


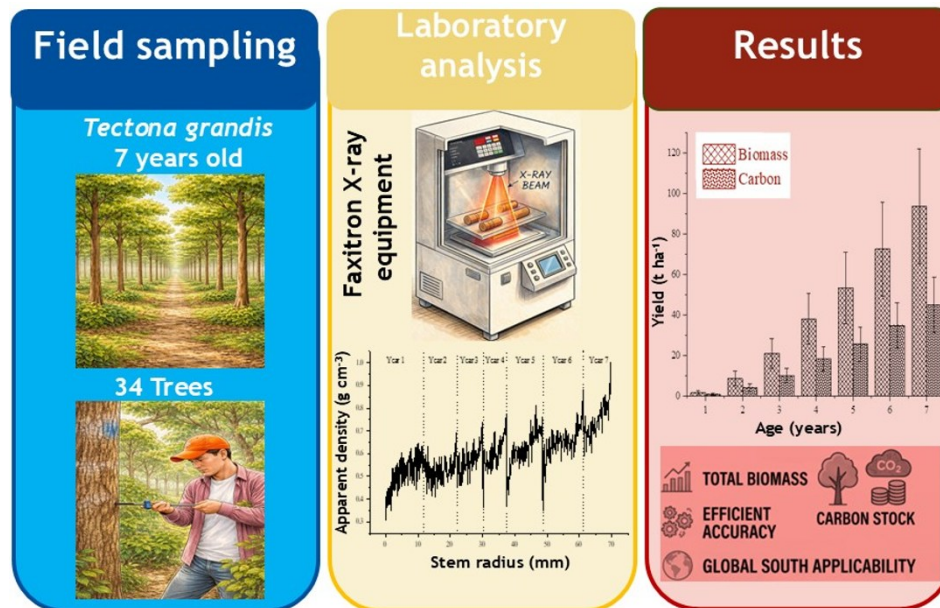
Annual Carbon Storage in Young *Tectona grandis* Plantations Using Tree Ring Analysis and X-Ray Densitometry

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GRAPHICAL ABSTRACT



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Tectona grandis plantations are crucial for carbon sequestration in tropical regions. This study aimed to estimate annual carbon storage in teak plantations stems using a novel integration tree ring analysis and high-resolution X-ray densitometry. The authors sampled 34 trees from a 7-year-old teak plantation in southeastern Peru. Four increment cores were extracted from each tree to measure growth rings and wood density. Unlike traditional static allometric equations, the data were used to reconstruct annual tree growth and estimate biomass and carbon storage per hectare by capturing inter-annual wood density variability. Results showed a significant carbon storage capacity in stems of 45 t C ha⁻¹ at 7 years of age, with an annual increment of 6.4 t C ha⁻¹ yr⁻¹, demonstrating a positive growth trend that outperformed several regional native species. Gompertz's model predicted that teak stems could store up to 69.2 t C ha⁻¹ by 10 years. The study confirms that teak plantations are a highly efficient carbon sink, and that this dendro-densitometric approach provides a precise, non-destructive methodological framework for certifying carbon credits and optimizing forest management in the Global South.

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Keywords: Biomass; Carbon sequestration; Growth rings; Mean annual increment; Wood density

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INTRODUCTION

Climate change is one of the greatest concerns due to severe impacts on temperature and precipitation patterns affecting ecosystem equilibrium and human development. Climate change is closely linked to rising carbon dioxide (CO₂) concentrations. This increase stems from intensified industrial activity and land-use change driven by agriculture and livestock expansion (Bhatti *et al.* 2024). Deforestation and land degradation, common in the Amazon region, are key factors in CO₂ emissions and the alteration of carbon balance in soils, as observed in recent studies (Rocha *et al.* 2025).

In this context, the recovery of degraded areas, formed by land use change, through reforestation and restoration, is one of the strategies to reduce the CO₂ concentration.

Forested areas can play an important role in capturing and storing carbon from the atmosphere, thus mitigating CO₂ emissions (Houghton 2005). Trees use CO₂ during photosynthesis, and approximately 50% of their biomass is carbon (Olorunfemi *et al.* 2019), which makes forest plantations an effective method of carbon capture and sequestration. However, this carbon fraction is not universal; it fluctuates according to tree species and environmental conditions, as variations in wood density and metabolic processes influence the concentration of carbon compounds in the tissues (Olorunfemi *et al.* 2019; Hornink *et al.* 2025). This variation highlights the importance of analyzing specific tree components to better understand their contribution to total sequestration. Reforestation has been shown to significantly enhance carbon storage in ecosystems, with vegetation having the most substantial impact on carbon sequestration. Studies indicate that reforestation in degraded soils can result in substantial increases in carbon storage across different plantation types (Li *et al.* 2024). Forest plantations are valued for timber production; however, the ecosystem services they provide, such as carbon sequestration and biodiversity conservation, are still undervalued due to methodological diversity and conceptual fragmentation in economic valuation (

and O'Hagan-Luff 2026). The recent Clean Development Mechanism (CDM) allows for the implementation of emission-reduction projects to generate saleable certified emission reduction (CER) credits (Derwisch *et al.* 2009). Furthermore, the tree stem contains approximately 58.5% to 75% of the total carbon stored in the aboveground biomass of the tree (stem, branches, and leaves) (Kraenzel *et al.* 2003; Hiratsuka *et al.* 2005; Derwisch *et al.* 2009). The stem is typically the primary component used for long-lived forest products: furniture, flooring and construction panels. These products can sequester carbon for decades or even centuries before it is re-emitted into the atmosphere.

Tectona grandis Linn. F. (teak) is one of the most important tropical hardwood species in the international market for high-quality timber. The strong demand for *T. grandis* wood has led to the establishment of plantations within and outside its countries of origin (Kollert and Kleine 2017). In Peru, commercial *T. grandis* plantations have been planted since 2010, using selected seeds and highly productive clones from Brazil and Costa Rica. The largest plantations in Perú are concentrated in Madre de Dios and Huánuco. In addition to the importance of wood supply, these plantations are carbon sinks. Previous studies in Costa Rica show that *T. grandis* plantations between 8 and 47 years old can accumulate 70 to 221 t ha⁻¹ of biomass in their stems (Cordero and Kanninen 2003a), which is equivalent to 35 and 110 t C ha⁻¹. In Peru, there are no studies about the carbon storage capacity in *T. grandis* forest plantations. As this species becomes more important for wood production, knowing the amount of carbon fixed in stems over rotation will help to estimate the valuation for the carbon market.

In contrast, the carbon storage capacity also depends on the management practices adopted and the edaphoclimatic conditions of the site (Silveira *et al.* 2020). Thus, studies should be conducted for the region of interest for more reliable estimates of stored carbon by *T. grandis* forest plantations. Most studies of carbon fixed in trees have determined the amounts indirectly using only allometric equations on the entire aboveground biomass (stem, branches, and leaves), at a particular age, which makes it difficult to build a growth model for carbon storage as a function of tree age. The current study proposes the application of a non-destructive technique for estimating trees' fixed carbon from growth rings analysis, combined with X-ray densitometry. These high-resolution techniques are essential because the variation in wood density and radial growth across time significantly

shifts the patterns of biomass production in tropical trees (Hornink *et al.* 2025). Furthermore, these methods allow the reconstruction of tree growth and wood density for each growth ring (Tomazello *et al.* 2008). *T. grandis* develops well-differentiated annual growth rings (Venegas-González 2013), facilitating growth reconstruction to develop suitable predictive models of stem carbon storage in *T. grandis* forest plantations.

In this context, the study aimed to estimate the annual-scale carbon storage capacity of the stems in *T. grandis* plantations throughout seven years and to build a carbon storage prediction model. The study was guided by the hypothesis that the integration of annual growth ring analysis and X-ray densitometry allows for a more precise reconstruction of carbon sequestration rates than traditional allometric methods, capturing the inter-annual variability of wood density. This hypothesis was tested by comparing the annual reconstructed data with established growth models (Gompertz), thereby evaluating the consistency of carbon accumulation patterns over the first seven years of growth. Beyond its local application, this study serves as a methodological framework for the rapid and precise assessment of carbon dynamics in tropical hardwoods worldwide. By integrating high-resolution techniques like X-ray densitometry, we provide a scalable approach to calibrate carbon models in regions where destructive sampling is restricted or data is scarce.

EXPERIMENTAL

Study Site

The study was conducted at a seven-year-old *T. grandis* plantation owned by Reforestadora Amazonica SAC company, which is located 21 kilometers from Iberia city along the Interoceanic highway (PE-30C), on the Iberia – Iñapari route, in the Tahuamanu district, Madre de Dios department, Perú (Fig. 1).

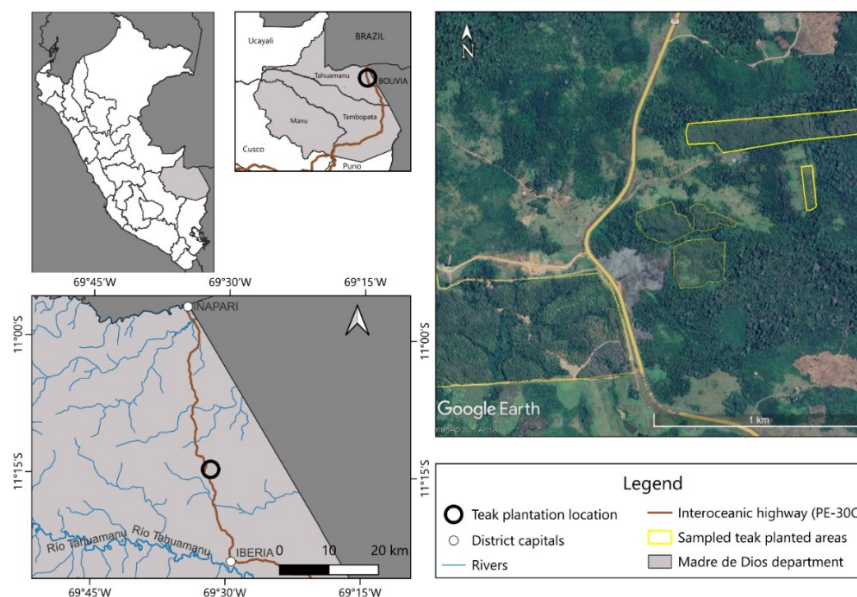


Fig. 1. Location of the study area. The 34 teak trees were randomly sampled from two planted areas, indicated by thicker yellow lines.

The plantation is situated at an elevation ranging from 200 to 210 m.a.s.l. The mean temperature is 27 °C, varying between 10 and 20 °C in the coldest months (May to August) and from 29 to 38 °C in the hottest months (September to November). Mean annual precipitation is 2,299 mm (Senamhi 2008). The region experiences two well-defined seasons: a dry season from May to October (483 mm) and a rainy season from November to April (1,427 mm) (Zepner *et al.* 2021).

The *T. grandis* plantation was established in late 2011 using seedlings from seeds of highly productive trees produced by PROTECA (Mato Grosso, Brazil). Trees were planted at a spacing of 3 m x 3 m. Silvicultural management included annual pruning and 25% thinning at age 4. At the time of planting, standard fertilization (nitrogen, potassium, phosphorus, and micronutrients) was applied in holes next to the plants. The rotation age for harvest is 22 years. For the study, 34 trees were randomly sampled in 2018, when the plantation was seven years old.

Collection and Preparation of Wood Core Samples

Wood cores were extracted from 34 trees (four cores per tree) at breast height (1.3 m). Cores were prepared following standard procedures for dendrochronological analysis (Stokes and Smiley 1996). The growth rings were delimited by visual inspection under a stereomicroscope (x 20 magnification) (Fig. 2).



Fig. 2. Growth ring boundaries (white arrows) of *Tectona grandis* "teak" trees from forest plantations in Madre de Dios

Tree Growth Reconstruction

Cores were digitized at 1200 dpi in .tif format for ring width measurement with a resolution of 0.01 mm using ImageJ software. Ring-width series of the four radii were averaged, obtaining a single ring-width series per tree, which was cross-correlated visually and using COFECHA program (Holmes *et al.* 1986).

Current annual increment (CAI) of diameter at breast height (dbh) for a given age was calculated using Eq. 1:

$$CAI-dbh = 2 \times ring\ width \quad (1)$$

Stem volume yield (v) inside bark for a given age was calculated by the volume Eq. 2 for *T. grandis* (Cordero and Kanninen 2003b):

$$v = (-0.0084 + 0.0297 \times dbh)^2 \quad (2)$$

Then the current annual increment of stem volume in m³ per hectare (CAI-Vh) for a given age "n" was estimated using Eq. 3:

$$CAI-Vh = (v_n - v_{n-1}) \times stand\ density \times \frac{\% plant\ survival}{100} \times \frac{(100 - \% thinning)}{100} \quad (3)$$

Stand density was 1,110 trees per hectare, plant survival was 95% at seven years of age, and thinning percentage was 25% at the end of the fourth year.

Wood Density of Growth Rings from X-ray Densitometry Analysis

One core per tree was fixed between two wooden supports and cut in the transverse direction (2 mm thick) in a double circular saw, placed in an air-conditioned room at 20 °C, 60 to 65% relative humidity for 24 h to reach 12% moisture content. Subsequently, X-ray images of the core samples were obtained using the Faxitron MX-20 Cabinet X-Ray Imaging System (Faxitron X-Ray Corporation, Lincolnshire, IL, USA) at LAIM Laboratory - Universidade de São Paulo (USP) (Quintilhan *et al.* 2021). X-ray images were analyzed in WINDENDRO Density 2017a® software (Regent Instruments Inc.), obtaining the apparent density profile (interval of 34 µm) to calculate the average apparent density of each growth ring (AD) in each tree.

Wood basic density for each growth ring (BD), defined as oven-dried mass divided by fresh volume in g cm⁻³, was estimated from its relationship with AD by Eq. 4 (Ortega Rodriguez and Tomazello-Filho 2019):

$$BD = 0.1237 + 0.528AD \quad (4)$$

Determination of Carbon Stored in Tree Stems

The current annual increment of biomass (CAI-B) for a given age in metric tons (t) per hectare (ha) was calculated using Eq. 5:

$$CAI-B = \sum_{i=1}^{N-1} (BD \times 1000 \times CAI-Vh) \quad (5)$$

According to Brown (1997), carbon (C) accounts for 48% of the biomass, then the current annual increment of carbon (CAI-C) for a given age in t ha⁻¹ is determined by the Eq. 6:

$$ICA-C = ICA-B \times 0.48 \quad (6)$$

Mean Annual Increment (MAI-C) and Carbon Yield Were Also Calculated

To analyze all of these equations, data, and figures, the statistical analysis was performed using R Software with the RStudio interface version 4.4.3 (R Core Team 2025). Carbon yield as a function of age was modeled using the Gompertz model. The fit quality of the model was evaluated by the adjusted determination coefficient (R²) and the square root of the mean squared error (RMSE).

RESULTS AND DISCUSSION

Cross-dating and Wood Density Profiles of Tree Rings

The intercorrelation of tree growth rings series with the master series was 0.41, which was higher than the critical intercorrelation of 0.34 at 99% significance. Ring width increased in the 2nd year and thereafter decreased (Fig. 3).

The results of cross-dating showed that *T. grandis* trees had a common growth pattern among them, indicating the formation of annual rings (Brienen and Zuidema 2005), due to the seasonality of precipitation, with a dry season (June to August) where precipitation decreases to less than 50 mm monthly, and a rainy season (November to March) during which precipitation can exceed 300 mm monthly in the wettest month (Senamhi 2008).

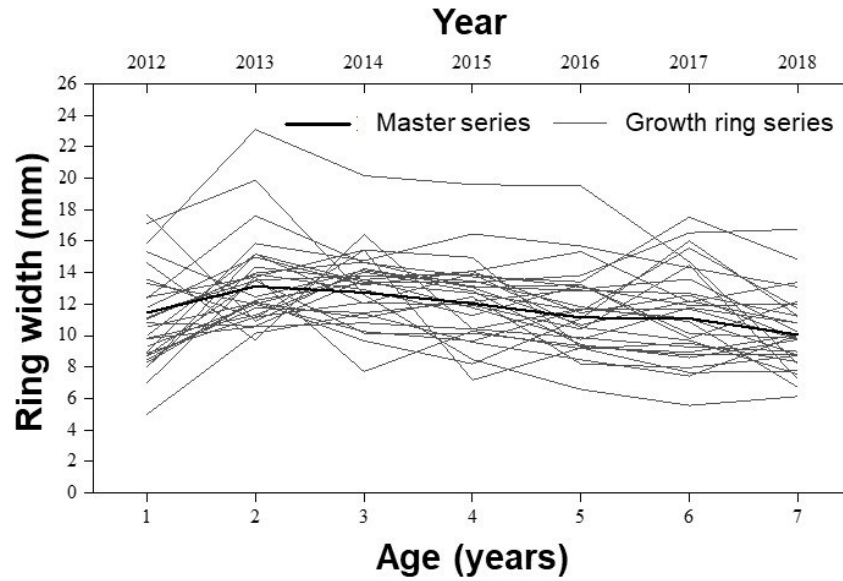


Fig. 3. Tree growth ring and master series of *Tectona grandis* trees

The annual decrease in ring width (Fig. 3) is a characteristic pattern in woody plants. As tree diameter expands, anticlinal division of cambium cells increases to sustain growth, while periclinal division is reduced. This process results in rings with greater circumference and narrower width (Bowyer *et al.* 2007).

Wood density radial profile showed the well-defined boundaries of the growth rings, characterized by low density in the early wood region increasing to the latewood until a maximum peak, which defined the ring limit, and then a sharp decrease (Fig. 4).

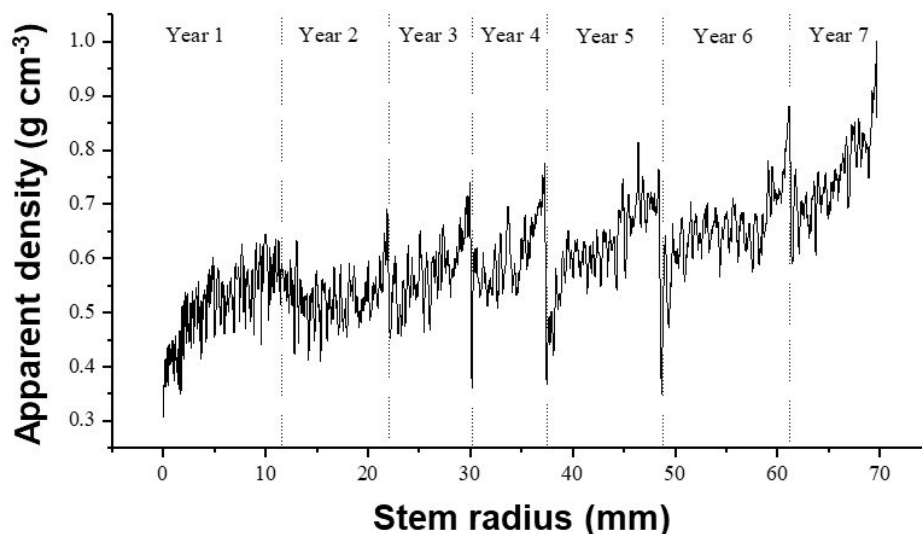


Fig. 4. Wood density radial profile built by X-ray densitometry analysis, from radial cores of *Tectona grandis* trees

Wood apparent density increased from pith to the bark (Fig. 4) and varied from 0.30 g cm^{-3} to 1 g cm^{-3} , with a mean of 0.62 g cm^{-3} . In contrast, mean wood basic density was 0.42 g cm^{-3} , 0.43 g cm^{-3} , 0.44 g cm^{-3} , 0.45 g cm^{-3} , 0.45 g cm^{-3} , 0.48 g cm^{-3} , and 0.50 g cm^{-3} , respectively, at 1st, 2nd, 3rd, 4th, 5th, 6th, and 7th year of age (Fig. 5).

Furthermore, the wood density profiles obtained through the non-destructive method provide insights into the structural quality of the stored carbon. High-density wood, as observed in the later rings, ensures longer carbon residence times in timber products. This aligns with Zhu *et al.* (2026), who argued that forest management must prioritize species that not only grow fast but also produce high-density biomass to ensure the long-term effectiveness of terrestrial carbon pools.

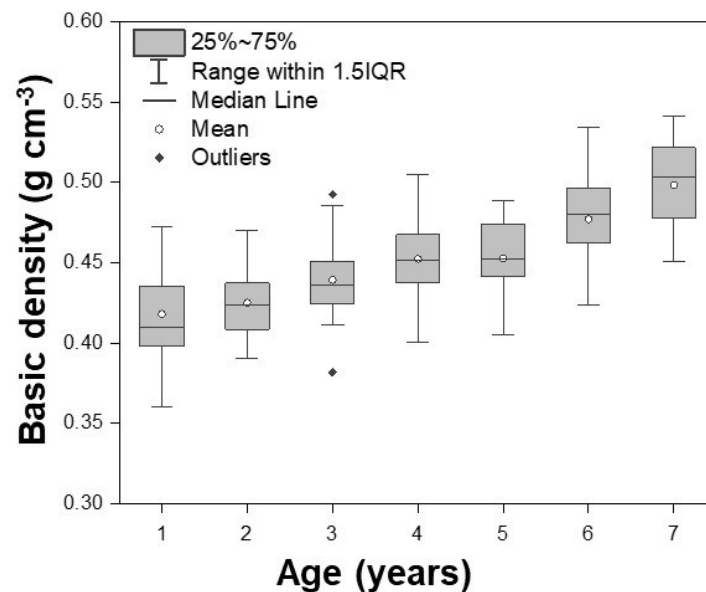


Fig. 5. Annual variation of wood basic density on *Tectona grandis* trees

The mean wood apparent density value of *T. grandis* trees measured 0.62 g cm^{-3} , which agrees with other reports in Brazil (0.64 g cm^{-3}) (Venegas-González 2013) or in Costa Rica (0.55 to 0.87 g cm^{-3}) (Moya *et al.* 2009), showing that *T. grandis* presents little variation in wood density between these neotropical zones. In Africa, wood apparent density is slightly higher, ranging from 0.65 to 0.73 g cm^{-3} in young and adult *T. grandis* trees (Kokutse *et al.* 2004), while in Asia it is 0.62 to 0.70 g cm^{-3} .

Annual Carbon Storage in Tree Stems

We observed that CAI-C of stems increased steadily from the 1st to 4th year of age, followed by a slight decrease at the 5th year, due to 25% thinning. However, CAI-C reached the maximum value at the 7th year of age. Mean values of CAI-C were 0.8, 3.3, 5.9, 8.2, 7.3, 9.2, and 10.1 t C ha^{-1} , respectively, from 1 to 7 years of age in the *T. grandis* plantation (Fig. 6).

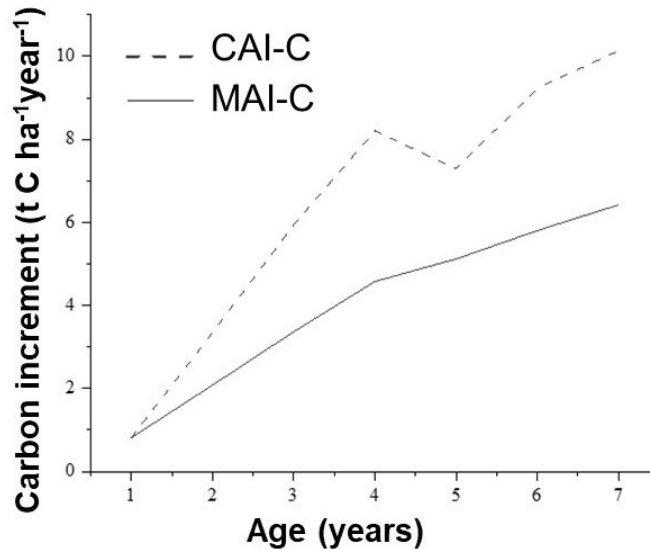


Fig. 6. Curves of current annual increment of carbon (CAI-C) and mean annual increment of carbon (MAI-C) in metric tons of carbon per hectare per year ($t C ha^{-1} year^{-1}$) stored in the *Tectona grandis* tree stems

The MAI-C increased steadily with age, which indicated that the MAI-C will continue to increase after 7 years. The IMA-C was determined to be about 0.8, 2.1, 3.4, 4.6, 5.1, 5.8, and 6.4 $t C ha^{-1} year^{-1}$ from the 1st to 7th year of age, respectively.

At 7 years of age, the biomass yield of stems was 93.7 $t ha^{-1}$, and therefore, the carbon yield was 45 $t C ha^{-1}$ (Fig. 7).

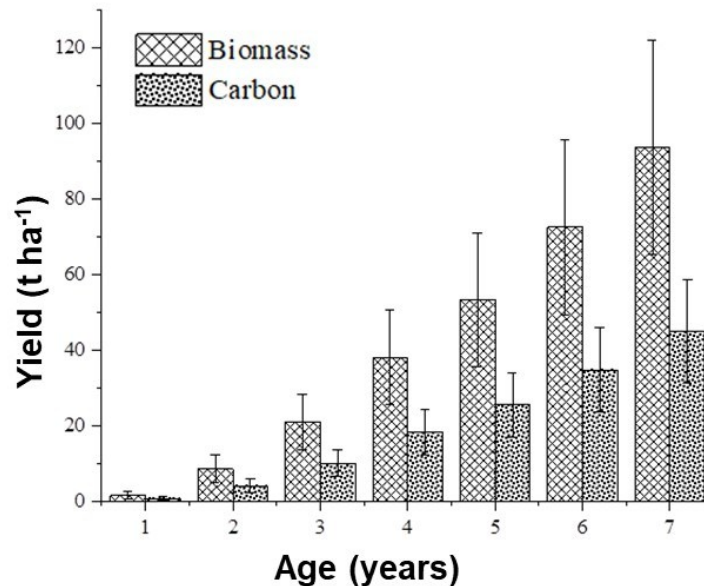


Fig. 7. Biomass and carbon yield of tree stems in metric tons per hectare ($t ha^{-1}$) throughout 7 years in *Tectona grandis* tree stems

This study emphasizes the importance of examining the stem as the primary component of aboveground biomass because it is the only part of the tree that is actually

harvested and transformed into various end-use products, such as furniture, construction timber, panels, veneers, flooring, and musical instruments. Over its lifetime (decades or centuries), carbon remains stored in these products before being re-released into the atmosphere. Furthermore, it is worth noting that woody tissue serves not only as a reservoir for carbon but also as a sink for other substances, including potentially harmful elements such as heavy metals. As the stem is the largest organ of the tree, it functions as a long-term storage site for these elements, reflecting its role as a stabilizer of environmental quality (Özel *et al.* 2024).

Most studies report total aboveground biomass, including stems, branches, and leaves. Consequently, comparison must account for the fact that stem-stored carbon represents approximately 65% of the aboveground biomass in young trees (Derwisch *et al.* 2009). Thus, the MAI-C in the tree stems up to the 7th year was 6.4 t C ha⁻¹ yr⁻¹ (Fig. 6), which is equivalent to 9.9 t C ha⁻¹ yr⁻¹ at the scale of total aboveground biomass. This value is within the range reported in different studies. MAI-C ranges from 2.9 to 17 t C ha⁻¹ yr⁻¹ depending on the age of the plantation (Derwisch *et al.* 2009; Gallegos *et al.* 2009; Kaul *et al.* 2010; Lopez Guzman 2017; Gerardo López *et al.* 2018). However, compared with plantations of similar age, the current study's results of carbon stored were higher. For example, MAI-C was 3.5 t C ha⁻¹ yr⁻¹ in 8-year-old plantations in Mexico (Gallegos *et al.* 2009), and 4.1 t C ha⁻¹ yr⁻¹ in 10-year-old plantations in Panama (Derwisch *et al.* 2009), which may be related to the slower growth of the trees in these sites. In this context, the results of this study indicate a high carbon storage capacity in *T. grandis* trees growing in Tahuamanu, Perú.

The use of X-ray densitometry in this study addresses a critical gap in tropical forest monitoring. Unlike traditional allometric models that often assume constant wood density, the present approach captures the high-frequency variability of carbon allocation. This is consistent with recent findings by Hornink *et al.* (2025), who emphasize that incorporating precise wood density measurements is essential for reducing uncertainties in global biomass estimates, especially in fast-growing tropical hardwoods.

To further support the effectiveness of *T. grandis* as a carbon sink, its performance can be contrasted with that of native vegetation in the same region. In Madre de Dios, natural forest formations such as terrace forests have been identified as primary carbon reservoirs due to their extension and density (Martel and Cairampoma 2012). However, the rapid accumulation of 45 t C ha⁻¹ observed in our 7-year-old teak plantation represents a highly efficient short-term sequestration rate when compared to the growth dynamics of native species such as *Cedrelinga cateniformis* in regional agroforestry systems (Murga-Orrillo *et al.* 2024). While native species such as *C. cateniformis* exhibit a long-term developmental trajectory, the early carbon yield of *T. grandis* highlights its strategic value for stabilizing carbon stocks in areas under high anthropogenic pressure, such as the southeastern Peruvian Amazon (Asner *et al.* 2014; Nicolau *et al.* 2019).

The sequestration rate of 6.4 t C ha⁻¹ yr⁻¹ found in Tahuamanu underscores the potential of teak plantations to act as intensive carbon sinks. This performance is particularly relevant in the current global context, where anthropogenic emissions continue to challenge climate stability. As noted by Bhatti *et al.* (2024), optimizing the carbon removal capacity of forest plantations is one of the most viable nature-based solutions to offset industrial CO₂ increases.

The integration of these techniques represents a dendro-densitometric approach that transcends local measurements. It establishes a reliable methodological framework

necessary for the accurate certification of carbon credits, ensuring that forest management strategies in the Global South are based on high-resolution biological data rather than generalized estimates.

The CAI and MAI curves (Fig. 6) indicated that the rotation for biomass production and carbon storage is greater than seven years. That is, the trees have greater carbon storage potential at a more mature stage. Studies at older ages or projections are necessary to know the optimal rotation.

Carbon Storage Model of Tree Stems

The Gompertz model (Eq. 7) showed good performance in predicting carbon yields ($R^2 = 0.79$ and $RMSE = 7.88 \text{ t C ha}^{-1}$) (Fig. 8).

$$\text{Carbon yield} = 83185.9687e^{-e^{(-0.30709(t-5.47433))}} \quad (7)$$

Extrapolating the model for 10 years of age, the carbon yield would be approximately 69.2 t C ha^{-1} , with a confidence interval of $\pm 15 \text{ t C ha}^{-1}$.

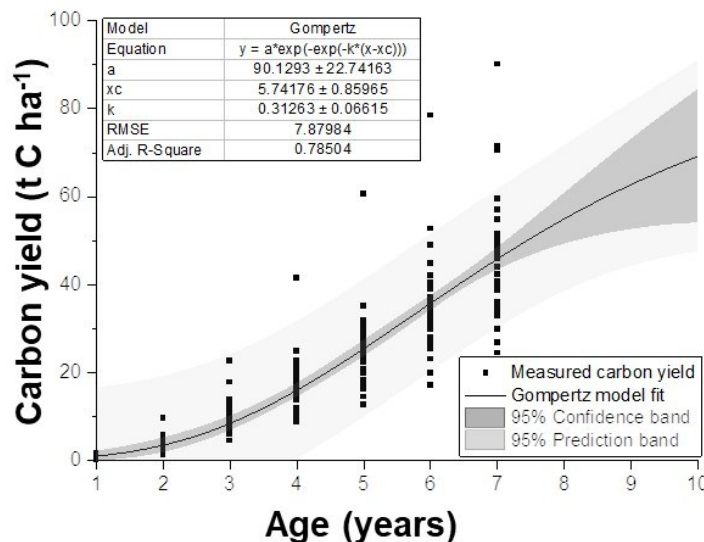


Fig. 8. Gompertz model fitted to the carbon yield measured in the stems of 34 *Tectona grandis* trees; the model was extrapolated for 8 to 10 years of age

The projection of carbon storage using the Gompertz model, until 10 years old (Fig. 8), showed that the tree stems could store $69.2 (\pm 15) \text{ t C ha}^{-1}$ until 10 years of age, *i.e.*, $6.9 \text{ t C ha}^{-1} \text{ yr}^{-1}$. Considering that stem biomass represents approximately 65% of the aboveground biomass of *T. grandis* (Derwisch *et al.* 2009), the carbon stored in aboveground biomass in a 10-year rotation is approximately 93.4 t C ha^{-1} , *i.e.*, $9.3 \text{ t C ha}^{-1} \text{ yr}^{-1}$. These estimates agree with direct measurements and projections in 15-year-old *T. grandis* plantations in Guatemala of $10.8 \text{ t C ha}^{-1} \text{ yr}^{-1}$ (Gerardo López *et al.* 2018). In mature 20-year-old plantations in Panama, aboveground biomass contained approximately 6 to $9.6 \text{ t C ha}^{-1} \text{ yr}^{-1}$ (Kraenzel *et al.* 2003; Derwisch *et al.* 2009).

Studies in India, where *T. grandis* originates, show that these trees store approximately $2 \text{ t C ha}^{-1} \text{ yr}^{-1}$ (Kaul *et al.* 2010). Compared to other species, *T. grandis* stores less carbon than *Populus* spp. ($8 \text{ t C ha}^{-1} \text{ yr}^{-1}$) or *Eucalyptus* spp. ($6 \text{ t C ha}^{-1} \text{ yr}^{-1}$). Kaul *et al.* (2010) showed that, with increasing rotation time, the carbon stock per year

decreases considerably. For example, with a 60-year rotation, the carbon stock is 3.7 t C ha⁻¹ yr⁻¹, decreasing to 1.7 t C ha⁻¹ yr⁻¹ in a 150-year rotation. In another study in India, 50-year-old *T. grandis* plantations were found to sequester approximately 3.6 t C ha⁻¹ yr⁻¹ (Sreejesh *et al.* 2013). In the Himalayan region, in young plantations of 1, 5, 11, 18, 24, and 30 years, the carbon stock ranged between 0.9 and 6 t C ha⁻¹ yr⁻¹ (Jha 2005).

The current study's findings, in line with the study by Dominguez-Salcedo and Portal-Cahuana (2024), further support the significant influence of environmental factors, particularly climate, on tree growth. The study by Dominguez-Salcedo and Portal-Cahuana emphasizes the relationship between *T. grandis* growth and climatic variables, such as precipitation and sea surface temperature anomalies, which mirrors the current authors' own observations in the Madre de Dios region. These results reinforce the notion that climate variability, both local and global, plays a pivotal role in the carbon sequestration potential of *T. grandis* plantations.

The current findings show that teak plantations are significant carbon reservoirs, where the products derived from harvested wood are long-lasting, functioning as “carbon sequestrators.” This is the first report providing an annual-scale estimate of the carbon stored in teak plantation tree stems, using non-destructive techniques such as growth ring analysis and X-ray densitometry. These methods offer a direct, practical, and reliable way to estimate biomass and carbon in tree stems.

It is important to consider that tree development and carbon sequestration are shaped by the interaction of multiple factors. As noted in recent studies, all phenotypic characteristics of plants are formed under the interaction of genetic structure and environmental factors (Sevik *et al.* 2021; Kurz *et al.* 2023). In addition to climate, practices such as fertilization and stress factors—including drought, radiation, and soil conditions—significantly affect plant growth and wood formation (Sadak and Bakhoum 2019; Ghoma *et al.* 2023). Furthermore, different levels of genetic diversity cause varying reactions to environmental stress (Özel *et al.*, 2024). Therefore, while the current results demonstrate a high potential for carbon storage in Tahuamanu, Peru, these findings should not be viewed as absolute values for the species, as studies conducted on different genotypes or in different regions might yield different growth signals and carbon yields.

CONCLUSIONS

1. The *T. grandis* plantation demonstrated a high carbon storage capacity in stem biomass (6.4 t C ha⁻¹ yr⁻¹), outperforming the sequestration rates of several native species in the Amazon. This efficiency highlights teak as a strategic tool for rapid climate change mitigation in tropical ecosystems under anthropogenic pressure.
2. According to the adjusted growth model, the estimated stem carbon storage of 69.2 t C ha⁻¹ at 10 years confirms these plantations as highly productive sinks. These findings provide a critical quantitative baseline for economic valuation in international carbon credit markets and Clean Development Mechanisms (CDM).
3. The study validates the hypothesis that growth ring analysis combined with X-ray densitometry provides a superior, non-destructive alternative to traditional allometry by capturing inter-annual wood density variability. This approach is shown to be a

precise and scalable method for monitoring carbon dynamics in tropical hardwoods globally.

4. This dendro-densitometric methodology offers a reliable tool for standardizing carbon quantification and certifying carbon credits. This research transcends the local Peruvian context by establishing a methodological framework applicable to other regions in the Global South to improve the accuracy of greenhouse gas inventories.

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