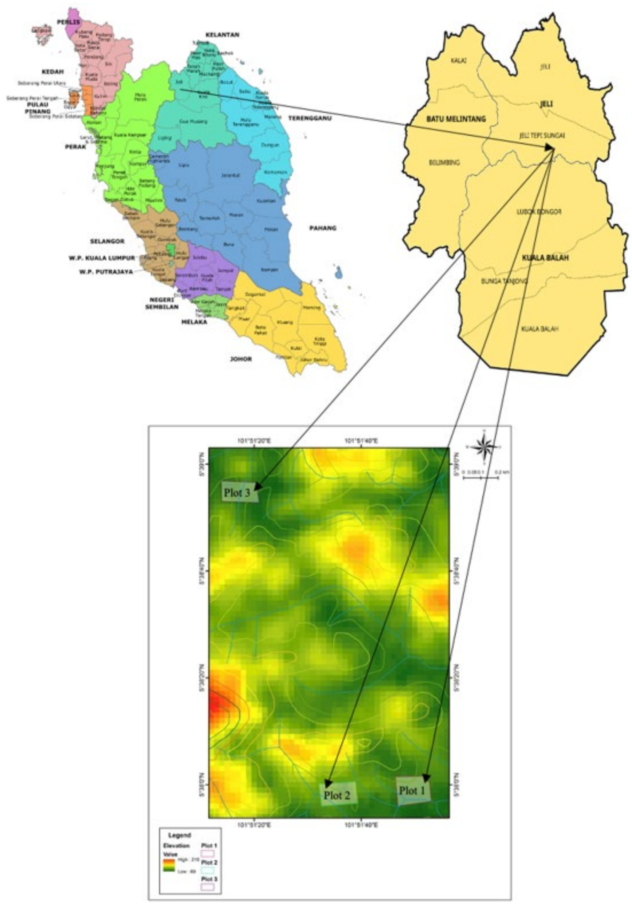

Figure 1: Study area of rubber plantation at Kampung Pasir Dusun, Jeli Kelantan.

2.1.1 Climate

The study site, Pasir Dusun in Jeli District, Kelantan, features a tropical rainforest climate with persistently high temperatures, humidity, and substantial rainfall throughout the year. Mean annual temperature is approximately 24.3 °C, with monthly averages ranging from 22.7 °C in January to 25.5 °C in April and May, and daily maximums reaching up to 30.5 °C (Climate-Data, 2025).

The region receives abundant precipitation, averaging around 2,716 mm per year, with the lowest monthly rainfall (~77 mm) occurring in February and the highest (~338 mm) in December. Relative humidity remains elevated year-round, ranging from approximately 80% in April to 91% in November and December (MetMalaysia, 2025). These climatic conditions promote lush, verdant vegetation and create an environment particularly well-suited to rubber and oil palm cultivation, supporting the ecological relevance of this biomass and carbon stock assessment study.

2.2 Methods

Aboveground was estimated from DBH using allometric equations. DBH of all stems with >5 cm was measured using a diameter tape across three sampling plots, yielding a total of 1,588 measured trees. DBH of each tree was measured at 1.3 m above the ground using a diameter tape, which includes a centimeter scale on one side and a direct diameter conversion on the other. Adjustments were applied in specific cases to ensure accuracy and consistency with established forestry protocols.

For leaning trees on level ground, measurements were taken from the side of inclination, whereas on sloping terrain, DBH was recorded from the upper side of the slope. In cases where trees forked below 1.3 m, each stem with a DBH ≥5 cm was treated as an individual stem and measured at the standard 1.3 m height. These measurement procedures follow internationally recognised forestry guidelines (Avery & Burkhart, 2015; Chave et al., 2014).

2.2.1 Aboveground biomass

Four allometric equations were applied to estimate aboveground biomass of rubber trees. The first equation by Schroth et al. (2002), developed from biomass measurements in tropical rubber monocultures of the Western Brazilian Amazon, was selected for its comparability with the stand conditions in this study. The model is shown in Equation (1).

$$AGB = -3.84 + 0.528(BA) + 0.001(BA)^2 \qquad (1)$$

Where,
AGB is aboveground biomass (kg)
BA is basal area (cm^2)

The second allometric equation was adopted from Castillo et al. (2016), conducted at the Mount Makiling Forest Reserve, Philippines. In this study, aboveground biomass of the rubber trees was quantified using empirical inventory data with the Brown (1997) model for moist tropical forests. Aboveground biomass was estimated from DBH measurements, with biomass calculated by classifying trees into DBH classes. The equation is presented in Equation (2).

$$AGB = 34.4703 - 8.0671(DBH) + 0.6589(DBH)^2 \qquad (2)$$

Where,
AGB is aboveground biomass (kg)
DBH is diameter at breast height (cm)

The third equation by Saragih et al. (2016) was adopted from a study in the Bukit Punggur Forest Management Unit, Provinsi Lampung, Indonesia. A non-destructive, species-specific model was applied to estimate aboveground biomass for rubber trees, under ecological and management conditions comparable to Kampung Pasir Dusun. The model is presented in Equation (3).

$$AGB = 3.42(DBH)^{1.15} \qquad (3)$$

Where,
AGB is aboveground biomass (kg)
DBH is diameter at breast height (cm)

The fourth equation by Omar et al. (2013) was adopted from a study on rubber and teak plantations in Peninsular Malaysia. Aboveground biomass was estimated using DBH as the sole predictive variable, with two equations applied for DBH <60 cm and 60–148 cm, respectively. The model is presented in Equation (4).

$$AGB = \exp[-2.134 + 2.530 \ln(DBH)] \qquad (4)$$

Where,
AGB is aboveground biomass (kg)
DBH is diameter at breast height (cm)

2.2.2 Carbon stock

Carbon stock was estimated by applying a carbon fraction of 0.47 (IPCC, 2006) to the aboveground biomass values. The calculation formula is presented in Equation (5).

$$Carbon\ stock\ (kg) = AGB\ (kg)\ X\ 0.47 \qquad (5)$$

2.3 Comparative analysis

Carbon stock values estimated from those four allometric equations were statistically compared using SPSS. One-way ANOVA with post-hoc tests was applied to evaluate significant differences and identify the most consistent estimation method.

3. RESULTS AND DISCUSSION

3.1 DBH class distribution of rubber tree in study area

From the field sampling, a total of 1,588 rubber trees individuals were recorded across the three study plots. Plot 1 contained the largest number of trees (n = 618), followed by Plot 3 (n = 492) and Plot 2 (n = 478). The DBH class distribution of these trees is illustrated in Figure 2, representing the structural composition of the rubber tree population in Kampung Pasir Dusun, Jeli, Kelantan.

The DBH class distribution of rubber trees in Kampung Pasir Dusun exhibits a pronounced unimodal pattern, with the majority of trees concentrated in intermediate size classes. Notably, the 15–19.9 cm class, comprising 753 trees, represents the stand's most vigorous cohort—likely nearing or at optimal latex production age (Krisnawati et al., 2011). The next cohort (10–14.9 cm; 445 trees) suggests active regeneration or recent planting (Hairiah et al., 2001), while the 20–24.9 cm class (317 trees) denotes more mature individuals with declining growth rates. Classes such as 5–9.9 cm, 25–29.9 cm, and 30–34.9 cm are sparsely populated, indicating limited recent recruitment and the rarity of over-mature trees due to harvesting, senescence, or natural stand dynamics (Slik, 2004).

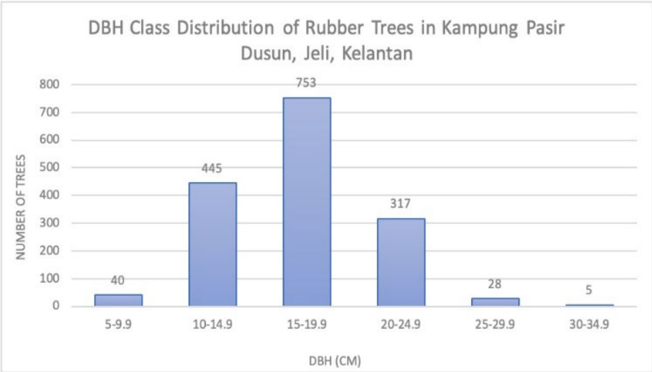

Figure 2: DBH class distribution of rubber trees in Kampung Pasir Dusun, Jeli, Kelantan.

This skewed distribution aligns with findings from rubber and other plantation systems in tropical regions. Chen et al. (2020) reported that younger rubber stands tend to cluster in mid-DBH classes, correlating peak biomass with stand age determined via remote sensing. Similarly, Brahma et al. (2017) found that biomass accumulation in Indian rubber stands increased dramatically with age—from ~28 Mg/ha at 6 years to ~169 Mg/ha by 34 years—highlighting age-related shifts in DBH distribution. These patterns collectively suggest that the stand in Pasir Dusun originated from synchronised planting events, with limited subsequent recruitment or retention of older trees.

Understanding this demographic structure is critical for both biomass estimation and ecological management. Unimodal DBH distributions, as observed here, inform allometric equation selection and improve carbon stock accuracy (Poorter et al., 2015). Future longitudinal monitoring is recommended to detect shifts in population structure that may arise from environmental change, management interventions, or natural succession.

3.1 Evaluation of aboveground biomass through allometric equations

Aboveground biomass values of those rubber trees were estimated using four allometric equations, and the results are summarised in Table 1. The estimation of aboveground biomass using four allometric equations demonstrated considerable variation across the study plots, with values ranging from 46.22 Mg/ha (Saragih et al., 2016) to 87.78 Mg/ha (Schroth et al., 2002). These findings reaffirm the substantial influence of model selection on biomass estimation, as highlighted by Chave et al. (2014). The higher estimate produced by Schroth et al. (2002) likely reflects an overestimation, as the equation was calibrated in diverse tropical forest conditions rather than in monoculture systems such as rubber plantations. Similar trends were observed by Rutishauser et al. (2017), who found that generalised tropical forest models often inflate biomass estimates when applied to monoculture or even-aged plantations.

Table 1: Aboveground biomass values using allometric equation.

Allometric Equation	Aboveground biomass (Mg/ha)			
	Plot 1	Plot 2	Plot 3	Total
Scrotch et al. (2002)	32.30	35.53	19.95	87.78
Castillo et al. (2016)	16.49	18.02	15.80	50.31
Saragih et al. (2016)	16.60	15.06	14.56	46.22
Omar et al. (2013)	28.88	30.92	27.36	87.16

Conversely, the conservative values derived from Castillo et al. (2016) and Saragih et al. (2016) suggest underestimation, particularly in older stands, a limitation consistent with findings by Kenzo et al. (2015), who reported that age-specific growth dynamics of rubber trees are not adequately captured in equations calibrated on younger stands. The estimate from Omar et al. (2013), which closely aligned with Schroth et al. (2002), demonstrates the potential of locally derived and remote-sensing–calibrated models to improve estimation reliability.

Nevertheless, these models also retain inherent uncertainties, as demonstrated by Avitabile et al. (2016), who emphasised the variability in satellite-calibrated models across different ecological settings. Importantly, across all models, Plot 2 consistently exhibited higher biomass than Plots 1 and 3, underscoring the critical role of site-specific conditions, such as soil fertility and microclimatic variations, in regulating biomass accumulation. This observation aligns with the findings of Poorter et al. (2015), who highlighted that fine-scale environmental heterogeneity exerts a strong influence on biomass patterns even within relatively small areas.

3.2 Estimation of carbon stock

Table 2 shows the carbon stock values estimated from the regarding aboveground biomass values. Carbon stock estimates ranged from 21.72 to 41.05 MgC/ha, depending on the allometric equation applied. The divergence reflects methodological differences, particularly the extent to which models account for species-specific parameters, stand age, and ecological context. Models calibrated in heterogeneous tropical forests (e.g., Schroth et al., 2002) consistently produced higher estimates, whereas those derived from rubber plantation studies (e.g., Castillo et al., 2016; Saragih et al., 2016) generated more conservative values.

Table 2: Carbon stock values.

Allometric Equation	Carbon stock (MgC/ha)			
	Plot 1	Plot 2	Plot 3	Total
Scrotch et al. (2002)	15.18	16.49	9.38	41.05
Castillo et al. (2016)	7.75	8.47	7.43	23.65
Saragih et al. (2016)	7.80	7.08	6.84	21.72
Omar et al. (2013)	13.58	14.53	12.86	40.97

Comparable patterns were reported by Ngo et al. (2013) in lowland tropical forests, where generalised models tended to overestimate carbon stocks relative to site- and species-specific equations. In contrast, the estimates from Omar et al. (2013) were more consistent with local conditions, suggesting that locally adapted equations can enhance the accuracy of carbon stock assessments. These results are consistent with the observations of Henry et al. (2011), who stressed the necessity of using species- and site-specific allometric equations to reduce bias in carbon accounting frameworks.

3.3 Comparative analysis of carbon stock based on different allometric equations

As shown in Figure 3, the total carbon stock is grouped by allometric equations, allowing straightforward comparison among them.

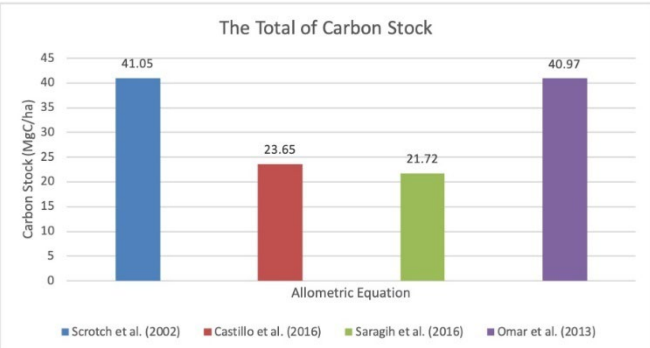

Figure 3: Total carbon stock across allometric equations.

Statistical analysis further confirmed that model selection significantly affects carbon stock estimation. The one-way ANOVA results in Table 3 revealed statistically significant differences ($p < 0.05$) among the four allometric equations, indicating that the choice of model substantially influences the estimation of aboveground biomass and carbon stock. This outcome underscores the critical role of model selection in carbon accounting, as inappropriate equations can introduce systematic biases.

Similar findings have been reported in previous studies, where variability in biomass estimates was attributed largely to the use of different allometric equations, often exceeding other sources of error (Picard et al., 2015). More recent evidence further emphasizes that model calibration to local species, stand structure, and management conditions is essential to ensure reliability in biomass and carbon stock assessments (Tiko et al., 2025).

Table 3: One-way ANOVA between allometric equations.

	Sum of squares	df	Mean square	F-value	p-value
Between allometric equations	0.22	3	0.07	423.99	0.00*

Note: * Significant at 95%

Meanwhile, Tukey's HSD post-hoc test (Table 4) revealed that models by Schroth et al. (2002) and Omar et al. (2013) consistently predicted higher carbon stock values, while Castillo et al. (2016) and Saragih et al. (2016) produced lower estimates. No significant difference was observed between Schroth et al. (2002) and Omar et al. (2013), suggesting that both models systematically overestimate values under the ecological conditions of the study site.

Table 4: Multiple comparisons from Tukey HSD post-hoc test.

Dependent variable	(I) Model	(J) Model	(I-J) Mean difference	Std. error	p-value
Allometric equations	Scrotch	Castillo	0.01	0.00	0.00*
		Saragih	0.01	0.00	0.00*
		Omar	0.00	0.00	0.98ns
	Castillo	Scrotch	-0.01	0.00	0.00*
		Saragih	0.00	0.00	0.04*
		Omar	-0.01	0.00	0.00*
	Saragih	Scrotch	-0.01	0.00	0.00*
		Castillo	0.00	0.00	0.04*
		Omar	-0.01	0.00	0.00*
	Omar	Scrotch	0.00	0.00	0.98ns
		Castillo	0.01	0.00	0.00*
		Saragih	0.01	0.00	0.00*

Note: * Significant at 95%
ns Not significant

These discrepancies are attributable to differences in calibration datasets and ecological assumptions, a challenge also identified by Picard et al. (2015) and Tiko et al. (2025), who demonstrated that factors such as stand structure, age distribution, and management regimes critically shape biomass modelling outcomes. Similar comparative analyses in oil palm (Morel et al., 2020) and teak plantations (Krisnawati et al., 2012) have also shown that inappropriate model selection can lead to either over- or underestimation of carbon storage potential.

Such systematic biases carry important implications for climate change mitigation policies, particularly in contexts where rubber plantations are increasingly recognised as carbon sinks. This underscores the importance of selecting models that are ecologically and geographically congruent with the study area to ensure reliable carbon stock estimates and accurate representation of the role of rubber plantations in global carbon sequestration.

4. CONCLUSION

These findings emphasise that selecting an allometric equation is not merely a methodological choice but a determinant factor that significantly influences the accuracy of biomass and carbon stock estimation. In the context of rubber plantations, careful consideration of species traits, stand age, and site-specific conditions is essential to minimise bias and enhance the reliability of carbon accounting. The observed variation in carbon stock estimates ranging from 21.72 to 41.05 MgC/ha—demonstrates the critical need for locally calibrated or validated equations. Equations developed in ecologically similar environments may offer more realistic estimates compared to generalised tropical forest equations. From a policy perspective, these results underscore the importance of using appropriate equations in national greenhouse gas inventories, carbon offset schemes, and REDD+ reporting. Inaccurate estimates could lead to misinformed decisions regarding land-use planning, carbon credit valuation, and forest conservation strategies.

Future study should focus on developing and validating allometric equations tailored to Malaysian rubber plantations, incorporating variables such as tree height, wood density, and stand age. Integrating remote sensing technologies with field-based models may further improve large-scale biomass assessments. Ultimately, improving the precision of carbon stock estimation in rubber plantations contributes not only to scientific understanding but also to the formulation of effective climate change mitigation and sustainable land management policies.

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