

Article

Refining Regional Carbon Estimates in Teak (*Tectona grandis* L.f.) Plantations Using Pantropical Allometry and Measured Carbon Fractions

Bayron Alexander Ruiz-Blandon ^{1,*}, Rosario Marilu Bernaola-Paucar ^{2,*}, Bertha Carolina Sotelo Alcántara ³, Leonor Neda Carbajal Cuadros ⁴, Kenyi Paul Hinostroza Mendoza ⁵, Julián Leonardo Mantari Mallqui ⁶, Yubel Mayela Carrasco Nuñez ⁷ and Hebert Ernesto Ramos Acuña ⁸

¹ Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias, Mexico City 04010, Mexico

² Escuela Profesional de Ingeniería Agroindustrial, Facultad de Ingeniería, Universidad Nacional Autónoma Altoandina de Tarma, Junín 12731, Peru

³ Facultad de Ingeniería Forestal y Ambiental, Universidad Nacional del Centro del Perú, Junín 12006, Peru; bsotelo@uncp.edu.pe

⁴ Escuela de Posgrado, Facultad de Ciencias Agrarias, Universidad Nacional de Huancavelica, Huancavelica 09001, Peru; 2023905002@unh.edu.pe

⁵ Facultad de Ingeniería en Industrias Alimentarias, Escuela de Ingeniería en Industrias Alimentarias, Universidad Nacional del Centro del Perú, El Tambo 12000, Peru; khinostroza@uncp.edu.pe

⁶ Facultad de Ciencias Agrarias, Escuela Profesional de Agronomía, Universidad Nacional de Huancavelica, Acobamba 09381, Peru; julian.mantari@unh.edu.pe

⁷ Facultad de Ingeniería, Carrera de Ingeniería Industrial, Universidad Tecnológica del Perú, Lima 15046, Peru; c26031@utp.edu.pe

⁸ Escuela Profesional de Zootecnia, Facultad de Ciencias de Ingeniería, Universidad Nacional de Huancavelica, Huancavelica 09001, Peru; hebert.ramos@unh.edu.pe

* Correspondence: ruiz.bayron@inifap.gob.mx (B.A.R.-B.); rbernaola@unaat.edu.pe (R.M.B.-P.)

Abstract

Teak plantations are widely promoted as productive forest systems with potential contributions to carbon storage and climate-oriented land management. However, plantation carbon estimates often rely on generic biomass-to-carbon conversion factors, which may overlook variation in carbon concentration among tree components. This study refined carbon estimates in tropical teak plantations in Nayarit, western Mexico, by combining pantropical allometry with measured carbon fractions. Carbon concentration was determined in leaves, branches, stem, roots, and total biomass, and carbon stocks were compared using the generic 0.47 factor and measured total biomass carbon fractions. Carbon concentration differed among biomass components, with leaves and branches remaining below 47%, while stem, roots, and total biomass exceeded this value. The measured total biomass carbon fraction averaged 48.24%, producing refined carbon estimates that were consistently higher than those obtained with the generic factor. Across plantation-age records, the refined approach increased carbon estimates by 1.33 Mg C ha⁻¹, equivalent to a mean relative adjustment of 2.67%. When projected as an illustrative scenario, this difference represented 133, 665, and 1330 Mg C over 100, 500, and 1000 ha, respectively. These findings show that measured carbon fractions can reduce one source of conversion-related uncertainty and refine plantation-level carbon estimates. Broader regional application would require larger and more representative plantation inventories.

Keywords: teak plantations; carbon accounting; measured carbon fractions; pantropical allometry; biomass-to-carbon conversion; regional carbon estimates; tropical forestry

Academic Editor: Tommaso Caloiero

Received: 12 June 2026

Revised: 23 June 2026

Accepted: 29 June 2026

Published: 30 June 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Teak (*Tectona grandis* L.f.) is among the most valuable tropical hardwoods in international markets, and its plantations have expanded beyond Asia into Africa and Latin America because of its timber quality, adaptability, and commercial demand [1]; this expansion has increased the need to evaluate teak plantations not only as productive systems, but also as managed forest covers that can contribute to carbon storage, climate mitigation, and land-use planning in tropical regions.

Planted forests are often promoted as part of climate-oriented land management because they can accumulate biomass, protect soils, support rural economies, and reduce pressure on natural forests when they are properly planned and managed [2]. In commercial teak systems, these services depend on site quality, plantation age, tree density, silvicultural practices, and the accuracy of the methods used to estimate biomass and carbon stocks [3].

Carbon accounting in tropical plantations is still affected by methodological uncertainty, especially when biomass is converted to carbon using fixed values, such as 0.47 or 0.50. These generic factors are useful for broad assessments, but they may overlook real variation in carbon concentration among tree components, species, and growing conditions [4].

This issue becomes more relevant when plot-level information is scaled to regional estimates, because small differences in carbon fractions can produce meaningful changes in reported carbon stocks. For forest plantations linked to mitigation, certification, or environmental reporting, this uncertainty can affect how their contribution to climate goals is interpreted [5].

Pantropical allometric equations have improved biomass estimation in tropical forests by allowing standardized calculations based on structural variables such as diameter, height, and wood density; their use is especially valuable when destructive sampling is not feasible or when regional carbon assessments require consistent methods across sites [6].

However, biomass estimation is only one part of the carbon-accounting process. Even when biomass is estimated with robust allometric equations, the final carbon value still depends on the conversion factor applied to dry biomass [4].

In Mexico, teak plantations have become part of commercial forestry in tropical regions, including areas where plantation age, management, and site conditions create strong variation in growth and biomass accumulation. Previous work has documented productivity, biomass, and carbon storage in teak plantations, but less attention has been given to how regional carbon estimates change when measured carbon fractions are used instead of a generic conversion factor [7].

This study addresses that gap by reframing local teak data as a methodological assessment for regional carbon estimation. The focus is not to repeat a conventional growth analysis, but to test whether measured carbon fractions can refine carbon estimates derived from pantropical allometry in tropical teak plantations. We hypothesized that carbon estimates obtained with measured carbon fractions would differ from those calculated with the generic 0.47 factor, and that these differences would be relevant for regional carbon accounting. The objective of this study was to refine regional carbon estimates in tropical teak plantations by combining pantropical allometric biomass estimation with measured carbon fractions. Specifically, this study aimed to: (a) estimate biomass in teak plantations using pantropical allometry; (b) compare carbon stocks obtained with the generic 0.47 factor and measured carbon fractions; and (c) evaluate the implications of these differences for regional carbon accounting, plantation management, and climate-oriented environmental reporting.

2. Materials and Methods

2.1. Study Area and Methodological Framework

The study was conducted in tropical teak (*Tectona grandis* L.f.) plantations located in Nayarit, western Mexico. The evaluated plantations were distributed across contrasting production conditions within the municipalities of Santiago Ixcuintla, Ruíz, Tepic, Tuxpan, San Blas and Rosamorada where commercial teak has been established as part of regional forest plantation systems.

The location of the study sites is shown in Figure 1. The map was prepared using official vector cartography from the National Institute of Statistics and Geography of Mexico, including state and municipal boundaries from the national geostatistical framework [8].

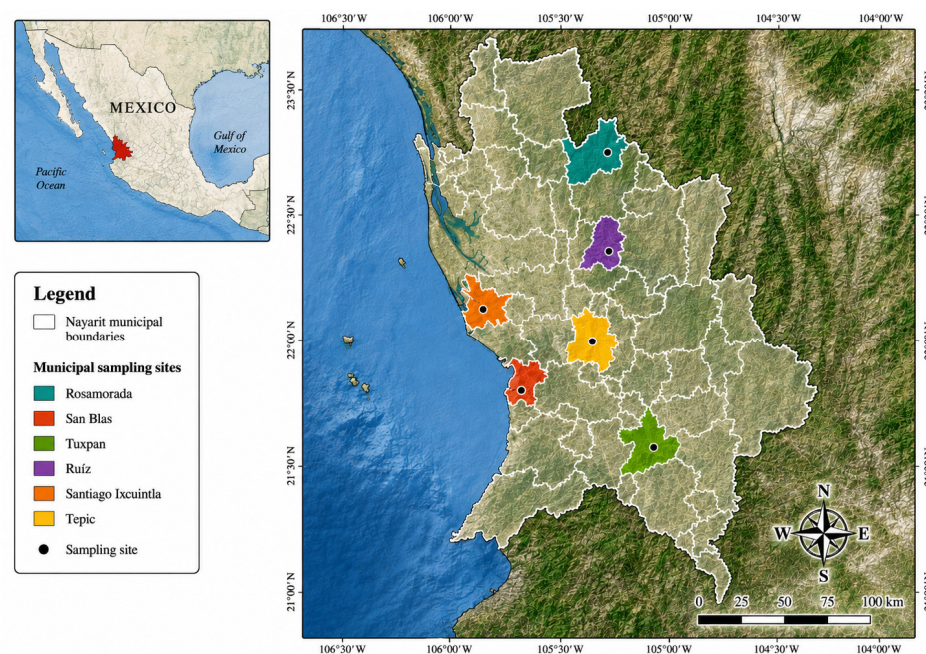


Figure 1. Location of teak (*Tectona grandis*) plantation sampling sites across six municipalities in Nayarit, western Mexico.

These sites represent contrasting plantation environments in Nayarit, including low-elevation coastal areas, valley conditions, and higher-elevation sites. The municipality-level environmental context is described below to clarify the range of climatic, altitudinal, and soil conditions represented in the study.

Rosamorada is located between 21°56' and 22°22' N and 104°55' and 105°35' W, with elevations from 0 to 1300 m. The area has mean annual temperatures of 22–28 °C and annual precipitation from 1000 to 2500 mm; Cambisols are among the dominant soils in the municipality [9].

San Blas is located between 21°20' and 21°45' N and 105°01' and 105°28' W, with elevations from 0 to 1200 m. Mean annual temperature ranges from 22 to 28 °C, and annual rainfall varies between 1300 and 2000 mm; Luvisols are commonly reported among the main soil groups [10].

Tuxpan is located between 21°50' and 22°01' N and 105°11' and 105°31' W, with elevations from 0 to 400 m. The municipality has mean temperatures of 26–28 °C and precipitation from 1200 to 2000 mm; Cambisols are reported as prevalent soils [11].

Ruíz is located between 21°52' and 22°10' N and 104°47' and 105°14' W, with an altitudinal range from 0 to 1700 m. The municipality has warm sub-humid climatic condi-

tions, mean annual temperatures from 19.6 to 26.9 °C, and annual precipitation from 979.3 to 2170.9 mm. Cambisols are the dominant soil group, which supports its relevance for evaluating teak plantations across an altitudinal gradient [12].

Santiago Ixcuintla is located between 21°37' and 22°18' N and 104°54' and 105°40' W, with elevations from 0 to 800 m. The municipality has warm and humid conditions, mean annual temperatures from 22 to 28 °C, and annual rainfall from 1000 to 2500 mm. Solonchaks occur in lowland areas, where salinity can influence land-use suitability, although high water availability favors biomass production in fast-growing plantations [13].

Tepic is located between 21°23' and 21°52' N and 104°35' and 105°09' W, with elevations from 100 to 2300 m. The municipality has semi-warm sub-humid conditions, mean annual temperatures from 20 to 24 °C, and annual precipitation from 176.3 to 1663.9 mm. Cambisols and other volcanic-derived soils occur in the area, providing contrasting site conditions for plantation development [14].

2.2. Methodological Framework for Carbon-Accounting Refinement

This study was designed as a methodological assessment of carbon estimation in tropical teak plantations. The main purpose was not to reanalyze plantation growth, productivity, or silvicultural performance, but to evaluate how carbon estimates change when dry biomass is converted using measured carbon fractions instead of a generic conversion factor.

Existing plantation data were used as structural inputs for biomass estimation and carbon conversion. Dasometric variables were therefore treated as calculation inputs, not as response variables. This decision allowed the analysis to focus on biomass-to-carbon conversion uncertainty and to avoid repeating previously reported growth-oriented results.

The methodological framework followed six linked steps: (a) organization of plantation structural data; (b) estimation of biomass using pantropical allometry; (c) determination of measured carbon fractions; (d) conversion of biomass into carbon under generic and measured-fraction scenarios; (e) comparison of absolute and relative differences between both carbon estimates; and (f) scenario projection of carbon adjustment across larger plantation areas (Figure 2). This framework connects laboratory-determined carbon fractions with plantation-scale carbon accounting. By doing so, the study evaluates whether the conventional 0.47 factor provides carbon estimates comparable to those obtained from measured teak carbon fractions, and whether the resulting adjustment is relevant for plantation-level carbon accounting.

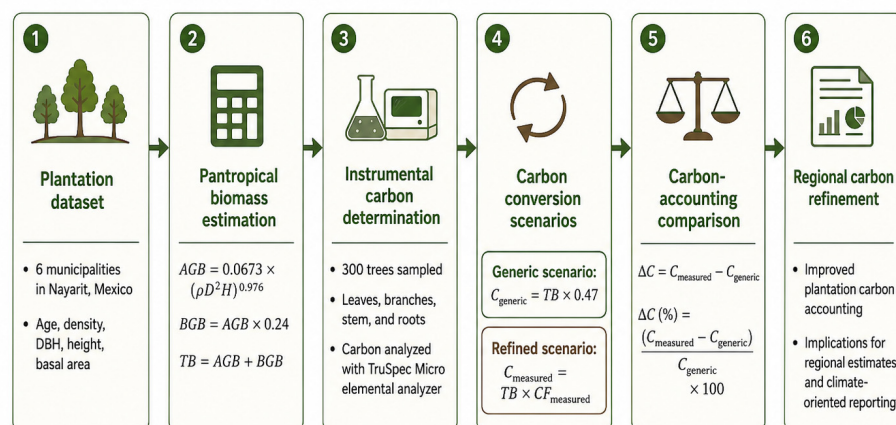


Figure 2. Methodological workflow for refining carbon estimates in teak (*Tectona grandis*) plantations.

2.3. Plantation Dataset and Structural Inputs

The analysis was based on a consolidated teak plantation dataset from the six evaluated municipalities. The dataset included stand age, tree density, diameter at breast height (DBH), total height (H), basal area, and biomass-related information. These variables were retained as structural inputs for biomass estimation and carbon conversion. The plantations covered contrasting ages and site conditions, which allowed carbon estimates to be compared across a regional plantation context. However, growth trends, productivity indicators, and silvicultural performance were not evaluated in this manuscript, since the study focused on the methodological effect of the biomass-to-carbon conversion factor.

DBH and H were used as tree-level predictors for biomass estimation. Tree density and basal area were used to express biomass and carbon estimates at the plantation scale and to support comparisons among carbon-accounting scenarios. The dataset was organized to compare two conversion approaches: the generic 0.47 factor and measured carbon fractions obtained through instrumental analysis. This structure allowed the analysis to evaluate how carbon-fraction selection affects final plantation-scale carbon estimates.

The dataset was therefore organized into two complementary analytical levels (Table 1). The first level corresponded to the carbon-fraction dataset, which included biomass samples from leaves, branches, stem, and roots collected across the six evaluated municipalities. This dataset was used to describe measured carbon concentration by biomass component and locality. The second level corresponded to the plantation-age dataset used for biomass and carbon-stock estimation. Each plantation-age record represented a summarized structural observation derived from field measurements of 50 trees. Therefore, plantation-age records were not treated as individual tree-level replicates, but as mean structural units for a given plantation condition. Localities were used as geographic grouping units, while plantation-age records provided the structural input for comparing generic and refined carbon-estimation scenarios.

Table 1. Data flow and analytical units used in the study.

Analysis	Localities Included	Plantation-Age Records	Trees	Component-Level Samples	Analytical Unit	Main Use in the Study
Study-area description	6	Not applicable	Not applicable	Not applicable	Municipality/locality	Study area description
Structural dataset	6	15	50 trees per plantation-age record	Not applicable	Plantation-age record	Biomass estimation
Carbon-fraction characterization	6	Not applicable	300	Up to 1200	Component sample/tree	Carbon concentration by component and locality
Generic vs. refined carbon comparison	6	15 usable records	Not applicable	Not applicable	Plantation-age record	Comparison between carbon-estimation scenarios
Paired statistical comparison	6	15 paired records	Not applicable	Not applicable	Paired plantation-age record	Statistical comparison between generic and refined estimates
Scaling scenario	6	15 records used to obtain mean difference	Not applicable	Not applicable	Mean Mg C ha ⁻¹ difference	Projection of carbon adjust-

ment across
larger areas

Plantation-age records are summarized values from 50 measured trees. “Not applicable” indicates that the observation level was not used in that analysis.

2.4. Biomass Estimation and Measured Carbon Fractions

Aboveground biomass was estimated using the pantropical allometric equation developed for tropical trees (1):

$$AGB = 0.0673 \times (\rho DBH^2 H)^{0.976} \quad (1)$$

where AGB is aboveground biomass, ρ is wood density, DBH is diameter at breast height, and H is total tree height. This equation was selected because it integrates tree size and wood density, allowing biomass estimation under tropical conditions when destructive sampling is not part of the current analytical design [6].

For this study, teak wood density was applied as a fixed species-level value of $\rho = 0.59 \text{ g cm}^{-3}$ for all plantation records. This value was based on the average basic density reported for *Tectona grandis* wood by [15]. A fixed value was used because measured wood density by tree, plantation record, or locality was not available in the dataset. Therefore, wood-density variation among sites was not modeled directly.

Belowground biomass was estimated from aboveground biomass using a root-to-shoot ratio of 0.24 (2):

$$BGB = AGB \times 0.24 \quad (2)$$

where BGB is belowground biomass and AGB is aboveground biomass. This value was applied to maintain consistency with forest carbon accounting procedures when direct root biomass measurements are not available [16]. The root-to-shoot ratio of 0.24 was used as a standard approximation for estimating belowground biomass when direct root measurements are not available. Since belowground biomass was derived from aboveground biomass, uncertainty associated with DBH, height, wood density, and the allometric equation was also transferred to total biomass and later to carbon estimates.

Total biomass was calculated as the sum of aboveground and belowground biomass (3):

$$TB = AGB + BGB \quad (3)$$

where TB is total biomass. Biomass estimates were expressed at the tree level and then scaled to the plantation level according to tree density (4):

$$Bha = TB \times N \quad (4)$$

where Bha is biomass per hectare and N is tree density per hectare.

For the generic carbon scenario, total carbon stock was estimated by multiplying biomass by the conventional carbon fraction of 0.47 (5):

$$C_{\text{generic}} = Bha \times 0.47 \quad (5)$$

For the refined scenario, carbon stock was estimated using measured carbon fractions (6):

$$C_{\text{measured}} = Bha \times CF_{\text{measured}} \quad (6)$$

where CF_{measured} represents the measured carbon fraction obtained from instrumental analysis.

The absolute difference between both carbon estimates was calculated as (7):

$$\Delta C = C_{\text{measured}} - C_{\text{generic}} \quad (7)$$

The relative difference was calculated as (8)

$$\Delta C (\%) = [(C_{\text{measured}} - C_{\text{generic}})/C_{\text{generic}}] \times 100 \quad (8)$$

These equations allowed the analysis to quantify whether the use of measured carbon fractions increased or decreased carbon estimates compared with the generic conversion factor. Biomass was therefore treated as an intermediate variable, while the main analytical focus was the difference between carbon-accounting scenarios.

2.5. Measured Carbon Fractions

Carbon concentration was determined in biomass samples obtained from teak plantations across the six evaluated municipalities. In each locality, 50 trees were sampled, and biomass subsamples were collected from leaves, branches, stem, and roots. This sampling structure represented 300 sampled trees and up to 1200 component-level biomass samples for carbon determination.

All samples were oven-dried until constant weight and ground to obtain homogeneous material for elemental analysis. Carbon concentration was determined using a TruSpec Micro elemental analyzer (LECO Corporation, St. Joseph, MI, USA) [17], which estimates carbon content in solid samples through combustion-based elemental analysis. Measurements were performed separately for leaves, branches, stem, roots, and total biomass samples. The total biomass carbon fraction was therefore obtained directly from elemental analysis and was not calculated as a simple arithmetic mean of the component fractions. This distinction is important because biomass components do not contribute equally to total biomass and a simple average of component carbon fractions would not be appropriate for plantation-scale carbon estimation.

Carbon concentration was expressed as percentage of dry biomass for each tree component. These values were converted to carbon fractions by dividing the percentage value by 100 and were later used in the refined carbon-accounting scenario.

The component-level analysis was retained because carbon concentration can vary among plant tissues. Therefore, using a single fixed factor for all biomass pools may mask differences among leaves, branches, stem, and roots [5].

Measured carbon fractions were summarized by component, total biomass, and locality. The directly measured total biomass carbon fraction was used in the refined carbon-accounting scenario, while component-level values were retained to describe tissue-level variation in carbon concentration.

2.6. Comparative Carbon-Accounting Analysis

The comparative analysis was designed to quantify how carbon-fraction selection modifies plantation-scale carbon estimates. The generic and refined scenarios were evaluated using the same biomass dataset, which allowed the observed differences to be attributed only to the conversion factor applied after biomass estimation.

Measured carbon fractions were first examined by tree component to identify which biomass pools showed values below or above the 0.47 reference factor. These component-level values were then integrated into the refined estimation scenario to assess their effect on total carbon stock.

The comparison between scenarios was based on absolute and relative differences. Absolute differences were expressed in Mg C ha^{-1} , while relative differences were expressed as percentages. Positive values indicated that the generic factor underestimated carbon stocks, whereas negative values indicated overestimation. This analytical structure allowed the study to move from laboratory-derived carbon fractions to their practical effect on regional teak plantation carbon accounting. The main interpretation focused on the magnitude and direction of the adjustment produced by replacing a fixed conversion factor with measured carbon fractions.

2.7. Statistical Analysis

Statistical analyses were performed using SAS version 9.4 [18]. Carbon fractions were first summarized by biomass component and locality using means and standard errors. The distribution of the data was evaluated through normality tests and graphical inspection of residuals, while homogeneity of variance was assessed before applying parametric comparisons [19,20].

Differences in measured carbon fractions among biomass components were evaluated using a mixed-effects approach, with biomass component as a fixed effect and locality and plantation-age record included as random terms. When component effects were significant, mean separation was performed at $p \leq 0.05$. Measured carbon fractions were also compared against the generic 0.47 factor using one-sample tests to identify components whose carbon concentration differed from the conventional reference value.

Generic and refined carbon estimates were compared as paired values because both scenarios were calculated from the same biomass dataset. This comparison was interpreted as a confirmatory comparison between carbon-estimation scenarios, rather than as strong independent statistical evidence, since the direction of the difference depends on the measured total biomass carbon fraction used in the refined scenario.

This statistical approach tested the hypothesis at two levels: first, whether measured carbon fractions differed from the generic 0.47 factor; and second, whether those differences affected plantation-scale carbon estimates.

A simple sensitivity check was performed to evaluate how biomass-related assumptions could affect carbon estimates. Wood density was varied by $\pm 10\%$ around the fixed teak value used in the main analysis, and the root-to-shoot ratio was evaluated using alternative values of 0.20 and 0.28 around the reference value of 0.24. This check was used only to describe the expected direction and approximate magnitude of change associated with these two assumptions; it was not treated as a full uncertainty analysis.

3. Results

3.1. Measured Carbon Fractions in Teak Biomass Components

Measured carbon concentration (Table 2) varied among teak biomass components, showing a clear separation between non-woody tissues and woody structural tissues. Leaves showed a mean carbon concentration of 46.36%, with values ranging from 45.5 to 47.7%, while branches averaged 46.24%, with a range of 45.1 to 47.2%. Both components were generally close to, or slightly below, the conventional 47% reference factor used in forest carbon estimates.

Table 2. Measured carbon concentration (%) by locality and biomass component in teak (*Tectona grandis*) plantations.

Locality	Leaves	Branches	Stem	Root	Total Biomass
Rosamorada	46.50 $\pm$ 0.41	46.20 $\pm$ 0.43	48.17 $\pm$ 0.27	48.85 $\pm$ 0.27	48.25 $\pm$ 0.40
San Blas	46.37 $\pm$ 0.49	46.23 $\pm$ 0.20	49.00 $\pm$ 0.26	49.30 $\pm$ 0.25	48.33 $\pm$ 0.19
Tuxpan	46.05 $\pm$ 0.05	46.35 $\pm$ 0.35	48.75 $\pm$ 0.05	49.20 $\pm$ 0.10	48.10 $\pm$ 0.10
Ruíz	46.37 $\pm$ 0.49	46.23 $\pm$ 0.20	49.00 $\pm$ 0.26	49.30 $\pm$ 0.25	48.33 $\pm$ 0.19
Santiago Ixcuintla	46.50 $\pm$ 0.41	46.20 $\pm$ 0.43	48.17 $\pm$ 0.27	48.85 $\pm$ 0.27	48.25 $\pm$ 0.40
Tepic	46.05 $\pm$ 0.05	46.35 $\pm$ 0.35	48.75 $\pm$ 0.05	49.20 $\pm$ 0.10	48.10 $\pm$ 0.10

Values are presented as means $\pm$ standard error. Locality-level values were checked against the raw dataset before revision. Repeated values among some locality pairs correspond to identical carbon-fraction summaries in the consolidated laboratory dataset used for this analysis.

Stem and root tissues showed higher carbon concentrations than leaves and branches. Stem carbon averaged 48.58%, ranging from 47.6 to 49.5%, while root carbon reached the highest mean value, with 49.08% and a range of 48.4 to 49.8%. The total biomass carbon fraction averaged 48.24%, with values between 47.5 and 49.3%.

This pattern indicates that the use of a single generic carbon factor does not represent all teak biomass components equally. The 0.47 factor was close to the values observed in leaves and branches, but lower than the measured carbon concentration in stem, root, and TB (Figure 3). This difference is relevant because woody tissues represent the main biomass pools used to estimate plantation-scale carbon stocks.

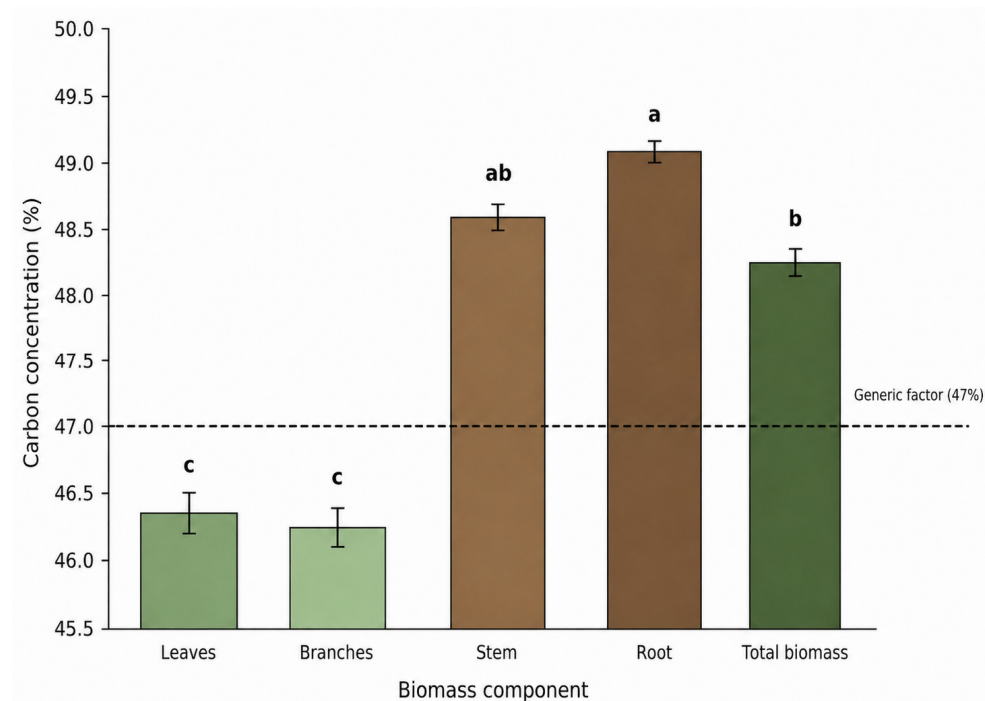


Figure 3. Mean carbon concentration by teak biomass component relative to the generic 47% conversion factor. Bars represent means $\pm$ standard error. Different lowercase letters indicate significant differences among biomass components according to Tukey's test ($p \leq 0.05$). The dashed line represents the generic carbon conversion factor commonly used in forest carbon estimates.

3.2. Generic and Refined Carbon Estimates by Locality

Refined carbon estimates were consistently higher than those obtained with the generic 0.47 factor across all evaluated localities. The paired comparison between generic and refined scenarios was significant ($p < 0.001$); however, this result was interpreted as a confirmatory comparison between carbon-estimation scenarios because both estimates were derived from the same biomass base. At the locality level, the absolute increase ranged from 0.52 ± 0.02 Mg C ha⁻¹ in Tuxpan to 1.84 ± 0.06 Mg C ha⁻¹ in Rosamorada. Ruíz, San Blas, Santiago Ixcuintla, and Tepic showed intermediate increases of 1.28 ± 0.03 , 1.15 ± 0.05 , 1.60 ± 0.04 , and 1.38 ± 0.03 Mg C ha⁻¹, respectively. Across the complete plantation-age dataset, the refined approach increased the mean carbon estimate by 1.33 ± 0.02 Mg C ha⁻¹ compared with the generic scenario (Table 3).

Table 3. Generic and refined carbon estimates by locality using pantropical allometry and measured total biomass carbon fraction.

Locality	<i>n</i> Plantation-Age Records	Generic C Estimate (Mg C ha ⁻¹)	Refined C Estimate (Mg C ha ⁻¹)	Difference (Mg C ha ⁻¹)
Ruíz	3	45.28 ± 0.94	46.56 ± 0.96	1.28 ± 0.03
San Blas	4	40.64 ± 1.83	41.79 ± 1.88	1.15 ± 0.05
Santiago Ixcuintla	4	60.02 ± 1.58	61.62 ± 1.62	1.60 ± 0.04
Tepic	2	59.17 ± 1.39	60.55 ± 1.43	1.38 ± 0.03
Tuxpan	1	22.22 ± 0.68	22.73 ± 0.69	0.52 ± 0.02
Rosamorada	1	69.29 ± 2.12	71.14 ± 2.18	1.84 ± 0.06
Overall	15	49.89 ± 0.83	51.22 ± 0.85	1.33 ± 0.02

Values are means ± standard error. Differences are refined minus generic estimates. The paired comparison was interpreted as a confirmatory comparison between carbon-estimation scenarios.

These results indicate that the generic 0.47 factor produced a consistent underestimation of carbon stocks in the evaluated teak plantation-age records. Although the adjustment was moderate in absolute terms, its direction was consistent across localities after recalculating biomass with pantropical allometry, wood density, height, and the root-to-shoot ratio. This pattern supports the use of measured carbon fractions when more precise plantation-level carbon accounting is required.

From a carbon-accounting perspective, the adjustment was moderate but systematic. This result is relevant because small differences per hectare can become important when estimates are scaled to plantation or regional reporting areas.

3.3. Carbon-Fraction Effect on Relative Estimation Change

The relative change in carbon estimates was directly linked to the measured total biomass carbon fraction used in the refined scenario. Records with total biomass carbon fractions closer to 47% showed smaller adjustments, whereas records with higher measured fractions produced larger increases in estimated carbon stock.

This pattern reflects the structure of the calculation rather than an independent statistical relationship. Since both scenarios used the same biomass dataset, the relative adjustment depended on the difference between the measured total biomass carbon fraction and the conventional 0.47 factor.

The relative increase remained positive across all plantation-age records, indicating that the generic factor underestimated carbon stocks whenever measured total biomass carbon fractions exceeded 47%. This result supports the use of measured carbon fractions as a refinement tool for plantation carbon accounting, especially when estimates are intended for regional reporting or mitigation assessments. The relationship is shown in Figure 4 as a visualization of the carbon-accounting adjustment.

3.4. Carbon-Estimation Bias Associated with the Generic Factor

The generic 0.47 factor produced a consistent underestimation of teak plantation carbon stocks when compared with the refined estimates based on measured total biomass carbon fractions. This bias was positive across all localities, indicating that the conventional factor introduced a directional underestimation rather than a random deviation.

At the locality level, relative underestimation remained within a narrow range, from 2.33% in Tepic to 2.83% in Ruíz and San Blas. Tuxpan showed a similar value of 2.34%, while Santiago Ixcuintla and Rosamorada showed relative underestimations of 2.67% and 2.66%, respectively. Across the full plantation-age dataset, the mean relative underestimation was 2.67%.

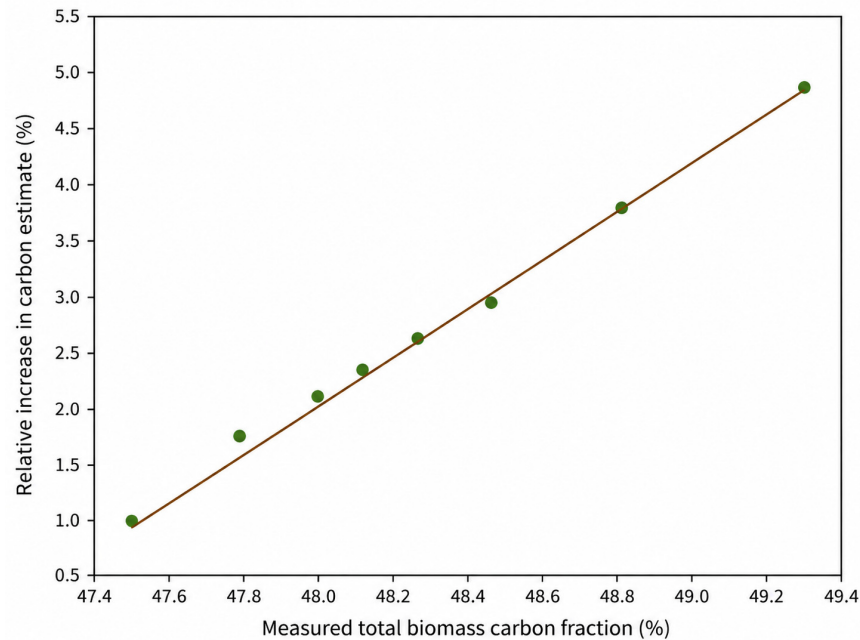


Figure 4. Relationship between measured total biomass carbon fraction and relative change in carbon estimates. Points represent plantation-age records with available measured carbon fractions ($n = 15$). The fitted line illustrates the calculation-driven relationship between the measured total biomass carbon fraction and the relative increase obtained after replacing the generic 0.47 factor.

Although the magnitude of the bias was moderate, its direction was uniform across all evaluated localities. This result is relevant for carbon accounting because small proportional underestimations at the hectare scale may become more meaningful when estimates are expanded to larger plantation areas or used in regional environmental reporting (Figure 5).

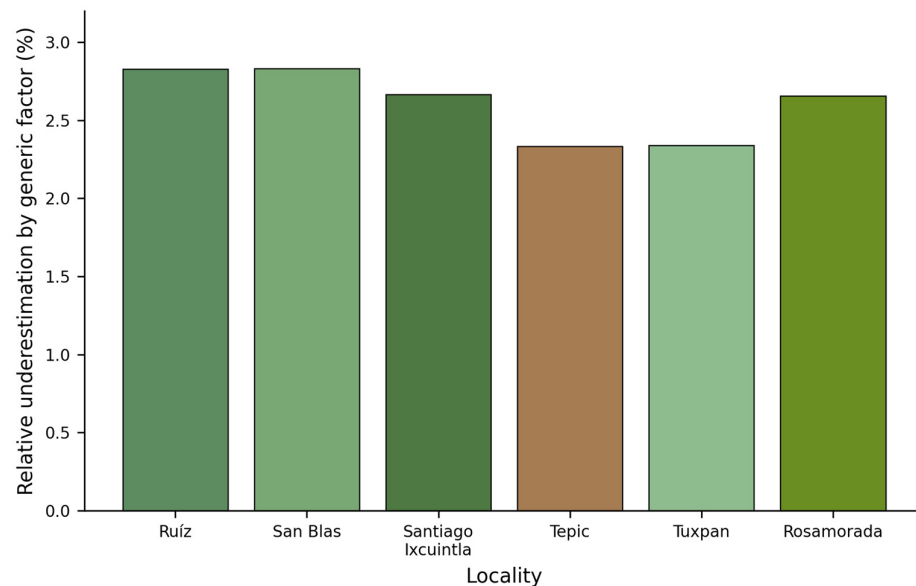


Figure 5. Carbon-estimation bias associated with the generic 0.47 factor in teak plantations. Bars represent the relative underestimation (%) produced by the generic factor compared with estimates based on measured total biomass carbon fractions.

3.5. Statistical Support for Carbon-Accounting Refinement

The statistical results summarized in Table 4 support the carbon-accounting refinement proposed in this study. Carbon concentration differed among biomass components, confirming that teak tissues did not share a single uniform carbon fraction. One-sample comparisons against the generic 47% factor showed two contrasting patterns. Leaves and branches were lower than the reference value, while stem, root, and total biomass were higher. This result confirms that the generic factor does not represent all biomass components equally.

The paired comparison between generic and refined carbon estimates was significant; however, it was interpreted as a confirmatory comparison between calculation scenarios because both estimates were derived from the same biomass base. Therefore, the statistical result supports the consistency of the adjustment, while the magnitude and direction of the change are explained by the measured total biomass carbon fraction (Table 4).

Table 4. Statistical summary of carbon-fraction differences and carbon-estimation comparisons.

Analysis	Comparison	Test	Statistic	<i>p</i> -Value	Interpretation
Carbon fraction among components	Leaves, branches, stem, root, total biomass	Mixed-effects model	$F(4, 20) = 234.39$	<0.001	Carbon concentration differed among biomass components
Leaves vs. 47%	Mean C fraction against 47%	One-sample <i>t</i> -test	$t = -4.14$	<0.001	Lower than the generic factor
Branches vs. 47%	Mean C fraction against 47%	One-sample <i>t</i> -test	$t = -5.60$	<0.001	Lower than the generic factor
Stem vs. 47%	Mean C fraction against 47%	One-sample <i>t</i> -test	$t = 12.26$	<0.001	Higher than the generic factor
Root vs. 47%	Mean C fraction against 47%	One-sample <i>t</i> -test	$t = 19.85$	<0.001	Higher than the generic factor
Total biomass vs. 47%	Mean C fraction against 47%	One-sample <i>t</i> -test	$t = 10.42$	<0.001	Higher than the generic factor
Generic vs. refined estimates	Carbon estimates across plantation-age records	Paired <i>t</i> -test	$t(14) = 9.29$	<0.001	Refined estimates were higher

Statistical significance was evaluated at $p \leq 0.05$. One-sample tests used 47% as the reference value. Statistics are reported with the corresponding test values and degrees of freedom where applicable. The paired comparison was interpreted as confirmatory because both carbon-estimation scenarios were derived from the same biomass base.

The sensitivity check showed that biomass-related assumptions changed the absolute carbon estimates, but not the direction of the generic/refined difference. Varying wood density by $\pm 10\%$ produced mean refined estimates from 45.80 to 55.70 Mg C ha⁻¹, while the refined-minus-generic difference remained positive, ranging from 1.19 to 1.45 Mg C ha⁻¹. Changing the root-to-shoot ratio from 0.20 to 0.28 produced mean refined estimates from 49.12 to 52.39 Mg C ha⁻¹, with positive differences between scenarios ranging from 1.28 to 1.36 Mg C ha⁻¹.

3.6. Scenario Projection of Carbon Adjustment Using Measured Carbon Fractions

The projected carbon adjustment increased with plantation area, reaching 133 Mg C over 100 ha, 665 Mg C over 500 ha, and 1330 Mg C over 1000 ha (Figure 6). These values were derived from the mean difference between refined and generic estimates, which was 1.33 Mg C ha⁻¹.

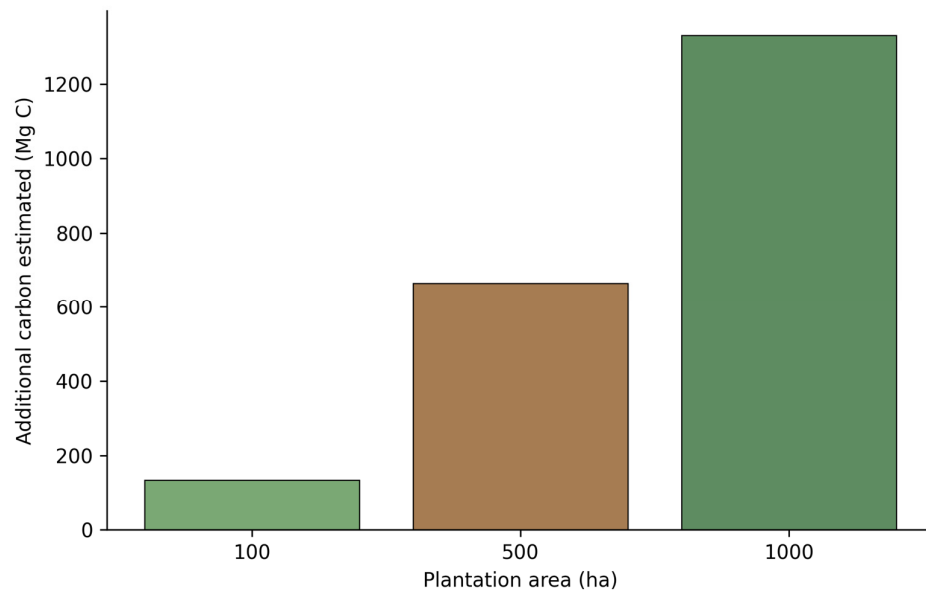


Figure 6. Scenario projection of carbon adjustment from using measured carbon fractions across increasing teak plantation areas. Bars represent an illustrative scaling scenario based on the mean difference between refined and generic estimates ($1.33 \text{ Mg C ha}^{-1}$; $n = 15$ plantation-age records).

This projection was not treated as an inferential regional estimate, but as an illustrative scaling scenario based on the mean observed difference between the two carbon-estimation scenarios. Its purpose was to show how a moderate hectare-level adjustment can become relevant when carbon estimates are expanded to larger plantation areas.

From a carbon-accounting perspective, measured carbon fractions can refine teak plantation estimates without changing the underlying biomass dataset. However, their use for regional reporting should be supported by larger and more representative plantation inventories. Therefore, the present results should be interpreted as plantation-level evidence with potential application to broader accounting frameworks when additional inventory data are available.

4. Discussion

4.1. Measured Carbon Fractions and Tissue-Level Variability

The carbon fractions measured in teak biomass showed that a single conversion factor does not represent all tree components with the same precision. Ref. [21] reported that refined wood carbon fractions can improve forest carbon estimates because carbon concentration varies among taxa, tissues, and reporting scales. In our case, leaves and branches remained below the generic 47% value, while stem, root, and TB exceeded it, showing that the direction of the bias depends on the biomass pool being converted.

The higher carbon concentration observed in stem and root tissues is consistent with component-level studies in tropical plantations. Ref. [22] found carbon values ranging from 41.08% to 49.97% among components in *Retrophyllum rospigliosii* plantations, while ref. [23] reported stem carbon fractions close to 0.48 in clonal *Gmelina arborea*. These values are close to the stem fraction found in our teak dataset and support separating woody tissues from foliage when carbon estimates are intended for plantation-scale accounting.

The lower values observed in leaves and branches also have practical meaning. Ref. [24] used CHNS-O analysis and reported component-level differences in carbon concentration among stem, root, leaves, and branches in tree-based systems. This supports our

finding that fixed conversion factors are less precise when the objective is refined carbon accounting rather than rapid biomass approximation.

The relevance of this variation increases when biomass estimates are scaled beyond individual plots. Ref. [25] showed that carbon fractions vary by taxonomic group, biome, tissue condition, and decay stage, which reinforces that carbon conversion is not a neutral step in forest carbon estimation. Our results follow that logic: the measured TB fraction was higher than 47%, which explains why the refined estimates consistently exceeded the generic scenario.

4.2. Effect of the Generic 0.47 Factor on Teak Carbon Estimates

The generic 0.47 factor remains useful for rapid carbon estimates, especially when measured carbon fractions are not available. However, our results showed that this factor produced a consistent underestimation of carbon stocks in the evaluated teak plantation-age records. This agrees with ref. [26], who noted that generic biomass-to-carbon conversion values may not be sufficiently accurate when carbon estimates are used for mitigation or offset assessments. In this study, the adjustment was moderate, but systematic, increasing refined estimates by an average of 1.33 Mg C ha⁻¹, equivalent to approximately 2.67% relative to the generic scenario.

Default carbon fractions are still widely used in plantation carbon assessments because they provide a practical option when laboratory measurements are unavailable. For example, ref. [27] used a default tropical forest carbon fraction close to 0.47, while ref. [28] indicated that measured carbon-fraction patterns can support carbon-accounting applications when sampling and validation are adequate. Our results support this view by showing that the directly measured total biomass carbon fraction changed the final estimate without altering the underlying biomass dataset.

The size of this adjustment should be interpreted carefully. It is smaller than other potential uncertainty sources in forest carbon estimation, such as allometric model choice, plot design, wood density, tree measurement error, and belowground biomass estimation [29]. Therefore, the result should not be read as a change in plantation productivity, but as a correction in the conversion of estimated biomass into carbon stock.

From an applied perspective, measured carbon fractions reduce one avoidable source of conversion uncertainty. This does not mean that the adjustment is larger than other uncertainty sources, but it improves the transparency of the biomass-to-carbon conversion step when estimates are scaled to larger plantation areas. However, broader regional use would require larger and more representative plantation inventories. The main contribution of this study is therefore methodological: measured teak carbon fractions can refine plantation-level estimates and provide a stronger basis for future carbon-accounting applications.

4.3. Scenario Implications for Plantation Carbon Accounting

The applied value of our results lies in showing that carbon estimates can change even when the biomass dataset remains unchanged. Ref. [30] reported that forest plantations store a measurable share of global biomass carbon, but also noted that spatially explicit plantation information remains a limitation for mitigation assessments. Our study addresses a narrower methodological point: after biomass is estimated, the carbon fraction used for conversion can shift the final stock value.

This finding is relevant because plantation carbon assessments increasingly combine field data, inventory records, and spatial products. Ref. [31] showed that plantation carbon estimation is moving toward broader spatial applications using remote sensing and inventory-based information. In this context, measured carbon fractions can improve local

calibration before estimates are scaled, but they should not be treated as regional evidence without larger and more representative plantation inventories.

The scenario projection illustrates this point. A moderate adjustment per hectare can become relevant when applied to larger managed areas, but the projection should be interpreted only as an illustrative scaling exercise. Other uncertainty sources, including data quality, model choice, wood density, and estimation procedures, may have equal or greater influence on final carbon estimates [30]. Therefore, the biomass-to-carbon conversion step should be viewed as one specific source of uncertainty among several.

For tropical plantations, the implication is not that teak stores more carbon because of the refined method, but that the same biomass can be translated into a more defensible carbon estimate. Ref. [32] showed that planted forests differ from natural forests in the drivers and limits of carbon accumulation, reinforcing the need to avoid overly broad assumptions across forest systems. This is also relevant for climate-oriented reporting, where transparent accounting rules and clear assumptions are needed at broader scales [33]. In this study, measured teak carbon fractions refined plantation-level estimates and may support regional accounting only when combined with broader inventory data.

4.4. Methodological Scope and Future Applications

The scope of this study was methodological rather than silvicultural. The analysis did not seek to reinterpret plantation growth, but to isolate one source of uncertainty in carbon accounting: the biomass-to-carbon conversion step. This focus is consistent with studies showing that forest carbon estimates depend not only on field data, but also on the assumptions used to transform tree measurements into biomass and carbon values [34].

Using the same biomass dataset for both scenarios allowed the effect of carbon-fraction selection to be evaluated without confounding it with stand structure or site productivity. This design is useful because carbon-accounting uncertainty can arise from allometric model choice, sampling design, biomass allocation, and reporting procedures [35].

The sensitivity check also showed that wood density and the root-to-shoot ratio can modify the absolute magnitude of carbon estimates, although the direction of the generic/refined difference remained controlled by the carbon fraction used in each scenario.

This approach is compatible with efforts to improve transparency in forest carbon monitoring. The Global Forest Observations Initiative emphasizes clear methods and consistent activity and emission data, while the European Forest Institute links reliable forest carbon MRV with transparent estimation procedures and international reporting needs [36]. Within that context, measured carbon fractions can serve as a local parameter for improving plantation-level estimates before any broader scaling is attempted.

Future applications could extend this framework to other tropical plantation species, mixed production systems, or inventories where biomass estimates are available but carbon fractions remain generic. REDD+ reporting analyses show that biomass-model and measurement uncertainties are important but not always fully reported, supporting the need for targeted refinements that make carbon estimates more defensible [37]. For teak plantations, the main contribution is therefore practical: measured carbon fractions can reduce one avoidable source of conversion uncertainty, while broader application requires larger and more representative inventory data [38].

4.5. Toward More Standardized Carbon Measurement in Teak Plantations

Teak plantations are part of a global tropical hardwood system, with information reported across countries in Asia, Africa, and Latin America. The Global Teak Resources and Market Assessment 2022 compiled country-level teak information using a standardized expert-based questionnaire, showing that teak is increasingly evaluated through comparable international datasets rather than only isolated local inventories [39].

This broader context makes transparent carbon-accounting procedures important. MRV systems require consistent methods, clear assumptions, and reliable carbon-stock information so that estimates can be compared across projects and reporting scales [40]. Within this framework, measured carbon fractions can improve one specific step that is often treated as fixed: the conversion of biomass into carbon. The present study does not propose a universal teak carbon standard but shows that a locally measured parameter can refine plantation-level estimates and reduce one avoidable source of conversion uncertainty.

A stronger pathway for teak carbon accounting would combine standardized field measurements, transparent allometric selection, and measured or regionally validated carbon fractions. This would allow teak-producing regions to compare carbon estimates more fairly while still recognizing differences in site conditions, management history, and plantation age. For broader application, however, measured carbon fractions should be supported by larger and more representative inventories. In this sense, the results provide a methodological refinement for teak plantation carbon accounting, not evidence of global or regional carbon-stock change [41].

5. Conclusions

This study showed that carbon estimates in tropical teak plantations are sensitive to the biomass-to-carbon conversion factor used after biomass estimation. Measured carbon fractions varied among biomass components, with leaves and branches below the generic 47% value, and stem, roots, and total biomass above it. This component-level variation confirms that a single fixed factor does not represent all teak biomass pools with the same precision.

The use of measured total biomass carbon fractions produced consistently higher carbon estimates than the generic 0.47 factor. Across plantation-age records, the refined approach increased carbon estimates by 1.33 Mg C ha⁻¹, equivalent to a mean relative adjustment of 2.67%. Although this adjustment was moderate at the hectare scale, its direction was consistent across localities, indicating that the generic factor introduced a systematic underestimation in the evaluated plantation dataset.

The main contribution of this work is methodological and applied. By keeping the same biomass dataset and changing only the carbon conversion parameter, the study isolated one specific source of uncertainty in plantation carbon accounting. This approach provides a simple and transparent way to refine plantation-level estimates without reinterpreting plantation growth or productivity. For broader regional application, measured carbon fractions should be combined with larger and more representative plantation inventories, standardized field measurements, transparent allometric selection, and locally or regionally validated carbon fractions.

Author Contributions: Conceptualization, B.A.R.-B.; methodology, B.A.R.-B.; software, B.A.R.-B. and Y.M.C.N.; validation, B.A.R.-B., R.M.B.-P. and B.C.S.A.; formal analysis, B.A.R.-B.; investigation, B.A.R.-B.; resources, R.M.B.-P.; data curation, R.M.B.-P., B.C.S.A., K.P.H.M. and L.N.C.C.; writing—original draft preparation, B.A.R.-B., J.L.M.M. and Y.M.C.N.; writing—review and editing, B.A.R.-B., R.M.B.-P.; B.C.S.A., L.N.C.C., K.P.H.M., J.L.M.M., Y.M.C.N. and H.E.R.A.; visualization, B.A.R.-B.; supervision, R.M.B.-P.; project administration, R.M.B.-P.; funding acquisition, B.A.R.-B. and R.M.B.-P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: All data supporting the findings of this study are available within the manuscript.

Acknowledgments: The author B.A.R.-B. gratefully acknowledges Marilyn Zuleth Ruiz Guzmán for her constant support, affection, and inspiration throughout the development of this work. Her presence has been a source of motivation and strength during the preparation of this manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AGB	Aboveground biomass
BGB	Belowground biomass
Bha	Biomass per hectare
DBH	Diameter at breast height
MRV	Measurement, reporting, and verification
TB	Total biomass

References

1. Kollert, W.; Kleine, M.; International Union of Forestry Research Organizations. (Eds.) *The Global Teak Study: Analysis, Evaluation and Future Potential of Teak Resources*; IUFRO world series; IUFRO: Vienna, Austria, 2017; ISBN 978-3-902762-77-1.
2. Bauhus, J.; van der Meer, P.; Kanninen, M. (Eds.) *Ecosystem Goods and Services from Plantation Forests*; Routledge: London, 2010; ISBN 978-1-84977-641-7.
3. Fernández-Moya, J.; Murillo, R.; Portuguese, E.; Fallas, J.L.; Ríos, V.; Kottman, F.; Verjans, J.M.; Mata, R.; Alvarado, A. Nutrient Accumulation and Export in Teak (*Tectona grandis* L.f.) Plantations of Central America. *iForest-Biogeosci. For.* **2015**, *8*, 33. <https://doi.org/10.3832/ifer1089-007>.
4. Martin, A.R.; Thomas, S.C. A Reassessment of Carbon Content in Tropical Trees. *PLoS ONE*. **2011**, *6*, e23533. <https://doi.org/10.1371/journal.pone.0023533>.
5. Thomas, S.C.; Martin, A.R. Carbon Content of Tree Tissues: A Synthesis. *Forests* **2012**, *3*, 332–352. <https://doi.org/10.3390/f3020332>.
6. Chave, J.; Réjou-Méchain, M.; Búrquez, A.; Chidumayo, E.; Colgan, M.S.; Delitti, W.B.C.; Duque, A.; Eid, T.; Fearnside, P.M.; Goodman, R.C.; et al. Improved Allometric Models to Estimate the Aboveground Biomass of Tropical Trees. *Glob. Change Biol.* **2014**, *20*, 3177–3190. <https://doi.org/10.1111/gcb.12629>.
7. Ruiz-Blandon, B.A.; Hernández-Alvarez, E.; Martínez-Trinidad, T.; Amaringo-Cordova, L.P.; Ucañay-Ayllon, T.M.; Bernaola-Paucar, R.M.; Hernández-Plascencia, G.; Orellana-Mendoza, E. Growth, Productivity, and Biomass–Carbon Allometry in Teak (*Tectona grandis*) Plantations of Western Mexico. *Forests* **2025**, *16*, 1521. <https://doi.org/10.3390/f16101521>.
8. INEGI Marco Geoestadístico Available online: <https://www.inegi.org.mx/app/biblioteca/ficha.html?upc=794551163061> (accessed on 7 June 2026).
9. INEGI. *Compendio de información geográfica municipal Rosamorada, Nayarit*; Instituto Nacional de Estadística y Geografía: Aguascalientes, México, 2010.
10. INEGI. *Compendio de información geográfica municipal San Blas, Nayarit*; Instituto Nacional de Estadística y Geografía: Aguascalientes, México, 2010.
11. INEGI. *Compendio de información geográfica municipal Tuxpan, Nayarit*; Instituto Nacional de Estadística y Geografía: Aguascalientes, México, 2010.
12. INEGI. *Compendio de Información Geográfica Municipal 2010: Ruíz, Nayarit*; Instituto Nacional de Estadística y Geografía: Aguascalientes, México, 2010.
13. INEGI. *Compendio de Información Geográfica Municipal 2010: Santiago Ixcuintla, Nayarit*; Instituto Nacional de Estadística y Geografía: Aguascalientes, México, 2010.
14. INEGI. *Compendio de Información Geográfica Municipal 2010: Tepic, Nayarit*; Instituto Nacional de Estadística y Geografía: Aguascalientes, México, 2010.
15. Telles Antonio, R.; Nájera Luna, J.A.; Alanís Rodríguez, E.; Aguirre Calderón, O.A.; Jiménez Pérez, J.; Gómez Cárdenas, M.; Muñoz Flores, H.J. Propiedades físico-mecánicas de la madera *Tectona grandis* L. f. de una plantación comercial en el estado de Michoacán. *Rev. Mex. Cienc. For.* **2017**, *8*, 37–56. <https://doi.org/10.29298/rmcf.v8i40.35>.
16. IPCC 2019 *Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*; IPCC: Geneva, Switzerland 2019.

17. LECO Corporation TruSpec Micro CHN/CHNS/O Available online: <https://www.leco.com/products/truspec/> (accessed on 7 June 2026).
18. SAS Institute Inc. *SAS/STAT User's Guide, Version 9.4*; SAS Institute Inc.: Cary, NC, USA, 2016.
19. Levene, H. Robust Tests for Equality of Variances. *Contrib. Probab. Stat.* **1960**, 278–292.
20. Shapiro, S.S.; Wilk, M.B. An Analysis of Variance Test for Normality (Complete Samples). *Biometrika* **1965**, 52, 591. <https://doi.org/10.2307/2333709>.
21. Doraisami, M.; Domke, G.M.; Martin, A.R. Improving Wood Carbon Fractions for Multiscale Forest Carbon Estimation. *Carbon Balance Manag.* **2024**, 19, 25. <https://doi.org/10.1186/s13021-024-00272-2>.
22. Ruiz-Erazo, C.E.; Riascos-Acosta, R.I.; Guerrero-Martínez, E.S.; Marín-Vélez, A.M.; Sierra, C.A.; Ramírez-Correa, J.A.; Ruiz-Erazo, C.E.; Riascos-Acosta, R.I.; Guerrero-Martínez, E.S.; Marín-Vélez, A.M.; et al. Carbon Sequestration Potential in Retrophyllum Rospigliosii (Pilg.) C. N. Page Plantations for Restoration Purposes in the Colombian Andean Region. *Rev. Chapingo Ser. Cienc. For. Ambient.* **2025**, 31, 1–17. <https://doi.org/10.5154/r.rchscfa.2024.04.009>.
23. Fonseca-González, W.; Murillo-Cruz, R.; Ávila-Arias, C.; Rojas-Vargas, M.; Parallada, R.M.S. Modelos de biomasa y carbono para árboles de Gmelina arborea en plantaciones clonales. *Rev. Cienc. Ambient.* **2021**, 55, 143–159. <https://doi.org/10.15359/rca.55-1.7>.
24. Chavan, S.B.; Dhillon, R.S.; Sirohi, C.; Saleh, I.A.; Uthappa, A.R.; Keerthika, A.; Jinger, D.; Halli, H.M.; Pradhan, A.; Kakade, V.; et al. Optimizing Planting Geometries in Eucalyptus-Based Food Production Systems for Enhanced Yield and Carbon Sequestration. *Front. Sustain. Food Syst.* **2024**, 8, 1386035. <https://doi.org/10.3389/fsufs.2024.1386035>.
25. Martin, A.R.; Domke, G.M.; Doraisami, M.; Thomas, S.C. Carbon Fractions in the World's Dead Wood. *Nat. Commun.* **2021**, 12, 889. <https://doi.org/10.1038/s41467-021-21149-9>.
26. Wu, H.; Xiang, W.; Fang, X.; Lei, P.; Ouyang, S.; Deng, X. Tree Functional Types Simplify Forest Carbon Stock Estimates Induced by Carbon Concentration Variations among Species in a Subtropical Area. *Sci. Rep.* **2017**, 7, 4992. <https://doi.org/10.1038/s41598-017-05306-z>.
27. Reta, G.T.; Tolera, M.; Mokria, M. Species-Specific Allometric Models for Estimating Aboveground Biomass and Carbon Stocks of Plantation Forests in Northcentral Ethiopia. *Sci. Rep.* **2026**, 16, 16865. <https://doi.org/10.1038/s41598-026-48435-0>.
28. Uttaruk, Y.; Laosuwan, T.; Sangpradid, S.; Samek, J.H.; Butthep, C.; Rotjanakusol, T.; Dumrongsukit, S.; Rouylarp, Y. Species-Specific Allometric Models for Biomass and Carbon Stock Estimation in Silver Oak (*Grevillea robusta*) Plantation Forests in Thailand: A Pilot-Scale Destructive Study. *Forests* **2026**, 17, 100. <https://doi.org/10.3390/f17010100>.
29. Qiu, B.; Li, S.; Cao, J.; Zhang, J.; Yang, K.; Luo, K.; Huang, K.; Jiang, X. Uncertainty Analysis of Forest Aboveground Carbon Stock Estimation Combining Sentinel-1 and Sentinel-2 Images. *Forests* **2024**, 15, 2134. <https://doi.org/10.3390/f15122134>.
30. Xu, W.; Cheng, Y.; Luo, M.; Mai, X.; Wang, W.; Zhang, W.; Wang, Y. Progress and Limitations in Forest Carbon Stock Estimation Using Remote Sensing Technologies: A Comprehensive Review. *Forests* **2025**, 16, 449. <https://doi.org/10.3390/f16030449>.
31. Khan, K.; Khan, S.N.; Ali, A.; Khokhar, M.F.; Khan, J.A. Estimating Aboveground Biomass and Carbon Sequestration in Afforestation Areas Using Optical/SAR Data Fusion and Machine Learning. *Remote Sens.* **2025**, 17, 934. <https://doi.org/10.3390/rs17050934>.
32. Wang, T.; Dong, L.; Liu, Z. Factors Driving Carbon Accumulation in Forest Biomass and Soil Organic Carbon across Natural Forests and Planted Forests in China. *Front. For. Glob. Change* **2024**, 6, 1333868. <https://doi.org/10.3389/ffgc.2023.1333868>.
33. Favero, A.; Austin, K.G. Charting Our Forest Future: National Supply Curves for Forest-Based CO₂ Mitigation. *npj Clim. Action* **2026**, 5, 6. <https://doi.org/10.1038/s44168-026-00335-9>.
34. Vorster, A.G.; Evangelista, P.H.; Stovall, A.E.L.; Ex, S. Variability and Uncertainty in Forest Biomass Estimates from the Tree to Landscape Scale: The Role of Allometric Equations. *Carbon Balance Manag.* **2020**, 15, 8. <https://doi.org/10.1186/s13021-020-00143-6>.
35. Ameztegui, A.; Rodrigues, M.; Granda, V. Uncertainty of Biomass Stocks in Spanish Forests: A Comprehensive Comparison of Allometric Equations. *Eur. J. Forest Res.* **2022**, 141, 395–407. <https://doi.org/10.1007/s10342-022-01444-w>.
36. Espejo, A.; Federici, S.; Green, C.; Amuchastegui, N.; d'Annunzio, R.; Balzter, H.; Bholanath, P.; Brack, C.; Brewer, C.; Birigazzi, L.; et al. *Integration of Remote-Sensing and Ground-Based Observations for Estimation of Emissions and Removals of Greenhouse Gases in Forests: Methods and Guidance from the Global Forest Observations Initiative*, 3rd ed.; U.N. Food and Agriculture Organization: Rome, Italy, 2020; 300p.
37. Butler, B.J.; Sass, E.M.; Gamarra, J.G.P.; Campbell, J.L.; Wayson, C.; Olguín, M.; Carrillo, O.; Yanai, R.D. Uncertainty in REDD+ Carbon Accounting: A Survey of Experts Involved in REDD+ Reporting. *Carbon Balance Manag.* **2024**, 19, 22. <https://doi.org/10.1186/s13021-024-00267-z>.

38. Yanai, R.D.; Wayson, C.; Lee, D.; Espejo, A.B.; Campbell, J.L.; Green, M.B.; Zuskwert, J.M.; Yoffe, S.B.; Aukema, J.E.; Lister, A.J.; et al. Improving Uncertainty in Forest Carbon Accounting for REDD+ Mitigation Efforts. *Environ. Res. Lett.* **2020**, *15*, 124002. <https://doi.org/10.1088/1748-9326/abb96f>.
39. Kollert, W.; Sasidharan, S.; Sreelakshmy, M. *Global Teak Resources and Market Assessment 2022*; IUFRO World Series; IUFRO: Vienna, Austria, 2024; Volume 44.
40. Thornbush, M.; Govind, A. Monitoring, Reporting, and Verification (MRV) Protocols Used in Carbon Trading Applied to Dry-land Nations in the Global South for Climate Change Mitigation. *Sustainability* **2025**, *17*, 11001. <https://doi.org/10.3390/su172411001>.
41. FAO. *Global Forest Resources Assessment 2025*; FAO: Rome, Italy, 2025; ISBN 978-92-5-140082-1.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.