

Allometric Model of Carbon Sequestration in Coconut (*Cocos nucifera* L.) Agroforestry System in Indonesia

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Abstract

Coconut (*Cocos nucifera* L.) plantations in Indonesia have not yet been recognized as a sector capable of reducing greenhouse gas emissions due to the limited information regarding their potential for significant carbon sequestration, economic value, and sustainability. This comprehensive analysis aims to quantify the carbon sequestration capacity of coconut plantations, advocate their participation in carbon trading mechanisms, and elucidate their potential contribution to Indonesia's Nationally Determined Contribution. A regression model was developed to assess the incremental growth in diameter and height of trees, utilizing data from multiple age classes and secondary data obtained from the Ministry of Agriculture between 2017 and 2023. The potential carbon sequestration of coconut plantations in Indonesia was estimated using selected biomass allometry models. Significant biomass volume increments were observed between 19 and 58 years. Carbon stocks range from 0.17 to 0.61 t C per mature tree, resulting in a total carbon stock of 75 t C ha⁻¹. Annual carbon sequestration increased by approximately 3%, amounting to 11 million t C from 2017 to 2023. This review underscores the potential role of coconut plantations in Indonesia and globally in carbon sequestration. Our methodology for identifying the growth behavior of a significant coconut variety in Indonesia can be utilized to estimate carbon sequestration for coconut plants at specific ages. It is advantageous to rejuvenate old coconut trees that are more than 58 years old to optimize their development 19 years after planting to unlock the sector's potential benefits as carbon sequesters, thereby enhancing its economic value.

Highlights

- Allometric models were employed to simulate the carbon sequestration process in coconut plantations located in Indonesia.
- The total carbon stock in Indonesia's coconut plantations increased from 60.9 million to 72.5 million tons of carbon (t C) between 2017 and 2023.
- The estimated total carbon sequestered from Indonesia's current coconut plantations is 11 million metric tons of carbon (t C) from 2017 to 2023.

1. Introduction

Coconuts (*Cocos nucifera* L.) are versatile plantation crops that demonstrate high adaptability in tropical regions, thriving in a wide range of soil types, from coastal to heavy clay soils (Alouw and Wulandari 2020; Subramanian et al. 2024). Coconut trees are commonly found throughout Indonesia, flourishing in both inland and coastal areas. Studies indicate that coconuts can grow in low-fertility soils, including sandy soils like Alfisols, Entisols, Ultisols, and Inceptisols, due to their extensive root systems, which enable efficient nutrient and water uptake from deeper soil layers (Malhotra et al. 2017; Nair et al. 2018; Gopal et al. 2022). As a vital resource for the Indonesian population, nearly every part of the coconut tree is utilized for daily life, serving purposes in food, feed, fuel, medicine, art, culture, and building materials (Alouw and Wulandari 2020; Subramanian et al. 2024). Products derived from coconuts include coconut sugar, desiccated coconut, coconut milk, beverages, cooking oil, virgin coconut oil (VCO), crude coconut oil, coconut water, and furniture (Alouw and Wulandari 2020; International Coconut Community 2022). Coconut palms are generally categorized into two groups—Tall and Dwarf palms—based on plant size and morphology. Tall palms can reach heights of 20–30 meters and flower after 5–7 years, while Dwarf palms reach only 8–10 meters and flower faster, within 3–4 years (Santos et al. 1996; Niraj and Jerard 2018).

Beyond their economic value, coconuts offer environmental benefits, such as mitigating greenhouse gas emissions. For instance, bioethanol and biodiesel derived from coconut oil can reduce smoke and CO₂ emissions when used as fossil fuel additives (Teoh et al. 2019). As shown in Fig. 1, CO₂ is one of the potent and largest contributors to global warming because it mainly absorbs reflected solar radiation (infrared radiation) from the Earth's surface that causes warmth. There is widespread agreement that increasing CO₂ will result in increasing global temperature. It leads to unexpected changes in vegetation, melting of ice in the North Pole and mountains, accounting for approximately 60% of global warming, and a significant warning signal that triggers a rise in global temperatures to around 1.9°C. This event poses substantial threats to human nutrition, potentially up to 15% of the population due to climate change, ozone layer depletion, ocean acidification, an increase in sea level by 38 meters. Additionally, it will disrupt Earth's Ecological balance and cause widespread water level rise in various regions worldwide (Ravichandran et al. 2024).

Coconut wood, an eco-friendly alternative to traditional timber, is used for construction, furniture, and energy, helping reduce demand for wood and potentially mitigating deforestation (Anoop et al. 2011; Syed et al. 2020). Coconut charcoal, made from coconut shells, is an environmentally friendly fuel (Kabir Ahmad et al. 2022). Additionally, materials like bio-composites and geotextiles from coconut coir are widely recognized for their sustainability (Mahmud et al. 2023; Ravikumar et al. 2023). Coconut by-products, such as cocopeat, are used as eco-friendly growing media alternatives to peat (Olivier et al. 2022). Biomass residues, including leaves and branches, can be used for energy production through combustion and gasification, offering a viable alternative to coal after refinement through processes like torrefaction (Pestaño and Jose, 2016). Other applications include using virgin coconut oil (VCO) as a substitute for petrochemical-based oils in cosmetic and industrial products (Irawan et al. 2022) and employing coconut fibers in bioplastics (Muhammad et al. 2018).

Indonesia's central coconut-producing regions are Riau, North Sulawesi, and East Java, with an average national productivity of 1.12 t ha⁻¹ y⁻¹, lower than that of India, Sri Lanka, and Thailand. However, coconut plantation areas in Indonesia have been declining, shrinking by 3.4% from 3,473 thousand hectares in 2017 to 3,355 thousand hectares in 2021, with an estimated decrease to 3,323 thousand hectares by 2023 (Directorate General of Estate Crops 2022). In contrast, oil palm plantation areas continue to expand, with oil palm becoming a leading export commodity. Reducing coconut plantation areas challenges increasing national coconut production, necessitating intensification programs to boost productivity.

Most coconut plantations in Indonesia are owned by smallholders, constituting 98–99% of the total plantation area, with the remaining portion held by state-owned and large private plantations (Directorate General of Estate Crops 2022). This ownership structure poses challenges in advancing plantation management, as smallholder plantations often lack optimal agricultural inputs and maintenance compared to corporate plantations. Consequently, coconut production has stagnated in recent years. Additionally, Indonesia lags in coconut product diversity and export revenue compared to leading coconut-exporting nations, with the primary exports being coconut oil, crude coconut oil (copra), and desiccated coconut (Alouw and Wulandari 2020).

As a perennial crop, coconut trees absorb significant amounts of carbon over their long lifespan, extending up to 100 years. Studies conducted in tropical countries have demonstrated that coconut plantations possess remarkable carbon sequestration capabilities. These plantations can sequester approximately 13 to 109 t C ha⁻¹, making them highly effective carbon sinks compared to other land cover types. Notably, their carbon sequestration potential is comparable to that of secondary forests (Table 1). In comparison to oil palm plantations (*Elaeis guineensis*), coconut carbon storage capacity is double of what they can store. This carbon sequestration potential is attributed to their extensive above- and below-ground biomass and the continuous addition of organic matter through litter fall. However, it has been proven that Above-ground biomass (AGB) contributed significantly up to 80% to the total

Biomass that can be used as a single parameter to estimate the potential of carbon sequestration from plants, particularly for coconut (Zahabu et al. 2018; Zella and Lawi 2019; Tamang et al. 2021).

Table 1
Potential carbon stock from coconut plantation vs others type of land covers in tropical countries.

Reference, country	Land cover/ common name	Above-Ground Carbon tC ha ⁻¹	Below-Ground Carbon t C ha ⁻¹	Litter Carbon t C ha ⁻¹	Soil Organic Carbon 0–30 t C ha ⁻¹	Total Carbon stock t C ha ⁻¹	Planting density trees ha ⁻¹	Sampling procedures
Nur et al. 2022, Indonesia	Cocos nucifera/ Coconut	80.41	Na	Na	Na	80.41	Na	Research areas covering 5.5 h, simple random sampling plots (20 x 20 m), Above ground carbon stock measurement only
Khasanah et al. 2015, Indonesia	<i>Elaeis guineensis/</i> Oil palm	34.85–38.83	0.46–0.52	0.96–2.36	Na	36.27–41.71		25 palm oil plantations, 180 plots, age and plantation management, soil types criteria
Tamang et al. 2021, India	<i>Anacardium occidentale/</i> Cashew	0.085	0.02	Na	Na	0.11	Na	Plot level (50 x 50 m) with 3 replication, dbh > 10 cm, academix institutional landscape, unknown age
	Cocos nucifera/ Coconut	24	6.24	Na	Na	30.24	Na	
	<i>Elaeis guineensis/</i> Oil palm	1.775	0.46	Na	Na	2.24	Na	
	<i>Hevea brasiliensis/</i> Rubber	4.49	1.165	Na	Na	5.66	Na	
Sampaio et al. 2021, Brazil	Cocos nucifera/ Coconut	Na	Na	Na	Na	49.00	105–205	International Panel on Climate Change (IPCC) 2007
Carlos et al. 2015, Brazil	<i>Elaeis guineensis/</i> Oil palm	Na	Na	Na	Na	40	Na	Commercial plantation, 3–36 years old, sampling trees each 100 m
Antiporda et al. 2024, Philippines	Cocos nucifera/ Coconut	13	Na	Na	Na	Na	Na	Syntetic Aperture Radar and Remote sensing Above ground Carbon Stock, R2 of 0.72 with

Reference, country	Land cover/ common name	Above-Ground Carbon tC ha ⁻¹	Below-Ground Carbon t C ha ⁻¹	Litter Carbon t C ha ⁻¹	Soil Organic Carbon 0–30 t C ha ⁻¹	Total Carbon stock t C ha ⁻¹	Planting density trees ha ⁻¹	Sampling procedures
								RMSE 0.143 ton/ pixel, 20 x 20 m plot, 40 plots
Pulhin et al. 2014, Philippines	<i>Elaeis guineensis</i> / Oil palm	Na	Na	Na	Na	55	Na	6 samples representatives of area. 9 years old
Grieco et al. 2024, Ghana	Forests	255.45– 272.35	66.04– 70.44	2.39– 12.55	57.03– 117.17	396.48– 457.7	1086	Single plantation types, two sites per plantation types, covering areas of research by 1344 km ²
	Secondary Forests	33.05– 78.71	8.59– 20.46	2.90– 3.39	62.37– 74.29	106.92– 176.85	258– 667	
	Cocos nucifera/ Coconut	17.58– 114.14	4.57– 14.11	NA	28.17– 68.85	87.43– 109.99	125– 325	
	<i>Elaeis guineensis</i> / Oil palm	3.38– 3.80	0.68– 0.76	2.62– 8.94	57.26– 65.85	67.61– 69.91	400– 500	
	<i>Hevea brasiliensis</i> / Rubber	10.72– 162.89	3.54– 21.14	1.86– 2.94	48.18– 64.38	80.50– 225.43	400– 700	
	<i>Theobroma cocoa</i> / Cacao	19.54– 21.23	5.08– 5.52	2.95– 3.94	34.92– 57.03	63.48– 86.73	1500– 2600	

Coconut trees also protect soil against heavy rainfall, helping preserve soil quality (Kumar 2011; Thomas and Krishnakumar 2024). By increasing soil carbon content, coconut trees can enhance soil health and contribute to terrestrial carbon storage (Kumar 2011; Subramanian et al. 2024). Furthermore, coconut-based agricultural systems mimic forest ecosystems, accumulating substantial biomass and capturing atmospheric carbon (Bhagya et al. 2017; Tamang et al. 2021) and improving soil carbon (Russell 2002). Coconut exhibits remarkable adaptability and can be intercropped with other plants. This practice strikes a balance by integrating substantial carbon storage with agricultural productivity. Consequently, coconut emerges as a viable solution for climate change mitigation within tropical regions. Application of regenerative agriculture practices (Tan and Kuebbing 2023) or through Incorporating nutrient management systems (Naveen Kumar and Maheswarappa 2019; Shinde et al. 2020), diverse cropping systems (Bhagya et al. 2017) and agroecological approaches (Ranasinghe and Thimothias 2012) has been shown to increase carbon sequestration in coconut plantations. In India, integrated nutrient management improved carbon stocks, while intercropping systems enhanced carbon storage compared to monoculture systems in coconut (Naveen Kumar and Maheswarappa 2019; Shinde et al. 2020). Globally, agroforestry systems benefit communities and ecosystems, with extensive areas under agroforestry, palm orchards, and urban trees totalling 105.27 million hectares (FAO 2020). Although such systems have high carbon sequestration potential, they are often excluded from

forest statistics and natural resource assessments (Rathnayake and Mizunoya 2023), emphasizing the need for broader recognition of coconut agriculture's role in climate mitigation.

Indonesia's Nationally Determined Contribution (NDC) reflects its commitment to reducing greenhouse gas emissions below a specified baseline. The National Registration System of Indonesian Climate Change Mitigation reported that Indonesia reduced emissions by 46%, equivalent to 113 million tons of carbon, in 2022—progress toward meeting NDC targets for 2030 (Ministry of Environment and Forestry 2022). Coconut plantations, covering 3.3 million hectares, could potentially sequester 265 million tons of carbon, with an estimated sequestration rate of 80.4 t C ha^{-1} (Nur et al. 2022). However, this estimate may be biased due to the use of non-specific allometric models for coconut biomass in Indonesia, underscoring the need for more precise, region-specific models to better support Indonesia's climate goals. Developing reliable methodologies for carbon sequestration assessment in coconut plantations could also facilitate the growth of carbon markets in this sector.

Other tropical countries, such as Sri Lanka and India, report notable carbon sequestration potentials in their coconut plantations. Sri Lanka's coconuts sequester $4.8\text{--}22.8 \text{ t C ha}^{-1} \text{ y}^{-1}$ (Ranasinghe and Thimothias 2012) and intercropping system in India can increase carbon sequestration to $131.72\text{--}140.06 \text{ t C ha}^{-1}$ compared to 98.2 t C ha^{-1} in monoculture systems (Bhagya et al. 2017). In Indonesia, research on coconut carbon sequestration is limited, though agroforestry systems in West Java exhibit a carbon stock ranging from 37 to $108.9 \text{ t C ha}^{-1}$ (Siarudin et al. 2021). Further studies are needed to understand the effects of local factors such as coconut variety, plant age, and agroclimatic conditions on carbon sequestration in Indonesian coconut plantations.

The main objective of this study is to estimate the biomass and carbon sequestration potential of coconut plantations, focusing on the growth characteristics specific to Indonesian coconuts. This research aims to promote the participation of Indonesia's coconut sector in carbon trading, supporting the country's NDC targets.

2. Methodology

2.1 Data Collection

Primary data

This study utilized one of Indonesia's most commercially important coconut varieties, the Mapanget tall coconut (approximately 96% of cultivated tall coconut, Balitpalma, unpublished). The assessment of Diameter at Breast Height (DBH) and tree height (TH) was conducted on June 14, 2024, at the experimental coconut plantation of the Indonesian Instruments Standardization Testing Center for Palms, located in Mapanget District, North Sulawesi, Indonesia. This area is close to the beach and is situated 50 m height above sea level. Data were obtained from 20 coconut trees of six different ages: 17, 22, 30, 44, 67, and 97 years old, all of which were initially planted with a spacing of 9×9 meters. In total, 6 blocks were sampled from two different experimental coconut plantation, as shown in Fig. 2.

The diameter of the DBH was measured using a diameter tape at various age categories, as presented in Table 2.

Table 2
Data of measured diameter at breast height (DBH).

Descriptive value	Age17 (n = 20)	Age22 (n = 20)	Age30 (n = 20)	Age44 (n = 20)	Age67 (n = 20)	Age97 (n = 20)
Mean (cm)	102.7	104.7	111.4	102.15	110.55	107.05
Stdev	12.4	5.4	5.7	6.3	7.6	8.5
CV (%)	12.1	5.2	5.1	6.2	6.8	7.9

Stdev, standard deviation; CV, coefficient of variations; age referred to years.

In addition, one representative tree based on the average DBH of each age category was selected. Then, their photographs were taken by smartphone for TH measurement using image analysis software (ImageJ). This technique uses a calibrated pixel in the image by a known height object on the side of the measured object (Schneider et al. 2012) (Fig. 3). This method was employed because laser rangefinders encounter challenges in outdoor applications due to high sunlight intensity, rendering laser marks imperceptible.

To ensure the quality of measurement, the accuracy of the software for height measurement was evaluated. We conducted an indoor evaluation of the measurement and compared it with the height meter laser rangefinder (ROHS, China) as shown in Fig. 4. The results were presented in Table 3. It showed that ImageJ software is comparable with standard height measurement using laser rangefinder.

Thirty photographs were taken and measured by two operators. ImageJ was calibrated using the known height of 1.56 meters and subsequently measured the 2.4-meter height mark (a). Two operators measured the height of the 2.4-meter mark using a laser rangefinder (b).

Table 3
Descriptive statistic value from two methods, i.e. ImageJ software and laser rangefinder,

Statistic	ImageJ (n = 30)		Laser Rangefinder (n = 30)	
	Operator 1	Operator 2	Operator 1	Operator 2
Mean	2.31	2.32	2.46	2.41
SD	0.04	0.01	0.04	0.04
CV	1.70	0.38	1.80	1.77
RMSE	0.09	0.08	0.07	0.04

RMSE was measured compared the true measurement of height by tape meter at 2.4 meter vs the two methods.

Secondary data

This study's secondary data was sourced from research publications and the Directorate General of Estate Crops. This data includes information on the area occupied by coconut plantations, the number of coconut trees, and the average sizes of these plantations. To estimate the biomass stock, the total area was assumed to consist only of tall coconut plantations, as the cultivation of dwarf and hybrid varieties remains limited in Indonesia (about 5%). The Initial planting density was 9 m $\times$ 9 m, resulting in 123 coconut palms per hectare. Notably, a significant portion of

Indonesia’s coconut palms are at a mature age, approximately 35 years, as reported by the Directorate General of Estate Crops (2022). Further details regarding the secondary data are presented in Table 4.

Table 4
Selected secondary data used in this study.

Type of Data	Tall coconut characteristic	Reference
The average age of coconut trees in Indonesia (years old)	20–50; avg. 35	Directorate General of Estate Crops (2022)
Dbh (cm) at avg. age (cm)	20–30; 25	Santos et al. (1996), Mardiatmoko and Ariyanti (2011)
Tree height at avg. age (m)	20–30; 25	Santos et al. (1996), Mardiatmoko and Ariyanti (2011)
Stem density (g cm ⁻³)	0.40–0.52; 0.46	Rana et al. (2015)
Total area (ha)	3,294,273*	Directorate General of Estate Crops (2022)
Number of trees (trees ha ⁻¹)	9 × 9 m: 123 trees	Mardiatmoko and Ariyanti, (2011)

*Estimated data.

2.2 Development of logistic growth model for DBH and TH and slope analysis

The primary data of the DBH and TH were used to establish logistic growth models to estimate biomass's annual increments (k or growth rate), expressed in stem diameter and height of the sampled coconut trees. However, since coconut trees at a very young age are scarce compared to the age currently being investigated, we used information from other references indicating that fully developed stems of tall coconut trees typically have a growth rate of 0.5 to 1.5 m y⁻¹ for tree height, and 40 cm y⁻¹ for diameter at 3–4 years after planting (Santos et al. 1996; Chan and Elevitch 2006; Mardiatmoko and Ariyanti 2011). Therefore, we assumed that coconut trees at 4 years old can attain a height of 4 m and a diameter of 40 cm.

The rate of increase (*r*) and carrying capacity (*K*) are the functions that reflect the interaction factors of genetics and environment for specific parameters (Kawano et al. 2020). This logistic model is helpful, especially when information on the growth is limited. Using the standard S-shaped curve function. The model equations for the diameter and height of coconut trees expressed as follows (Kawano et al. 2020)

$$Growth\ model = L / (1 + exp^{-k(x-x_0)})$$

L is asymptotic maximum height or DBH

k is the growth rate where it is adjusted to the obtained from primary data

x is the measured age

x₀ is the age at the half of L (midpoint in the sigmoid curve)

After the logistic parameters for DBH and TH were determined, slope analysis was conducted using R software. In mathematical, as it represents the rate of change of the function, the slope is a derivative of the logistics model:

$$f(\chi) = k \cdot L \cdot \exp^{-k(x-x_0)} / 1 + \exp^{-k(x-x_0)}$$

where the slope thresholds for DBH and TH were set at 1 and 0.1, respectively, as mentioned regarding the slow growth rate threshold in Santos et al. (1996). Consequently, any age with a slope less than the threshold is considered as non-productive, plateau increment growth, or peak growth.

2.3 Use of available allometry biomass models from other tropical countries

In this study, the analysis of biomass relies on a compilation of available allometric models for coconut trees, as well as other perennial plants, as presented in Table 5. Three primary allometric models are commonly employed to estimate the carbon stock of coconut trees:

1. Allometric Model 1: Developed specifically for coconut trees in Tanzania. This model is tailored to the unique growth characteristics and environmental conditions of coconut plantations in that region (Zahabu et al. 2018)
2. Allometric Model 2: Chave et al. (2005) introduced this model, which is regarded as the most robust allometric framework for trees growing in tropical forests characterized by annual rainfall ranging from 1500 to 4000 mm. Its wide acceptance is attributable to its comprehensive approach and applicability to diverse tropical tree species.
3. Allometric Model 3: This model was designed for non-branchless trees and is utilized to estimate the above-ground biomass for coconut trees in Trenggalek, Indonesia (Hairiah et al. 2001). Although this model is too conservative, it was used to estimate the biomass of coconut trees in Indonesia.

Table 5
Selected allometric models for predicting above-ground biomass in coconut trees.

Allometric model	Origin Country	Estimation quality	Reference	Remarks
Model 1. AGB = 3.7964 x ht ^{1.8130}	Tanzania, AFSEL	R ² = 0.78	Zahabu et al. (2018)	The model is specifically developed for <i>C. nucifera</i>
Model 2. AGB = 0.0509 x <i>p</i> x D ² x ht	Three continents: America, Asia, and Oceania	R ² = 0.95	Chave et al. (2005)	Global model from 2410 trees with diameter > 5 cm
Model 3. AGB = (π x <i>p</i> x D ² x ht)/40	Sumatra, Indonesia	NA	Hairiah et al. (2001)	Allometric for branchless trees

AGB, above ground biomass; ht, tree height in m; *p*, stem density in kg/m; D, stem diameter at breast height in m; π, phi or 3.14 constant value; NA, not available.

2.4 Activity Data Collection

To measure annual carbon sequestration in Indonesia, the total area of coconut plantations data provided by the Ministry of Agriculture from 2017 to 2023 is utilized (Fig. 4). In addition, the growth data, specifically height and

diameter, were estimated using logistic models that were fitted to primary data. This method allows us to get better accuracy in evaluating the carbon sequestration in coconut plantations over the specified period.

2.5 Estimation of Total Potential Carbon Stock, Carbon Sequestration from Indonesia's Coconut Plantation Using Three Allometric Models

The total carbon stock from coconut plantations in Indonesia was estimated using secondary data provided in Table 4 and was then generated using three models, as previewed in Table 5. The three models were evaluated, and one was selected based on its closest estimation value to Nur et al. (2022). This selected model was then used to accurately predict carbon stock and carbon sequestration from 2017 to 2023 if the average plantation age in 2023 is 35 years old (Directorate General of Estate Crops 2022). The total area of the plantation used for this analysis was 95% of the reported area in Fig. 4, as we assumed that the remaining 5% of coconut plantations consisted of limited areas of dwarf and hybrid coconut species.

2.6 Uncertainty analysis of carbon stock estimation

A Monte Carlo simulation methodology using R software was used to quantify the uncertainty in carbon stock estimates. Key parameters and assumptions included:

1. Biomass Model: the best biomass model will be used based on the results from comparison among the three models.
2. Height Estimation: Tree height was modeled as a logistic function of age ($\text{height} = \text{height_model}(\text{age})$), with stand ages ranging uniformly between 29 and 35 years.
3. Spatial Coverage: The total coconut plantation area was modeled as a normal distribution with a mean of 3,217,236 ha and a standard deviation of 48,611.52 ha to account for mapping uncertainties.
4. Tree Density: A uniform distribution of 100–146 trees ha^{-1} was used ($\pm 20\%$ variation around the mean density of 123 trees ha^{-1}).
5. Carbon Fraction: A conservative carbon content of 47% (0.47) of biomass was applied, consistent with IPCC guidelines for tropical woody biomass.
6. Per-Hectare Carbon Stock: Calculated as a function of biomass and tree density, converted to metric tons of carbon per hectare (t C ha^{-1}).
7. National-Level Carbon Stock: Derived by scaling per-hectare estimates with the simulated plantation area.
8. Simulation Protocol: The analysis employed 10,000 iterations with a fixed random seed (`set.seed(123)`) to ensure reproducibility of the stochastic simulations.

2.7 Estimation of the Economic Value from Carbon Markets for Indonesia's Coconuts Plantations

The carbon trading mechanism in Indonesia is regulated by Presidential Regulation No. 98 in 2021, which outlines the procedures and guidelines for implementing carbon pricing in the country which also guided the REDD + implementation (BPK 2021) and Indonesia Financial Services Authority (OJK) regulation No. 14 in 2023. To estimate the total carbon sequestered by coconut plantations, minimum and maximum accrued economic values per ton of carbon were applied, varying from 2 to 18 USD based on the Indonesia Carbon Exchange report (IDX Carbon 2024). This framework enables us to forecast the economic potential of carbon markets for Indonesia's coconut plantations effectively.

3. Growth analysis for optimum biomass and potential carbon sequestration on coconut trees

Based on the growth model and slope analysis (Fig. 5), DBH rapidly increased during the early growth phase, age between 4 to 19 years, with the diameter reaching its maximum increments at 107.53 cm as the tree matures. Different trends showed in the height of coconut trees, which gradually increased with significant growth up to 58 years of age. Following this period, the growth rate slowed, and the height peaked at 18.63 meters. The results indicated that secondary growth (diameter) was stabilized sooner than primary growth (tree height). For Tall coconut trees, the growth rate is slow at early ages, productive between 6 to 10 years, and continues in significant incremental growth up to 40 years (Santos et al. 1996; Chan and Elevitch 2006). This information can be used for improvement in agricultural practices or as data to develop better management strategies for coconut plantations, for example, such as to determine the optimum initial planting spacing and nutrient management by providing insights into the tree's physical development over time.

Concerning carbon stock, our findings suggest that the age of 58 years is the limit for potential increments in biomass production, and the height of coconut trees is the most reliable indicator for explaining variations in biomass. Santos et al. (1996) noted that tall coconut trees attained maximum heights between 20 to 30 meters after reaching 60 years of age. Additionally, Chan and Elevitch (2006) highlighted that a significant growth rate in tree height often occurs before the trees reach 40 years. This strategy to optimize the production of biomass would also increase soil carbon sequestration because an increased in biomass is an indicator of efficient photosynthesis, which feeds increased microbial growth stabilization (Mattila and Vihanto 2024). In addition, the use of a single parameter, such as tree height, was also demonstrated by Zahabu et al. (2018) for the development of a coconut biomass model in Tanzania. This relationship can be explained biologically: the coconut stem does not have a cambium layer, which makes incremental growth less significant once the stem is fully developed. In summary, these findings emphasize the importance of early growth monitoring and strategic management to optimize both the growth and carbon sequestration capability of coconut plantations.

4. Three allometric biomass model analysis for potential carbon stock from coconut plantations

Table 6 presents the estimated total carbon stock (C-stock) of coconut trees in Indonesia using three different allometric models calculated from secondary data shown in Table 4. There are significant variations in carbon stock calculations depending on which allometric models are utilized, emphasizing the critical importance of selecting appropriate models for accurate carbon stock assessment. Among the three models evaluated, Model 1, developed by Zahabu et al. (2018) for Tanzanian coconut trees, estimates the carbon stock of Indonesia's coconut plantation at approximately 75.1 t C ha^{-1} or 0.61 tons C per mature tree, which has the highest estimation compared to the other two models. This model was developed using DBH ranging from 19 to 40 cm and tree height varied between 1.6 to 21 m Zahabu et al. (2018). In this study, the model was used to estimate tree biomass using secondary data from Indonesia's coconut trees which are 25 meters, which means not covered by model variation, leading to bias estimation. Similar high C-stock estimations have been reported in small coconut plantations in Indonesia. In that context, an average DBH of 20 cm was associated with a C-stock estimation of $80.41 \text{ t C ha}^{-1}$, although details regarding the number of trees per hectare were not provided (Nur et al. 2022).

Furthermore, in Tanzania, the total C-stock of coconut trees can range from 0.013 to 0.12 t C per mature tree at an average height of 9.5 meters (Zahabu et al. 2018). The data on the height of coconut trees caused this discrepancy in the estimation of C stock per mature tree. On the other hand, the remaining models resulted in lower values of Above

Ground Biomass (AGB), resulting to very low C-stock estimations by model 2 and 3 (Table 6). Of these contexts, the discrepancy can be attributed to additional parameters, primarily basic density and DBH values, in those models (Chave et al. 2009; Goodman et al. 2013). As noted, the two models that generated lower C-stock estimation were developed for dicotyledonous tree species. These species have higher basic density and a greater DBH variation than monocotyledonous trees, such as coconut trees, which show more height variation than diameter (Chave et al. 2009; Zella and Lawi 2019). Thus, the findings obtained in this study align consistently with the results reported by Nur et al. (2022), further reinforcing the importance of selecting an appropriate model for assessing carbon stocks in coconut plantations.

Table 6
Indonesia's carbon stock estimated using three allometric models.

Parameter	Model 1 Zahabu et al. (2018)	Model 2 Chave et al. (2005)	Model 3 Hairiah et al. (2001)
Coconut tree AGB (t)	1.30	0.37	0.56
Coconut tree AGB per ha (t ha ⁻¹)	160	45	69
Indonesia's coconut AGB (t)	504,692,183	142,064,320	219,097,233
C-stock per ha (t C ha ⁻¹)	75.13	21.15	32.62
C-stock per Coco. tree (t C tree ⁻¹)	0.61	0.17	0.27
total C-stock of Indonesia's coconut tree (t C)	237,205,326	66,770,231	102,975,699

Data was calculated from secondary data (Table 4).

5. Potential coconut plantation in Indonesia and other tropical region as significant carbon sequester sector

Using Model 1, developed by Zahabu et al. (2018), the carbon sequestration of Indonesia's coconut plantations was estimated using height data generated by the developed logistic model for coconut height (Fig. 6). The data showed a clear positive relationship between the height of coconut trees and the carbon stock per ha. This increase in height corresponds linearly to the increase in C-stock, reflecting the impact of increments in biomass as trees mature and indicating that taller trees would sequester more carbon than shorter trees. The results obtained in this study strongly emphasize the importance of allowing trees to reach maturity for maximum carbon sequestration benefits. With its substantial biomass, a mature tree is a significant carbon sink, contributing to climate change mitigation efforts. In comparison, studies in India have reported that carbon stock from a one-hectare area (comprising 171 trees) could potentially store 31.69 t C (Pragasan and Kalaiselvi 2024). In this study, the C-stock per ha area was estimated using a planting arrangement of 9 by 9 meters, comprising 123 trees per hectare area, resulting in comparable findings to those reported for coconut trees in India (Pragasan and Kalaiselvi 2024).

The total carbon stock in Indonesia's coconut plantations rose from 60.9 million to 72.5 million tons of carbon from 2017 to 2023, with stable increasing values every year (Table 7). This trend occurred when the coconut plantation areas decreased yearly from 3.299 to 3.157 million ha. At this condition, the carbon sequestration rate increased by 2.4 to 3.5% per year, resulting in a total sequestration of 11.6 million tons of carbon. Annually, Indonesia's coconut

plantations sequester approximately 18.4 to 23.0 tons of carbon per ha (Fig. 6). The results reflect the important role of coconut plantations, and this amount of sequestration rate can be improved through best practices in agricultural sciences. For example, Research in Maharashtra, India, recognized an enhancement of 21% in carbon stock from polyculture (31.1 t C ha⁻¹) to monoculture (25.7 t C ha⁻¹) coconut gardens, particularly in conjunction with nutmeg and various nutrient treatments (Shinde et al. 2020). Similarly, in Kerala, India, *Syzigium cumini* alongside the coconut garden had effectively boosted the carbon sequestration and recorded an improvement of 19% from 51.14 t C ha⁻¹ in monoculture to 60.93 t C ha⁻¹ in polyculture (Bhagya et al. 2017). Therefore, although the current study is our first attempt to estimate the carbon sequestration potential for coconut plantations in Indonesia, the observed carbon sequestration rates per hectare per year correspond with those documented for coconut monoculture in India (Bhagya et al. 2017; Shinde et al. 2020; Pragasan and Kalaiselvi 2024). Moreover, this alignment of findings stated the importance of coconut plantations in carbon sequestration efforts globally.

Table 7
 Estimation of carbon sequestration in coconut plantations in Indonesia from 2017 to 2023

Period	Total area (95%) of Tall coconut plantations (ha)	Total C-stock (t C)	Sequestration per year (t C)	Rate of C-sequestration (%)
2017 (29 yo)	3,299,569	60,874,300	0	NA
2018 (30 yo)	3,247,053	62,354,362	1,480,063	2.4
2019 (31 yo)	3,231,798	64,503,769	2,149,406	3.4
2020 (32 yo)	3,222,393	66,750,733	2,246,964	3.5
2021 (33 yo)	3,187,758	68,435,891	1,685,158	2.5
2022 (34 yo)	3,175,007	70,544,097	2,108,206	3.1
2023 (35 yo)	3,157,070	72,498,087	1,953,990	2.8
Total			11,623,787	
Yo, years old; NA, not available				

6. Uncertainty analysis of carbon stock estimation

Using the best biomass model provided by Zahabu et al., which is Biomass = 3.7964 * Height^{1.8130}, uncertainty analysis of carbon stock was simulated by Monte Carlo analysis as provided in Table 8. Based on the analysis, the uncertainty of the carbon stock estimation was ± 12.6% with 90% CI for C-stock per ha and total C-stock were 16–25 t C ha⁻¹ and 53–81 million t C, respectively.

Table 8
Results of Monte Carlo Analysis

Descriptive statistic	C stock (t C ha ⁻¹)	Total C stock (Million t C)
Mean	20.71	66.64
SD	2.6	8.42
5th Percentile	16.61	53.36
95th Percentile	25.15	81.00
Median	20.63	66.36
Minimum	15.03	46.83
Maximum	27.23	90.24
CV %	12.6%	

SD, Standard Deviation; CV, Coefficient of Variation.

7. Potential profit from carbon market mechanisms for coconut plantations

In developing countries such as Indonesia, coconut plantations have not been integrated into carbon market mechanisms. The Voluntary Carbon Markets (VCM) as mechanism to facilitate private, individual, and non-affiliated government organizations, to contribute in global carbon emissions reduction efforts through voluntary carbon offsets. It allows businesses and individuals to purchase carbon credits generated through verified projects that reduce, avoid, or sequester greenhouse gas emissions. REDD + is among the most sold offsets (Hamrick and Gallant 2017). It means through framework of National REDD+, farmers can capitalize their coconut plantations as an effort to reduce emissions from deforestation/afforestation and/ or non-carbon benefits, such as conservation of biological diversity, protection of hydrological and ecological functions, improve livelihood, forest and land governance, and protection of essential ecosystems (Masripatin et al. 2022). In addition, CDM (Clean and Development Mechanism) through protecting and/or restoring carbon-absorbing ecosystems is also can be approached to gain potential economic of coconut plantations (Kumar 2011). All of these mechanisms required commitments on project developments, monitoring, and verification activities, as following: 1) Assessment of the carbon sequestration baseline over the past two years, 2) Establishment of the mitigation plan to enhance the carbon sequestration rate over the subsequent five years, 3) Certification to validate the carbon credits generated, 4) Buyer identification through carbon markets, 5) Monitoring and reporting on the mitigation project progress as stipulated in the carbon certification process.

In Indonesia, carbon pricing mechanisms are regulated by Indonesian President Regulation No. 98 of 2021. To date, the potential accrues for average economic benefit ranges from \$2 to \$18 per ton of CO₂ sequestered, resulting in potential accrues from \$546 million to \$4.9 billion (Table 9). These economic gains could be further maximized by the application of agroforestry or intercropping agricultural systems, primarily with other perennial crops, such as cocoa, coffee, and cashews. Specifically, if coconut is integrated with cocoa in an agroforestry system, this could significantly enhance carbon storage, potentially exceeding 100 tons per hectare, and increase soil carbon content (Somarriba et al. 2013). In addition, carbon trading is applicable globally since Article 6 of the Paris Agreement

regarding the crediting mechanism was adopted. This article facilitates international cooperation on carbon markets and other strategies to achieve emissions reduction targets (UNFCCC 2024)

Table 9
Estimation of the potential economic gains from coconut plantations in the carbon market.

Indonesia's coconut plantation (ha)	Assumed total trees	AGB (t) by model 1	C-stock (t C)	CO ₂ stock (t CO ₂)	Min. gain 2 USD per t CO ₂ (USD)	Max. gain 18 USD per t CO ₂ (USD)
3,157,070	388,319,610	0.41	74,517,741	273,480,111	546,960,221	4,922,641,992

Data was calculated using a tree height of 13.2 m (logistic model at 35 years of age) and model 1 developed by Zahabu et al. (2018). One t C equivalent to 3.67 t CO₂. Number of trees per ha is 123. Biomass to C conversion factor is 0.47.

8. Sustainability strategies on coconut agriculture management

Despite these offered economic benefits, achieving the optimum biomass always engaged considerable investments in areas such as fertilization, land maintenance (including weeding), rejuvenation practices, research and development, and capacity-building initiatives (Rodrigues et al. 2018a). A farmer is expected to be knowledgeable in applying fertilization and integrated nutrient management, as these practices affect soil fertility and growth quality (Cierjacks et al. 2016; Shinde et al. 2020; Thoumazeau et al. 2024). In addition, a cost-benefit analysis should be conducted before investing in fertilizers, as understanding the correlation between fertilizer application, biomass production, including impact to soil health, can enable farmers to make informed decisions regarding their costs (Rodrigues et al. 2018b; Thoumazeau et al. 2024). In the context of ecological-based management systems, It is recommended to aim for a balance between organic and inorganic fertilizers. This strategic combination could yield significant long-term improvements in soil health while maintaining agricultural productivity (Mantiquilla et al. 1994; Thoumazeau et al. 2024). Similarly, in the context of agroforestry systems, Michel et al. (2024) found that socioeconomic factors and site-specific dynamics influence the contrasting management practices and yields. In India, intensive management for coconut plantations, such as implementing year-round drip irrigation and a full dose of recommended inorganic and organic fertilizers, could improve up to 300 percent of productivity (Naresh Kumar and Aggarwal 2013). In addition,(Agus et al. 2024) developed a method to optimize and sustain intensification programs for palm oil plantation by developing extrapolation domain frameworks. These frameworks are based on spatial data, including climate, topography, and soil variables, and they should also apply to coconut plantations. A better understanding of all these parameters is essential for optimizing yields in coconut agroforestry that boosts carbon sequester's capability. Therefore, engaging coconut plantations in carbon markets provides financial incentives and enhances corporate branding related to sustainability management. This engagement could lead to a more holistic approach to agroforestry, aligning economic benefits with environmental stewardship. All of this information emphasized that applied ecological intensification practices, supported by effective management, might substantially enhance the ecological sustainability and economic productivity of coconut plantations.

9. Conclusions

This study successfully developed logistic growth models that offer valuable insights into the growth dynamics of Indonesia's coconut trees. Tree height is one of the reliable indicators of the tree's biomass and explains the variation

in the carbon sequestration capacity. Based on these growth characteristics, optimization from 19 to 58 years would significantly improve carbon sequestration and economic benefits. This potentially significant role as a carbon sink promotes the participation of coconut plantations in carbon credit markets and is further certified as a climate change mitigation project.

Based on the overview presented in this study, several recommendations can be made to promote sustainability, enhance productivity, and optimize the utilization of coconut plantations in Indonesia:

1. Recognition of coconut plantations' potential: It is essential for all stakeholders, particularly farmers, to acknowledge the significant potential of coconut plantations. This awareness should lead to the inclusion of coconut tree species in the REDD + scheme. By integrating coconut plantations into this framework, stakeholders can contribute to global climate goals while exploring sustainable coconut cultivation's economic benefits.
2. Encouragement of research and development: All stakeholders, including the government and private sectors, should prioritize and promote research and development within coconut plantations. Research focusing on carbon sequestration and the development of allometry models is crucial. Such efforts will not only enhance our understanding of the carbon storage capabilities of coconut trees but also provide insights into best practices that can improve the overall health and productivity of these vital agricultural systems.
3. Sustainable management practices: to ensure the long-term productivity and sustainability of coconut plantations, stakeholders must advocate for replanting coconut trees at age 58. Additionally, applying fertilizers and weeding, along with adopting silvicultural best practices, will significantly boost biomass production and enhance the carbon sequestration capacity of coconut plantations. By implementing these practices, the longevity and health of coconut trees can be assured, ultimately leading to a more productive and sustainable agricultural landscape.

Therefore, the collaborative efforts of all stakeholders in recognizing the potential of coconut plantations, promoting targeted research, and implementing sustainable management practices are crucial for fostering a sustainable and productive coconut farming sector in Indonesia. These initiatives will benefit the environment and enhance the economic viability of coconut cultivation for future generations.

Declarations

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Conflict of interest

The authors declare that they have no conflict of interest.

Data availability

Data will be made available on request.

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Figures

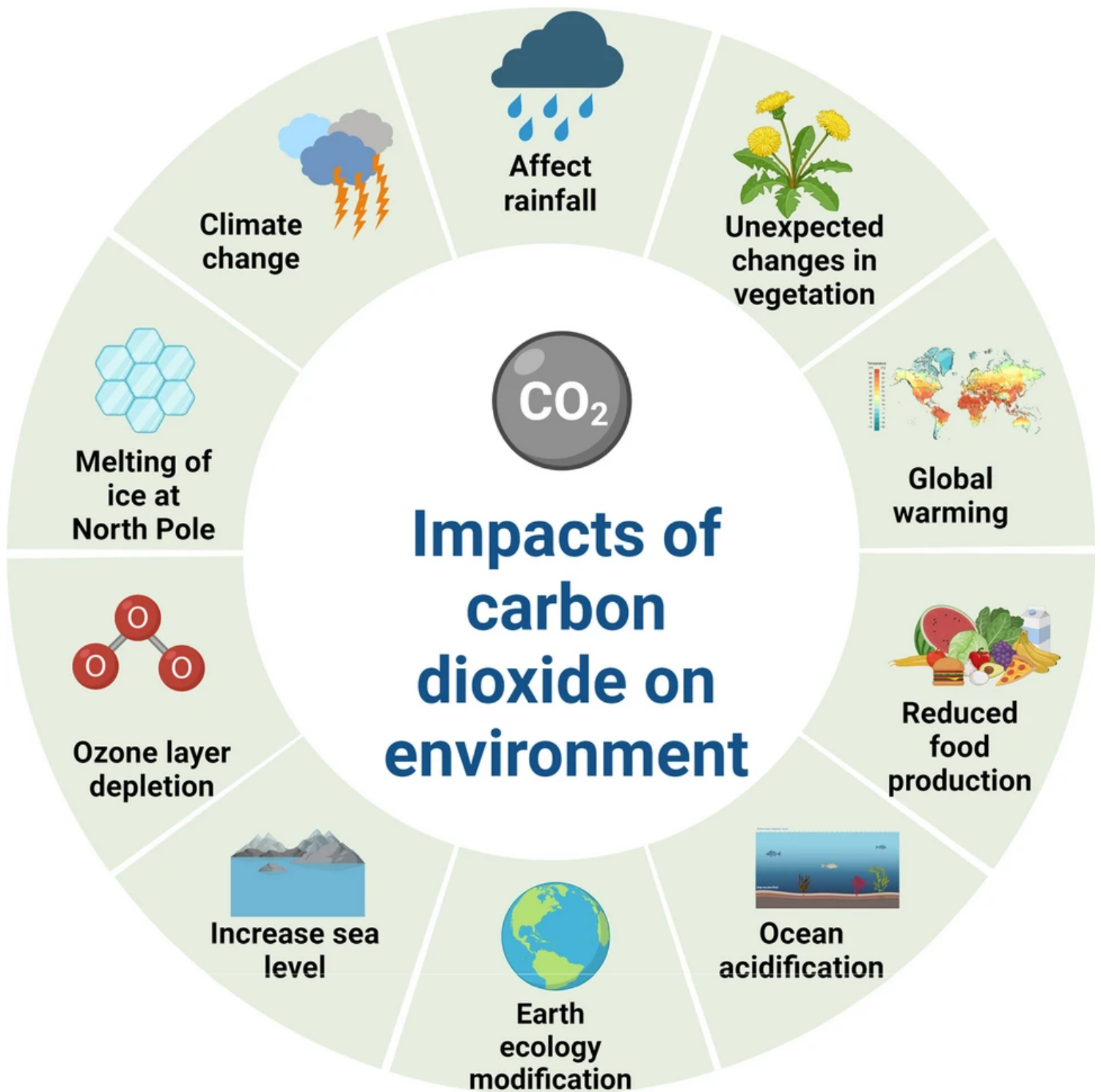


Figure 1

Impact of carbon dioxide on the environmental (Ravichandran et al. 2024). Copyright from Springer Nature with license number 5961281503478.

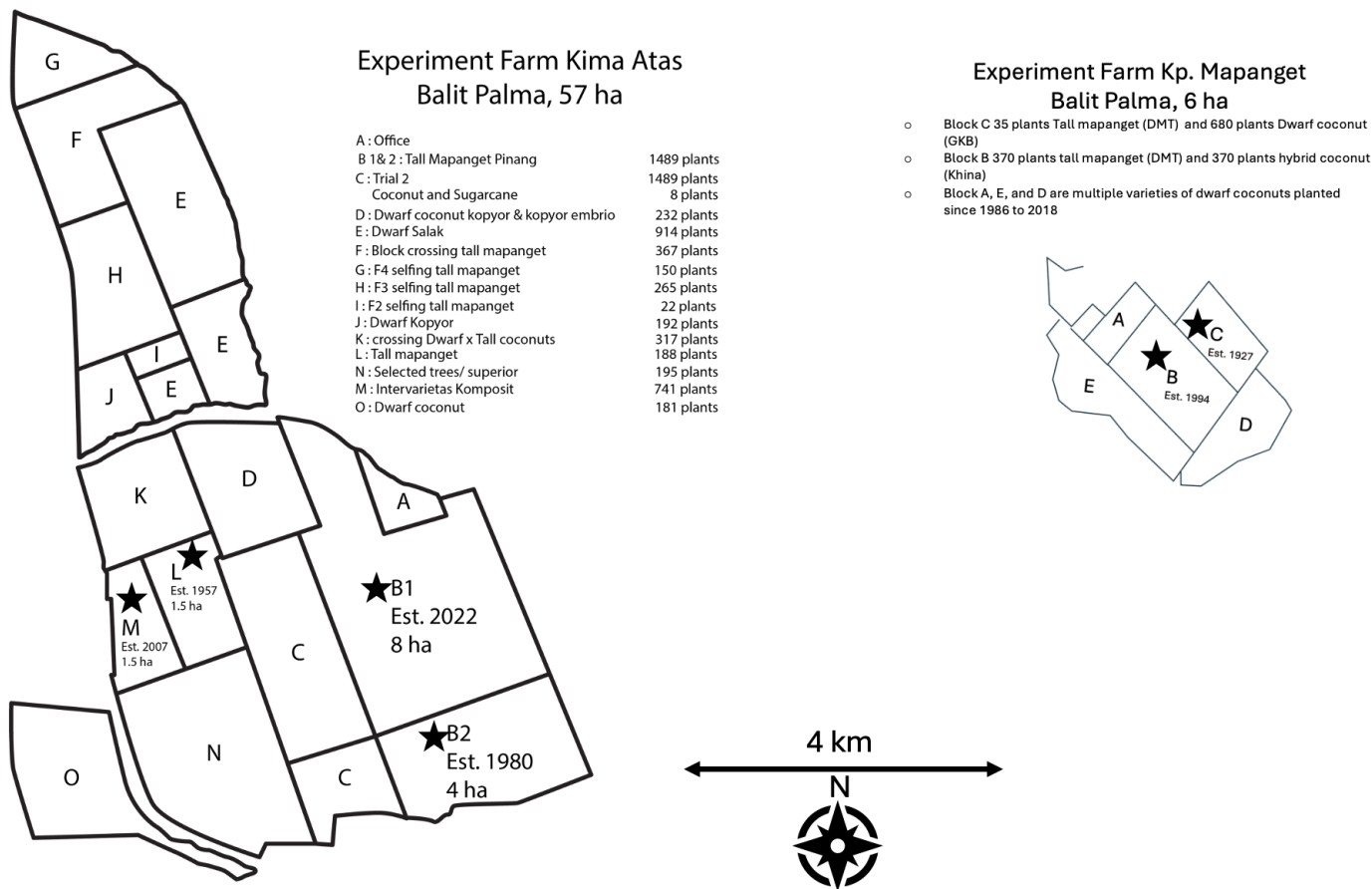


Figure 2

Experimental coconut plantation layout used in this study.

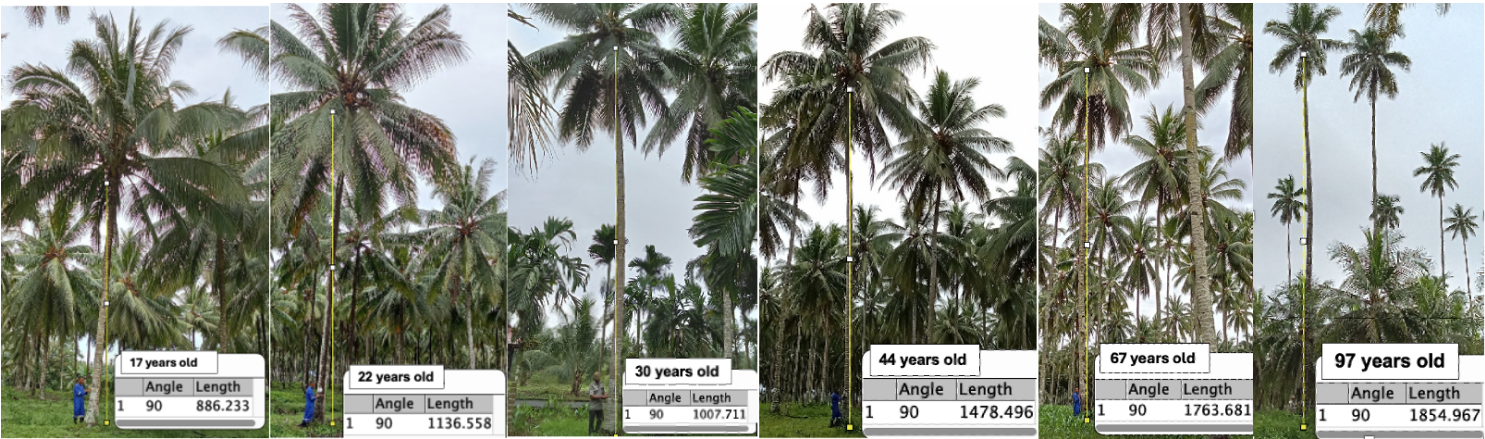


Figure 3

Indirect measurement of coconut tree height using ImageJ analysis software, expressed in centimetres (cm).

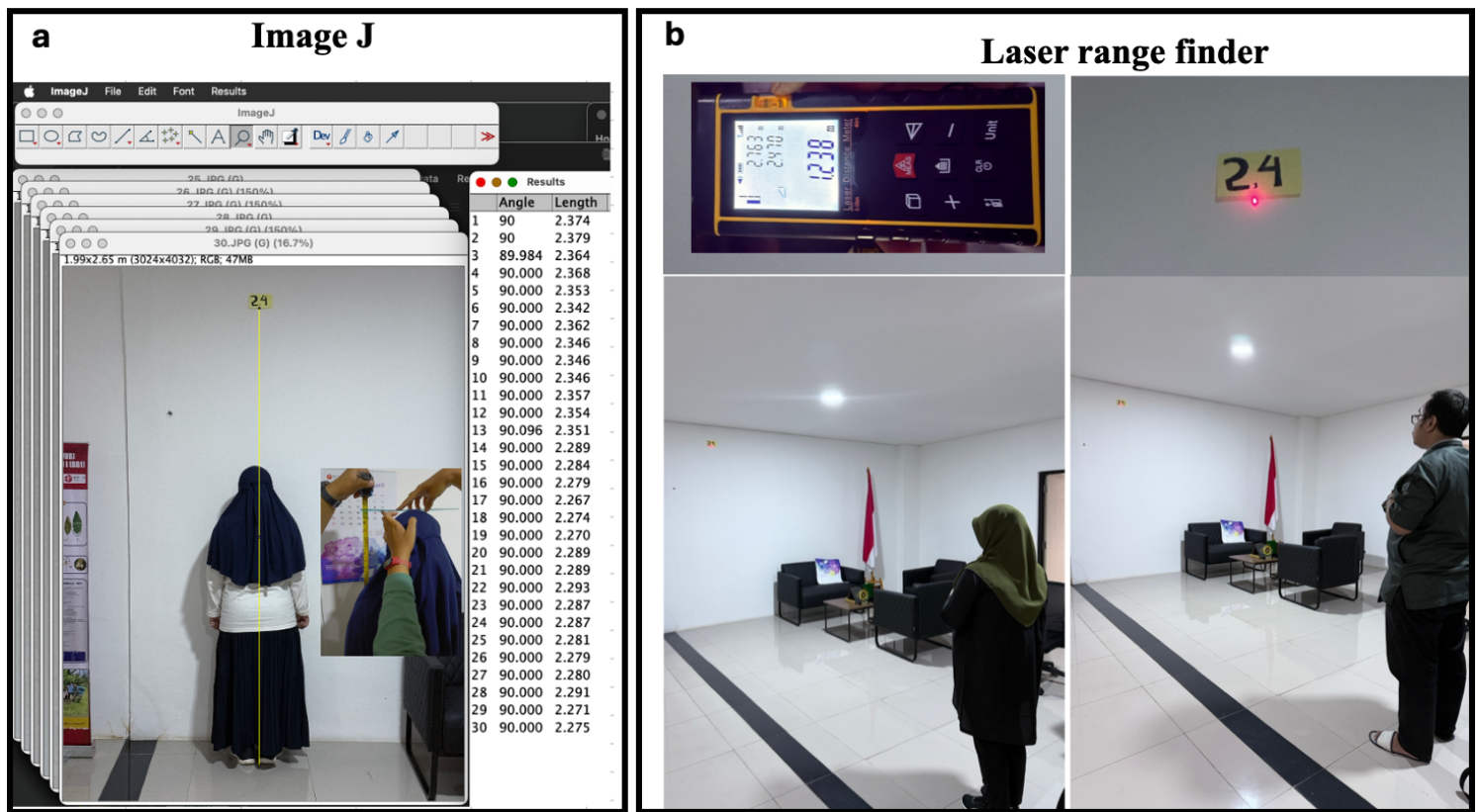


Figure 4

Fig. 3 Evaluation of the height measurements using imageJ software and laser range finder

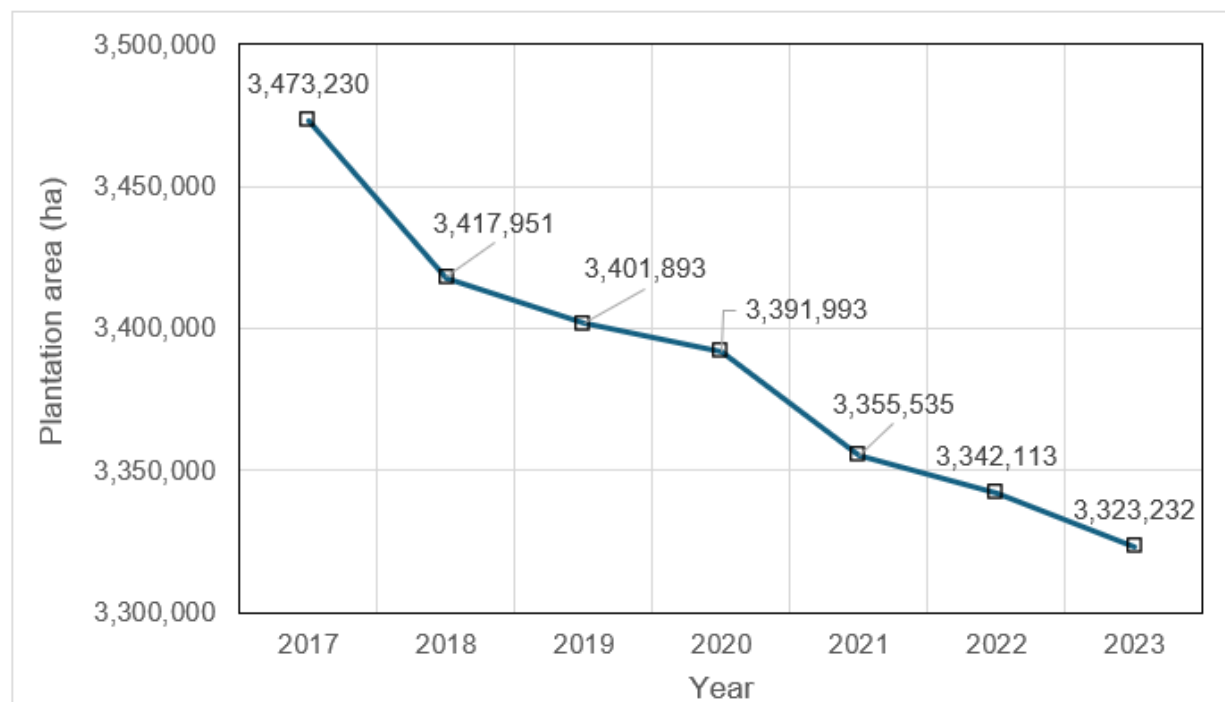


Figure 5

Fig. 4 The change in the total area of coconut plantations in Indonesia over the years.

Source: Directorate General of Estate Crops (2022).

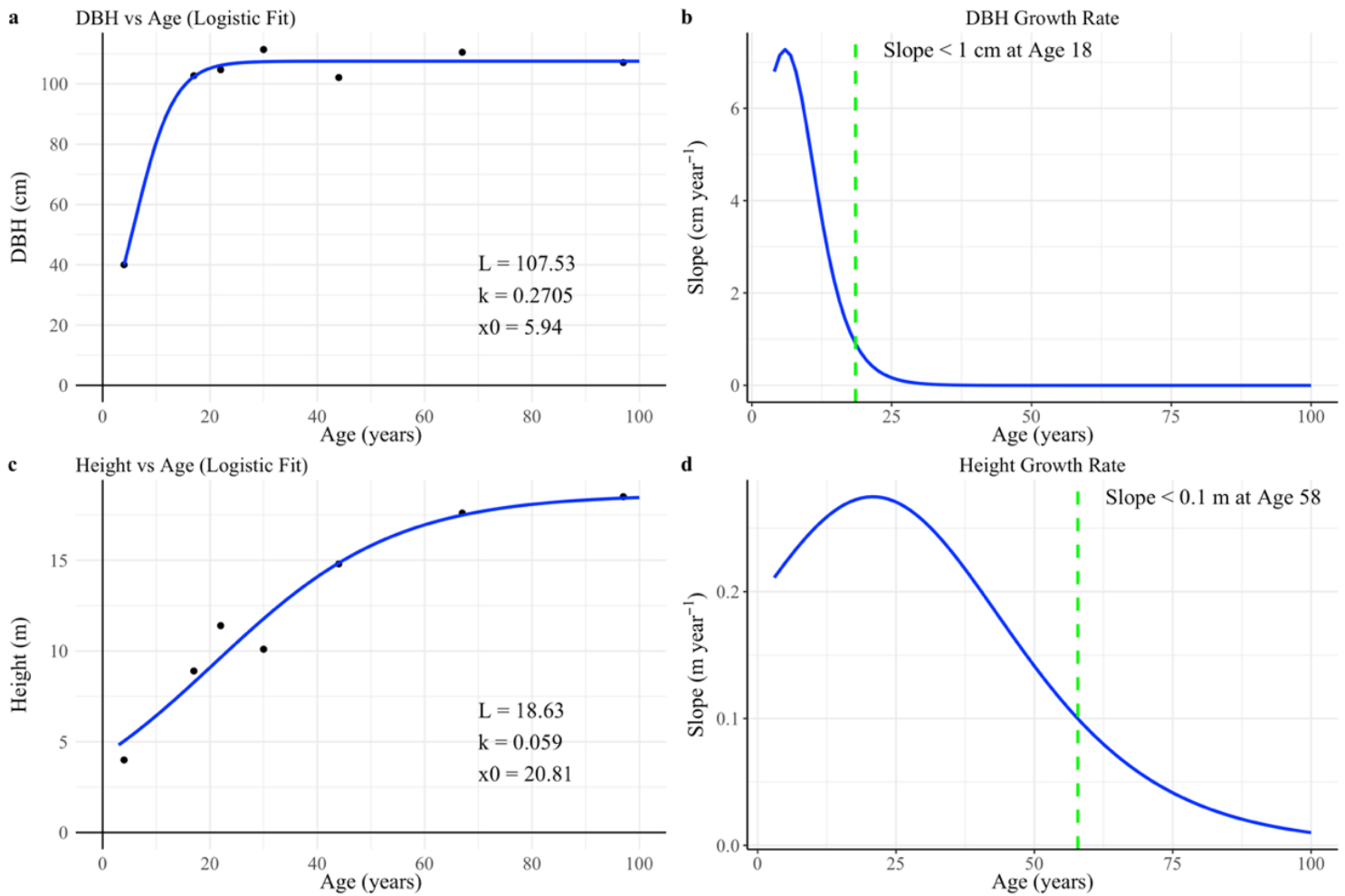


Figure 6

Fig. 5 Logistic growth modeling of diameter at breast height (DBH) and total height (TH) of *Cocos nucifera* based on age. (a) DBH growth with logistic curve fit ($L = 107.53 \text{ cm}$, $k = 0.2705$, $x_0 = 5.94 \text{ years}$), (b) First derivative of DBH curve showing the growth rate; DBH increment declines below 1 cm y^{-1} at age 18, (c) Height growth with logistic curve fit ($L = 18.63 \text{ m}$, $k = 0.059$, $x_0 = 20.81 \text{ years}$), (d) First derivative of height curve; height increment falls below 0.1 m y^{-1} at age 58.

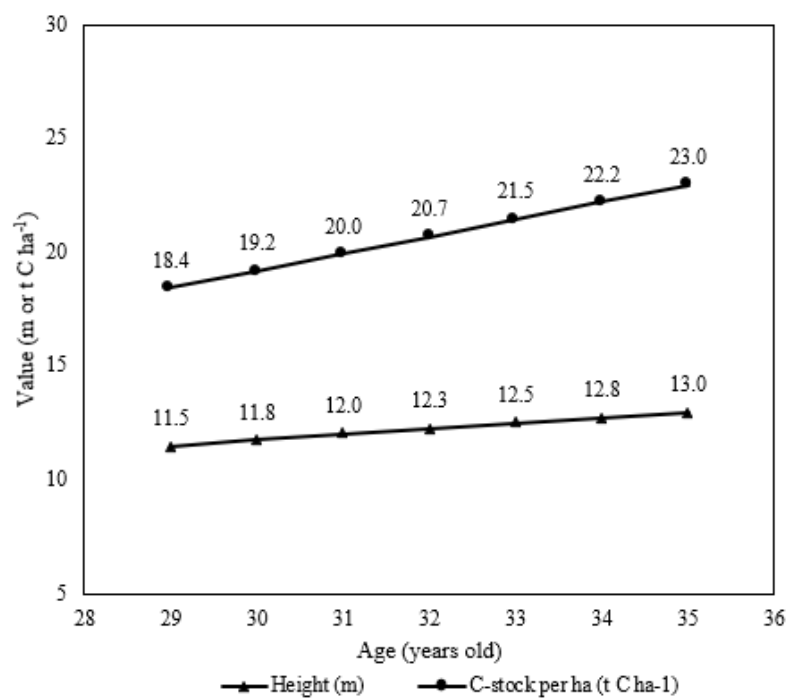


Figure 7

Fig. 6 Relationship between coconut tree height and carbon stock at different ages.

Supplementary Files

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- [floatimage1.png](#)